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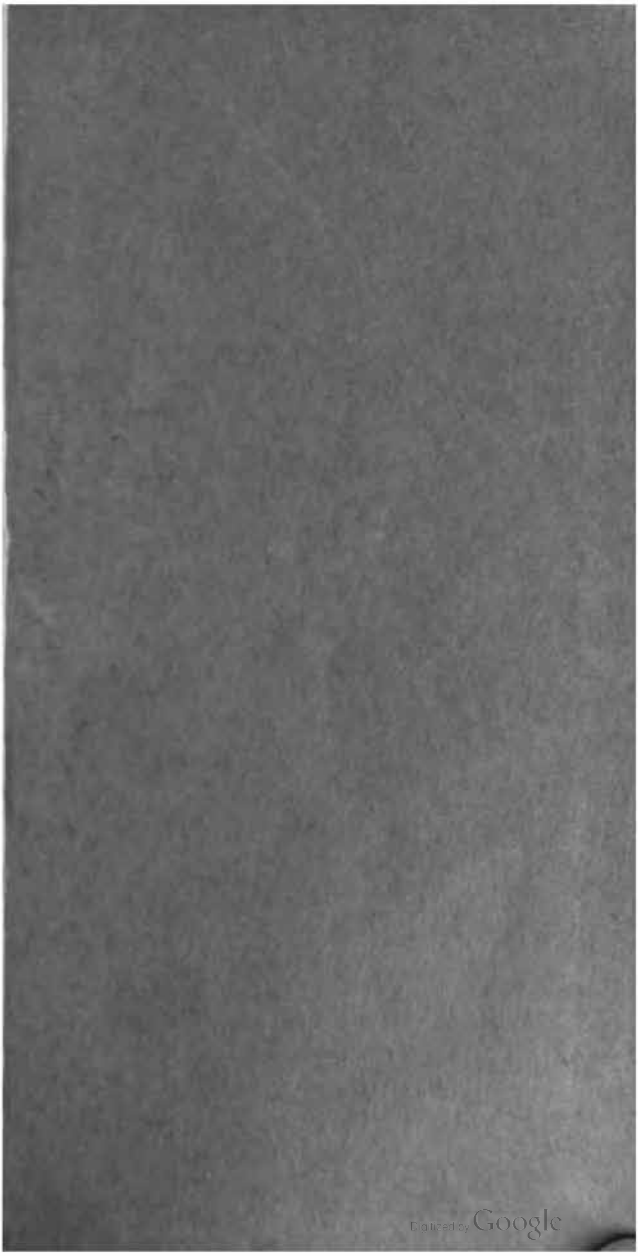
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HANDBOOK

FOR

ELECTRICAL ENGINEERS

A REFERENCE BOOK FOR PRACTICING
ENGINEERS AND STUDENTS
OF ENGINEERING

COMPILED BY A STAFF OF SPECIALISTS

HAROLD PENDER
EDITOR-IN-CHIEF

WILLIAM A. DEL MAR
ASSOCIATE EDITOR-IN-CHIEF

SECOND EDITION
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1922

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The Publishers and the Editor-in-Chief will be grateful to reader this volume who will kindly call attention to any errors of omissio commission therein. It is intended to make our publications stand works of study and reference, and, to that end, the greatest accurac sought. It rarely happens that the early editions of books are free fr errors; but it is the endeavor of the Publishers to have them remov and it is therefore desired that the Editor-in-Chief may be aided in task of revision, from time to time, by the kindly criticism of read

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PREFACE TO SECOND EDITION

THE steady demand for this book since its first appearance in 1914 has shown conclusively that an encyclopedic handbook of Electrical Engineering is an indispensable tool to the engineer. Its use in a number of large universities has also shown that the encyclopedic arrangement is well adapted to the purposes of the class room.

Although in many respects electrical engineering practice to-day is much the same as it was in 1914, there have nevertheless been noteworthy developments in several branches of the industry, for example, in radio-communication, electric welding, electric ship propulsion, etc. Electrical science has also made considerable progress, especially in the development of the electron theory and its application to engineering.

In order to keep this Handbook abreast of the times, the publishers requested the editor in 1920 to undertake a thorough revision of the book. In line with this request, each article was submitted to the orginal contributor or other qualified person with the request that he go over it carefully, add new matter where the development of the art warranted, and bring the article up to date.

The result of this review was that nearly every article in the book has been revised, the amount of revision varying from a few lines to the entire article, according to the desires of the authors. While the greater part of the revisions appear in paragraphs interspersed throughout the book, new articles have been added on the following subjects:

Frequency Changers.
Ignition, Electric.
Phase Converters and Balancers.
Ships, Electric Propulsion of.
Starting and Lighting Systems for Automobiles.
Welding, Electric.

The following articles have been completely rewritten:

Ammeters.
Ampere-hour Meters.
Corona, Electric.
Dams.
Demand Meters.
Depreciation.
Electron Theory.
Heating and Cooking by Electricity.
Hydraulics.
Hydrology.
Insulating Materials.
Lighting of Trains by Electricity.
Oil, transformer.
Radio Communication (replacing the articles on Detectors, Electric Wave; Waves, Electromagnetic; Wave meters; Wireless Telegraphy and Wireless Telephony.
Standarization Rules and Standard Specifications.
Water Wheels and their Settings.
Water Wheels, Speed regulation of.

In addition to the above, extensive changes have been made in the following articles:

Alloys.
Buildings, Allowable Unit Stresses in.
Cross-Arms.

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Electrolysis.
Frequency Indicators.
Generators, Alternating Current.
Grounding for Electric Circuits.
Heat and Thermal Properties.
Insulators, Overhead.
Lamps and Illumination.
Motors, Alternating-current Commutator.
Oscillographs.
Power Factor Indicators and Reactive Volt-ampere Indicators.
Resistance and Conductance.
Rubber.
Signalling, Railway.
Synchronizers and Synchroscopes.
Transformers, Instrument.
Voltmeters.
Watt-hour Meters.
Wattmeters.
Wires and Cables, Bare.
Wires and Cables, Insulated.
Wiring of Buildings.

The Standards of the American Institute of Electrical Engineers (formerly known as the Standardization Rules) are given in full at the end of the book. These standards are a verbatim copy of the 1922 edition and are reproduced with the permission of the Board of Directors of the Institute. It is the plan of the publishers to revise these Standards whenever a new edition is published by the Institute, which in the past has been about every two years.

While the encyclopedic arrangement of the book especially commends it for reference purposes, no difficulty attends its use for consecutive study, if the order given in the *Topical List of Articles* is followed. This list is arranged in the order usually followed in the course of class studies. Some teachers may prefer to vary the order of reading, and will find it easier to do so by the aid of such a list, than where the text itself is arranged in some arbitrary order.

Care has been taken to make each article a readable compendium on its subject and not merely a series of disconnected paragraphs containing miscellaneous data, a too common fault in books of this class.

In the preparation of the Second Edition, the editor has been fortunate in having associated with him, as Associate Editor-in-Chief, Mr. William A. Del Mar. Mr. Del Mar has supervised all articles dealing with Electric Railways, Wires and Cables, Transmission and Distribution, Switch Gear and Control Apparatus, Electric Meters and Instruments for commercial use, Mathematics, and Mathematical Tables. These articles make up about one-third of the entire book.

A glance at the make-up of the "Editorial Staff" will show the care with which experts in each line have been selected. In several cases men were selected because of notable investigations or researches which they were conducting at the time along the lines of the articles assigned to them.

The editor takes this opportunity to express his sincere appreciation of the earnest effort of all members of the Editorial Staff to make this new edition of the Handbook throughly representative of modern engineering practice.

HAROLD PENDER

PHILADELPHIA, PA.,
September 1, 1922.

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FROM THE PREFACE TO THE FIRST EDITION

1. This Handbook has been prepared primarily for the practicing engineer. With this end in view the matter has been so arranged as to be most readily found, and all *theoretical discussions have been segregated into separate articles.* Fundamental or "theoretical" principles are fully but concisely treated in articles dealing with such matters and nothing else, e.g., such article as *Electricity and Magnetism, Principles of; Alternating Currents; Electrochemistry, Principles of; Mechanics, Principles of; Hydraulics; etc.* Therefore, in articles dealing with practical matters only enough is said of theory to indicate the general principle of which the matter in hand may be a specific application.

2. This book is primarily for Electrical Engineers, but the general arrangement of the subject matter and the method of treatment adopted will make the book a useful reference book for mechanical, civil, mining and other engineers who have occasion to utilize any of the numerous applications of electricity in their special fields. Considerable space has been devoted to those matters pertaining to the applications of motors in all branches of modern industry; see the article on *Motors, Industrial Applications of*, and the numerous cross references there given.

3. Although this book deals primarily with electrotechnical matters, a large amount of space has been devoted to those mechanical and civil engineering subjects which are closely related to electrical engineering practice.

4. Numerous mathematical tables and relations are given. Among these may be mentioned the articles on *Logarithms, Trigonometric Functions, Hyperbolic Functions, Exponential Functions, Derivatives, Integrals, Indeterminate Forms, Equations*, etc.

5. In spite of the fact that this book contains upwards of 2000 pages, many of the articles have been greatly condensed. However, it has been the consistent endeavor of the editorial staff to make each article sufficiently complete so that the information given therein should be of the greatest practical value.

6. Although this book has been prepared primarily for the practicing engineer, it is believed that the method of treatment adopted will render many of the articles suitable as the bases for courses of lectures in technical schools. A teacher usually has his own method of presenting a subject, and sometimes a textbook proves more of a handicap than a help; yet every teacher recognizes the desirability of putting in the hands of his students some sort of synopsis or syllabus which will serve as a general guide.

7. Experience has shown that the alphabetical arrangement is eminently fitted for an encyclopedia of general information; a like arrangement is equally applicable to a reference book dealing only with engineering topics. The subject matter of this book has therefore been disposed in 266 articles alphabetically arranged. The user of the book will undoubtediy find it more convenient at first to refer directly to this detailed index, but as soon as he becomes acquainted with the main article headings, he will be able to turn directly to the article containing the information he may be seeking without referring to the index.

8. One feature of this Handbook which should prove particularly helpful is that the same plan of treatment has been consistently followed in all the articles, at least wherever possible. This applies particularly to articles dealing with apparatus or machinery, the plan of treatment being:

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a. General Description and Definitions.
b. Brief Statement of Application.
c. Principle of Operation.
d. Design.
e. Testing.
f. Performance.
g. Specifications.
h. Installation.
i. Operation.
j. Dimensions, Weights and Costs.
k. Bibliography.

In some instances it was found advisable to vary this scheme more or less, but the general sequence of topics was adhered to as closely as possible. At the beginning of each article occupying more than fifteen pages is given a brief table of contents.

9. It is believed that the cost data given in the various articles will prove particularly valuable when properly used. These data in most instances are given as unit costs, and usually the ordinary *range* of cost is given. It has been the experience of the writer that students and recent technical graduates are sadly lacking in even the roughest idea of the cost of apparatus and structures. It is primarily to supply a rough idea of such costs that the cost curves and figures are given in the various articles. The cost data given will also be found suitable for preliminary estimates; but for close estimating, current prices should of course be obtained from the makers of the apparatus, or, in the case of construction work, some one having personal experience in similar work should be consulted.

10. The bibliography given at the end of each article is intended to direct the reader to more extended information in treatises and current periodicals. The space available for these bibliographies has made it necessary to omit many important works and technical articles. The references are usually those in which the writer of the article in question is most familiar and which he has found most useful. They are therefore in no sense complete, but will be found a very useful guide in the search for additional information. In many instances a blank space of a half page or more is left after the bibliography; this space may be advantageously utilized by the insertion of references to new books and articles as they appear.

11. The articles in this Handbook have been prepared by an editorial staff of experts; this staff is given on pp. iii and iv.

The Editor-in-Chief wishes to take this opportunity of expressing his sincere appreciation of the hearty coöperation of the entire editorial staff and of the spirit of coöperation and generosity shown by the publishers throughout the preparation of this book.

HAROLD PENDER.

East Bluehill, Me.,
September 5, 1914.

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TOPICAL LIST OF ARTICLES

The articles listed under each main heading, except those of a statistical nature, are in an order appropriate for consecutive reading or assignment for class-room instruction.

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H. M. Goodwin (b)
R. G. Hudson (c)
P. G. Agnew (d)

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W. Kent

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ABBREVIATIONS AND SYMBOLS.—(*See also Units and Conversion Factors.*) At the meeting of the International Electrotechnical Commission in Berlin, in 1913, a list of abbreviations for electrotechnical and related quantities was adopted. The American Institute of Electrical Engineers has also adopted (1918) a list of such symbols, which for the most part is in agreement with the list of the I.E.C., but contains certain additional symbols not included in the I.E.C. list. In the following table both lists are given. See the *Standardization Rules of the A.I.E.E.* for symbols for photometric quantities.

STANDARD SYMBOLS AND ABBREVIATIONS

Name of quantity	Symbol for the quantity		Name of Unit, adopted by A.I.E.E.	Abbreviation for the unit to be used only after numerical values	
	Adopted by I.E.C. (*See Note 1*)	Adopted by A.I.E.E.		Adopted by I.E.C.	Adopted by A.I.E.E.
Acceleration due to gravity	g	g	centimeter per second per second	—	cm. per sec. per sec.
Acceleration due to gravity, Standard (=980.665 cm. per sec. per sec.) (*Note 5*)	—	g_n	centimeter per second per second	—	cm. per sec. per sec.
Admittance	—	Y, y	mho	—	—
Angles	α, β, γ, etc.	—	—	—	—
Angular velocity ($2\pi f$)	ω	ω	radian per second	—	—
Capacity (Capacitance)	C	C	farad	F	—
Conductance	G	g	mho	—	—
Conductivity (*Note 6*)	—	γ	mho per centimeter	—	mho per cm.
Current	I	I, i	ampere	A	—
Dielectric constant	ϵ	ϵ or k	—	—	—
Dielectric field intensity or electric force	—	F	—	—	—
Dielectric flux	—	ψ	—	—	—
Dielectric flux density	D	D	—	—	—
Efficiency	η	η	per cent	—	(*Note 7*)
Electromotive force (e.m.f.)	E	E, e	volt	V	—
Energy	W (U)	U or W	joule or watt-hour	—	—
Frequency	$f(\nu)$	f	cycle per second	—	~
Impedance	Z $(\mathfrak{Z})$	Z, z	ohm	(*Note 2*)	—
Inductance (or coefficient of self-induction)	L $(\mathfrak{L})$	L	henry	H	—

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STANDARD SYMBOLS AND ABBREVIATIONS (*Continued*)

Name of quantity	Symbol for the quantity: Adopted by I.E.C. (*See Note 1*)	Symbol for the quantity: Adopted by A.I.E.E.	Name of unit adopted by A.I.E.E.	Abbreviations for the unit to be used only after numerical values: Adopted by I.E.C.	Abbreviations for the unit to be used only after numerical values: Adopted by A.I.E.E.
Inductance, mutual (or coefficient of mutual induction)	M ($\mathfrak{M}$)	M	henry	H	—
Length	l (*Note 3*)	l	centimeter	cm.	cm.
Magnetic flux (*Note 4*)	Φ ($\mathcal{F}$)	Φ, ϕ	maxwell	—	—
Magnetic flux density	B ($\mathfrak{B}$)	B, $\mathfrak{B}$	gauss (*Note 4*)	—	—
Magnetization, intensity of	J ($\mathcal{J}$)	J	—	—	—
Magnetizing force or magnetic field intensity	H ($\mathcal{H}$)	H, $\mathcal{H}$	gilbert per centimeter or gauss	—	gilbert per cm.
Magnetomotive force (m.m.f.)	—	$\mathcal{F}$	gilbert (*Note 4*)	—	—
Mass	m (*Note 3*)	m	gram	—	g.
Period	T	—	—	—	—
Permeability	μ	μ	—	—	—
Phase displacement (or phase angle)	ϕ	θ, ϕ	degree or radian	—	(*Note 5*)
Potential difference (p.d.)	—	V, v or E, e	volt	V	—
Power	P	P, p	watt	W	—
Quantity of electricity	Q	Q, q	coulomb or ampere-hour	C	—
Reactance	X ($\mathfrak{X}$)	X, x	ohm	(*Note 2*)	—
Reluctance	S ($\mathfrak{R}$)	$\mathcal{R}$	—	—	—
Resistance	R	R, r	ohm	(*Note 2*)	—
Resistivity (*Note 6*)	ρ	ρ	ohm-centimeter	—	ohm-cm.
Revolutions per unit time	n	n	revolution per second	—	rev. per sec.
Susceptance	—	b	mho	—	—
Susceptibility	κ	κ	—	—	—
Temperature, absolute	T, Θ	—	degree centigrade	—	—
Temperature, centigrade	t(θ, ϑ)	T, t, θ	degree centigrade	—	deg.cent. (*Note 8*)
Time	t (*Note 3*)	t	second	—	sec.
Turns or number of conductors	—	N	convolution or turn	—	—
Voltage	—	E, e or V, v	volt	V	—
Work, mechanical	A (W)	W or A	joule or watt-hour	—	—

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NOTES. — (1) The symbols in brackets are recommended in case the principal symbol is unsuitable; instead of the script letters heavy-faced or other special type may be used. (2) One or other of the symbols O and Ω is recommended provisionally to represent the ohm. The symbol Ω should no longer be employed for the megohm. (3) In dimensional equations the capital letters *L*, *M* and *T* for length, mass and time respectively are to be employed. (4) An additional unit for m.m.f. is the "ampere-turn", for flux the "line", and for magnetic flux density "maxwell per sq. in." (5) This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45° latitude and sea level. Later researches, however, have shown that the most reliable value for 45° and sea-level is slightly different; but this does not affect the standard value given above. (6) The numerical values of these quantities are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube as commonly stated. (7) The symbol % is commonly used for per cent, but is not recommended by the A.I.E.E. (8) The symbol ° is commonly used for degree, ° C. for degree centigrade and ° F. for degree Fahrenheit; these symbols are not recommended by the A.I.E.E.

In addition to the symbols for the units given in the above table, the I.E.C. adopted (1913) the following signs to be used only after numerical values.

Volt-coulomb	VC	Kilovolt-ampere	kVA
Watt-hour	Wh	Kilowatt-hour	kWh
Volt-ampere	VA	Sign for milli-	m
Ampere-hour	Ah	Sign for kilo-	k
Milliampere	mA	Sign for micro- or micr-	μ
Kilowatt	kW	Sign for mega- or meg-	M

SPECIAL RULES IN REGARD TO SYMBOLS. — The following rules were also adopted at the Berlin meeting (1913) of I.E.C., and are concurred in by the Standards Committee of the A.I.E.E. The latter committee also recommends that vector quantities be printed in bold-face capitals.

Instantaneous values of electrical quantities which vary with the time to be represented by small letters. In case of ambiguity they may be followed by the subscript "t."

Virtual (*i.e., effective or r.m.s.*) or constant values of electrical quantities to be represented by capital letters.

Maximum values of periodic electrical and magnetic quantities to be represented by capital letters followed by the subscript "m."

In cases where it is desirable to distinguish magnetic quantities from electric quantities, magnetic quantities should be represented by capital letters of either script, heavy-faced or other special type. Script letters should not be used except for magnetic quantities.

Angles should be represented by small Greek letters.

Dimensionless and specific quantities should be represented wherever possible by small Greek letters.

Ordinary numerals as exponentials shall exclusively be employed to represent powers. (In consequence, it is desirable that the expression $\sin^{-1}x$, $\tan^{-1}x$, employed in certain countries, be expressed by arc sin x, arc tan x.)

The comma and the full-stop shall be employed for separating decimals according to the custom of the country, but the separation between any three digits constituting a whole number shall be indicated by a space and not by a full-stop or a comma(1 000 000).

For the multiplication of numbers and geometric quantities indicated by two letters, it is recommended to use the sign × and the full-stop only when there is no possible ambiguity.

To indicate division in a formula it is recommended that the horizontal bar and the colon be employed. Nevertheless the oblique line may be used when

there is no possibility of ambiguity; when necessary, ordinary brackets ( ), square brackets [ ], and braces { } may be employed to obtain clearness.

INSTITUTE (A.I.E.E.) STYLE. — The Editing Committee of the American Institute of Electrical Engineers issues a little pamphlet called "Suggestions to Authors," in which are given the rules of the Institute in regard to manuscript submitted for publication. The following list of abbreviations is taken from the last edition (1919) of these rules.

Name	A.I.E.E. style	Name	A.I.E.E. style
Alternating current	spell out, or a-c. as adjective.	Kilowatts	kw.
Amperes	spell out	Kilowatt-hours	kw-hr.
Brake horse power	b.h.p.	Magnetomotive force	m.m.f.
Boiler horse power	boiler h.p.	Mean effective pressure	spell out
British thermal units	B.t.u.	Miles	mi.
Candle power	c.p.	Miles per hour per second	mi. per hr. per sec.
Centigrade	cent.	Millimeters	mm.
Centimeters	cm.	Milligrams	mg.
Circular mils	cir. mils	Minutes	min.
Counter electromotive force	counter e.m.f.	Meters	m.
Cubic	cu.	Meter-kilograms	m-kg.
Diameter	spell out	Microfarad	spell out
Direct current	spell out, or d-c. as adjective.	Ohms	spell out
Electric horse power	e.h.p.	Per	spell out
Electromotive force	e.m.f.	Percentage	per cent, or % in tabular matter.
Fahrenheit	fahr.	Pounds	lb.
Feet	ft.	Power-factor	spell out
Foot-pounds	ft-lb.	Revolutions per minute	rev. per min., or r. p. m. in tabular matter.
Gallons	gal.	Seconds	sec.
Grains	gr.	Square	sq.
Grams	g.	Square-root-of-mean-square	effective, or r.m.s.
Gram-calories	g-cal.	Ton-mile	spell out
High-pressure cylinder	spell out	Tons	spell out
Hours	hr.	Volts	spell out
Inches	in.	Volt-amperes	spell out
Indicated horse power	i.h.p.	Watts	spell out
Kilogram	kg.	Watt-hours	watt-hr.
Kilogram-meters	kg-m.	Watts per candle power	watts per c.p.
Kilogram-calories	kg-cal.	Yards	yd.
Kilometers	km.		
Kilovolts	kv.		
Kilovolt-amperes	kv-a.		

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1. Use "Fig.," not "Figure." Example: "Fig. 3" and not "Figure 3."

2. In all decimal numbers having no units, a cipher should be placed before the decimal point. Example: "0.32 lb." not ".32 lb."

3. Use the word "*by*" instead of "x" in giving dimensions. Example: "8 by 12 in." not "8x12 in."

4. Never use the characters (') and (") to indicate either feet and inches, or minutes and seconds as period of time.

5. Do not use the expression "rotary" or "rotary converter"; use "converter" or "synchronous converter."

6. Do not use a descriptive adjective as a synonym for the noun described. Example: a "spare transformer," not a "spare"; a "portable instrument," not a "portable"; "automatic apparatus," not "automatics"; a "short circuit," not a "short."

7. Do not use the words "primary" and "secondary" in connection with transformer windings. Use instead "high-tension" and "low-tension."

8. Avoid dividing mathematical expressions into two or more parts if possible. If division is necessary, divide *after* a plus, minus or equality sign.

9. Use the English plural where there is a choice. For example: abscissas, not abscissae; formulas, not formulae.

10. Data is the plural form and takes plural verb, etc.

11. Make compounds of two-word adjectives, as direct-current motor, three-phase circuit, etc.

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ACIDS. — The properties of some of the more important acids used in the arts are given in the following paragraphs.

Aqua Regia is a mixture of one part of nitric acid and three parts of hydrochloric acid. It obtains its name from the fact that it will dissolve gold. It is used as an oxidizing agent and for dissolving metals, such as platinum, gold, etc., which are insoluble in other acids. It should be used as soon as possible after being prepared since it loses its characteristic properties after standing a short time. It is distinguished by its reddish yellow color and its chlorine-like odor.

Hydrochloric Acid or Muriatic Acid (HCl) is an aqueous solution of hydrogen chloride, a colorless, pungent gas. While the pure acid is colorless, the commercial acid is a yellowish liquid, the color being due to impurities. The concentrated acid has a specific gravity of 1.16 and contains 32 per cent of HCl. The dilute acid has a specific gravity of 1.09 and contains 18.4 per cent of HCl. Hydrochloric acid is used extensively in the manufacture of chlorine, hydrogen and bleaching powder and is prepared as a by-product of the soda manufacture. The acid is recognized by its odor and by the dense fumes it makes with ammonia.

Hydrofluoric Acid (HF) is an aqueous solution of anhydrous hydrogen fluoride, a colorless, fuming liquid. The acid, when saturated, has a specific gravity of 1.25. Its gas is poisonous if inhaled and causes swellings and pain if applied to the skin. It readily dissolves glass and must be kept in platinum, lead, rubber or wax vessels. The acid is most commonly used for etching glass.

Nitric Acid (HNO_3) is a colorless fuming liquid with a specific gravity of 1.55 at 0° C. Commercial nitric acid has a specific gravity of 1.414 at 15° C. and contains 68 per cent of the pure acid. The commercial acid is yellowish in color and the pure acid becomes yellow if exposed to the light. Nitric acid is a powerful oxidizing agent and decomposes organic substances. The acid is used in the manufacture of many chemical substances. Concentrated nitric acid is best recognized by the red fumes, which are given off when the acid is acting upon a metal.

Sulphuric Acid or Oil of Vitriol (H_2SO_4) is a colorless oily liquid. The concentrated acid has a specific gravity of 1.854 at 0° C. and contains 1.5 per cent of water. Commercial sulphuric acid, sometimes known as "brown acid," has a specific gravity of 1.720 and usually contains arsenic as an impurity. Sulphuric acid boils at 290° C., the temperature increasing to 338° C. as the boiling continues. The acid has a strong affinity for water and is frequently used as a drying agent. When diluted with water, the mixing should be performed gradually as great heat is evolved. The acid should be added to the water as the addition of water to the acid may produce violent explosions due to the ebullition of the water.

Sulphuric acid is used in the manufacture of many chemical substances, in dyeing and in refining petroleum. It is a fairly good conductor of electricity and is used in the lead type of storage batteries (q.v.). The acid is recognized by its weight, by its carbonizing action upon organic bodies and by the white precipitate formed by the addition of barium chloride.

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ALLOYS — (*See also Wires, Resistor.*) In this article is given a brief description of some of the more common alloys used in engineering work, together with specific data on some of their more important properties. It should be noted that there may be a considerable departure from the quantitative values given. Traces are not included in the chemical compositions given. The various alloys are listed alphabetically. Additional data on their various physical properties will be found in the articles on *Heat and Thermal Properties; Resistance and Conductance; Strength and Elasticity; Weight of Materials, etc.*

Acid-resisting Alloys. — Alloys of iron and chromium and of iron and silicon are used for containers, partly replacing stoneware, in the manufacture of acids. Ferro-chrome is not attacked by sulphuric or nitric acid, but is readily attacked by hydrochloric acid. Silicon-iron containing 14 to 15 per cent silicon (with a small amount of Mn) is likewise not attacked by sulphuric or nitric acid. Such an alloy has a specific gravity of about 7, a melting point of about 2500° F., a tensile strength of about 15,000 pounds per square inch, and a compressive strength of about 70,000 pounds per square inch. Acid-resisting silicon irons are sold under various trade names, such as "duriron," "tantiron," etc. (*W. C. Cornell, Chem. News, 116, p. 92, Aug. 24, 1917.*)

Aluminum Brass (70.5 Cu, 26.4 Zn, 3.1 Al). — The tensile strength is about 21 tons per square inch, the elastic limit 8.5 tons per square inch and the elongation 50 per cent. Aluminum brass is used when very accurate castings are desired, e.g., for pumps, valves, pinions and propellers. It can be rolled and forged while hot but is not easily worked when the aluminum content exceeds 4 per cent.

Aluminum Bronze (95 Cu, 5 Al). — The tensile strength is about 28 tons per square inch, the elastic limit 12 tons per square inch and the elongation 75 per cent. Aluminum bronze containing less than 7.5 per cent Al is very ductile. With more than 7.5 per cent Al the alloy becomes brittle but increases in tensile strength. Tubes, propellers and propeller shafts are sometimes made of aluminum bronze. It has not been found to withstand intense heat for any length of time without fracturing. It is sometimes drawn into wire for use as an electrical resistance.

Amalgams are alloys of mercury and other metals. When newly made amalgams are plastic but harden in a short time without appreciable expansion or contraction. The common metals combined with mercury to form amalgams are tin, copper, cadmium, bismuth, silver and gold. Amalgams are used for silvering glass and as a cement for metals and porcelain.

Anti-friction Metals are alloys of copper, tin, zinc, lead and antimony in various combinations. These alloys are commonly used in bearings for revolving shafts and for valve packings. See *Babbitt and Bearing Metals* below.

Babbitt Metal (4 Cu, 69 Zn, 19 Sn, 5 Pb, 3 Sb) is used extensively for bearings, the composition stated being that used for car bearings of the Pennsylvania Railroad. See also the article on *Bearings.*

Bearing Metals for use in specific cases are illustrated by the following examples: Locomotive (82 Cu, 8 Zn, 10 Sn), railway car (90 Cu, 10 Sn), low-speed bearing (16 Sn, 84 Pb). There are a large number of anti-friction metals in use, the object in the composition of each of them being to procure a metal which is as hard as possible but plastic enough to be moulded by the shaft into a shape offering a minimum friction.

Brass is an alloy of copper and zinc and often contains small percentages of lead, tin, arsenic, antimony, bismuth and iron. *Cast brass* usually consists of 66 per cent of copper and 34 per cent of zinc. *Low brasses,* suitable for hot

rolling contain from 55 per cent to 63 per cent of copper. *High brasses*, suitable for cold rolling and drawing, contain from 60 per cent to 70 per cent of copper. In drawing brass it must be annealed and cleaned in acid at frequent intervals to prevent fracture. The ductility of brass is impaired if the lead content exceeds 0.1 per cent, but in the case of brasses intended for turning about 2 per cent of lead is often added so that the brass may be turned at higher speed and possess a better finish. Brass is made harder by the addition of about 1 per cent of tin and is found to better withstand corrosion due to salt water. The presence of small quantities of arsenic, antimony or bismuth in brass is liable to cause it to crack when rolled. The addition of 1 per cent to 3 per cent of iron to brass produces a harder and stronger alloy. The tensile strength of commercial brass ranges from 15 to 40 tons per square inch and the elongation varies from 10 per cent to 40 per cent depending upon the composition.

Bronze is a name used to designate various alloys of copper and tin with other metals. Ordinary bronze is an alloy of copper. tin, and zinc, and melts about 980° C. See also *Aluminum Bronze*, *Manganese Bronze*, and *Phosphor Bronze* in this article.

Duralumin is an alloy whose composition varies between the limits Cu, 3 to 4.5 per cent; Mg, 0.4 to 1.0 per cent; Mn, 0 to 0.7 per cent; Fe, 0.4 to 10 per cent; Si, 0.3 to 0.6 per cent; and the balance aluminum. It has a specific gravity of 2.85 and possesses the remarkable property of being appreciably hardened by quenching from temperatures below its melting point and subsequent ageing. (*Amer. Inst. Min. Eng., Bull. No. 150, 1919.*)

Ferro-Alloys. — See above under *Acid-resisting Alloys* and the article on *Steel*.

Fusible (Low Melting Point) Metals consist of various alloys of bismuth, lead, tin and cadmium. The chemical composition of the common fusible metals and their melting points are given in the following table:

Alloy	Composition				Melting point °C.
	Bi	Pb	Sn	Cd	
Newton's alloy	50.0	31.25	18.75	.....	95
Rose's alloy	50.0	26.00	24.00	.....	100
Darcet's alloy	50.0	25.00	25.00	.....	93
Wood's alloy	50.0	24.00	14.00	12.00	66–71
Lipowitz' alloy	50.0	27.00	13.00	10.00	60

Lower melting points are obtained by the addition of mercury.

German Silver is an alloy of copper, nickel and zinc in various combinations. It is sometimes called nickel silver, argentan, packfong, silveroid, silverite or electrum. German silver is extensively used because of its ductility; it can be readily rolled, hammered and drawn. It is hard, tough and not easily corroded. Its composition varies from (50 Cu, 30 Ni, 20 Zn) to (57 Cu, 7 Ni 36 Zn), the nickel content decreasing as the zinc increases. The usual impurities found in German silver are iron, lead and tin. The presence of iron in the alloy makes it stronger, harder and more elastic. Tin makes the alloy brittle. Lead is sometimes added to render the alloy more workable but should not be added when the alloy is to be rolled. German silver is drawn into wires for use as a

ectrical resistance and has been drawn into tubes for use in locomotive boilers. e *Wires, Resistor*.

Gun Metal is a bronze consisting of about 90 per cent of copper and 10 per nt of tin. The tensile strength varies from 12 to 16 tons per square inch, pending upon the method of working. Melting point 980 to 995° C. It is echanically strong and elastic and withstands severe shocks without fracture. A small amount of lead is added to gun metal, the alloy is more easily turned filed. Better castings are made by the addition of a small amount of zinc d the alloy is made harder by adding a small percentage of iron.

Manganese Bronze is an alloy containing copper, tin, zinc, lead, iron and manganese in various combinations. Alloys containing from 4 per cent to 6 per nt of manganese possess high tensile strength at high temperatures and are before used for fire-box stays. High tensile strength at ordinary temperatures is obtained, however, by the addition of very small quantities of manganese. The composition of manganese bronze for certain specific uses is as ws. For hydraulic machinery (82 Cu, 8 Sn, 5 Zn, 3Pb, 2Mn); for forging 5 Cu, 38.4 Zn, 1.6 Fe, 0.02 Mn). The tensile strength ranges from 27 to tons per square inch but if the alloy is cold-rolled, a tensile strength of 50 tons square inch may be obtained. Manganese bronze is often used in place of or copper, when a higher tensile strength is required. It is not easily ed and may be bent when hot or cold.

Magnetic Alloys. — See the article on *Magnetic Properties of Iron and er Metals*.

Monel Metal is described in the article on *Wires, Resistance*. It has a sile strength of 40 tons per square inch at air temperature and 29 tons per are inch at 500° C. It is used for pump rods and valves as well as for resistor wires. (*J. Arnott, Engineering, 106, p. 451, Oct. 25, 1918.*)

Non-expansive Alloys are composed of iron, nickel and carbon. *Platinite* ains 46 per cent of nickel and 0.15 per cent of carbon. *Invar* contains 36 per nt of nickel and 0.2 per cent of carbon. Its coefficient of expansion ranges om 8×10^{-7} to 25×10^{-7} per degree centigrade. These alloys are used extensively in scientific instruments for standard measures of length and in candescent lamps where the wire connections fused into the glass must not small enough to fracture the glass.

Phosphor Bronze consists of copper, tin and phosphorus in various proportions, the phosphorus content rarely exceeding 2 per cent. The most useful property of phosphor bronze is its hardness and resistance to wear. Phosphor bronzes containing (A) 8 to 10 per cent of tin and 0.5 to 0.7 per cent of phosphorus are used for valves, pumps, propellers and boiler fittings, (B) 10 to 12 per nt of tin and 0.7 to 1 per cent of phosphorus are used for worms and gears nd (C) 10 to 12 per cent of tin and 1 to 1.5 per cent of phosphorus are used for ars, gears and bearings where the wear is excessive. The tensile strength ges from 10 to 15 tons per square inch, the elastic limit from 5 to 7 tons per uare inch and the percentage elongation from 2 to 6 per cent.

Platinum Substitutes. — Alloys of gold and silver with palladium have en recently developed as a substitute for platinum for contacts and sparking ints in magnetos.

Pyrophoric Alloys are certain alloys of rare earths, especially ferrocrium, which give a shower of sparks when filed or struck. Sb and Bi are added per cent) to harden the alloy and copper (5 per cent) to produce a low melting int and a smooth casting product. (*Engineering and Mining Journ., p. 212, 17.*)

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Resistance Alloys. — See article on *Wires, Resistor*.

Solder is an alloy of tin and lead. Cadmium may be used as a substitute fo part of the tin, 80 Pb, 10 Sn, 10 Cd being a satisfactory solder. *Hard* or ti solder contains 50 per cent of tin and 50 per cent of lead and melts at 370° F *Soft* or plumber's solder contains 33.3 per cent of tin and 66.6 per cent of lea and melts at 441° F.

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ALTERNATING CURRENTS. — (*See also Electricity and Magnetism, Principles of; Generators, Alternating-current; Motors, Alternating-current; Resistance and Conductance, Electric; Skin Effect; Transformers; Wave Analysis, &c.*).

GENERAL DEFINITIONS. — (*See also Standardisation Rules of the A.I.E.E.*). To avoid repetition the following definitions are given in terms of electric current; they also apply to electromotive forces, potential differences or to any other functions of time.

An alternating current is defined as a current which varies continuously with time from a constant maximum value in one direction to an equal maximum value in the opposite direction and back again to the same maximum in the first direction, repeating this cycle of values over and over again in *equal* intervals of time.

Period, Frequency and Alternations. — The period of an alternating current is the time taken for the current to pass through a complete cycle of positive and negative values.

The frequency or number of cycles per second is the number of periods per second.

The number of alternations per minute is the total number of times per minute that the current changes in direction, from positive to negative and from negative to positive. In engineering practice the number of cycles is usually referred to the second as the unit of time and the number of alternations is referred to the minute as the unit of time.

Let T be the period, f the frequency or number of cycles per second and a the number of alternations per minute, then

$$f = \frac{1}{T} \qquad \text{and} \qquad a = 120f = \frac{120}{T}. \tag{1}$$

The constant

$$\omega = 2\pi f = \frac{2\pi}{T} \tag{1a}$$

is sometimes called the angular velocity or angular frequency of the current. The name periodicity for this quantity is not recommended.

Instantaneous, Maximum and Average Values. — The instantaneous value of an alternating current is the value of the current at any instant. Instantaneous values of current, potential difference and electromotive force will be designated by small letters throughout this article, viz., i, v and e.

The maximum value of an alternating current is the numerical value of its maximum instantaneous value. Maximum values will be designated by capital letters with the subscript "m."

The average value of an alternating current for which the positive and negative half cycles are equal, which is usually the case, is defined as the numerical value of the average of its instantaneous values for a half cycle; the average over a complete cycle is of course zero. The general expression for the average value of a symmetrical current wave over a half cycle is

$$I_{\text{aver.}} = \frac{2}{T}\int_{t_1}^{t_1+\frac{1}{2}T} i\,dt, \tag{2}$$

where t_1 is a value of t at which $i = 0$; similarly for a voltage wave.

R.M.S. or Effective Values. — The square root of the mean of the squares of the instantaneous values of an alternating current over a complete period is called the r.m.s., or effective, value of the alternating current. In specifying the value of an alternating current as so many amperes this r.m.s. value is always meant unless specifically stated otherwise. In the same manner the square root of the mean of the squares of the instantaneous values of an alternating

potential difference over a complete period is called the r.m.s. value of the alternating potential difference. When the value of an alternating potential difference is specified as so many volts, this r.m.s. value is always meant unless specifically stated otherwise.

The reason for selecting this particular function of the instantaneous values of an alternating current or potential difference as the measure of the current or potential difference is that the deflection of all instruments used in alternating-current measurements is a function of this r.m.s. value. See *Ammeters, Electrodynamometers, Voltmeters, etc.* Moreover, the average power dissipated as heat in a resistance, r, when an alternating current of r.m.s. value I flows through it, is rI^2.

R.m.s. values will be designated throughout this article by capital letters without subscripts.

The general expression for the r.m.s. value of an alternating current is]

$$I = \sqrt{\frac{1}{T}\int_0^T i^2\,dt}, \tag{3}$$

and similarly for an alternating potential difference.

Form Factor. — The form factor of an alternating current is defined as the ratio of its r.m.s. to its average value, viz.,

$$\text{Form factor} = \frac{I}{I_{aver.}}, \tag{4}$$

and similarly for an alternating potential difference.

Crest or Peak Factor. — The crest factor, also called the peak factor or amplitude factor, of an alternating current is defined as the ratio of its maximum to its r.m.s. value, viz.,

$$\text{Crest factor} = \frac{I_m}{I}. \tag{5}$$

Instantaneous and Average Power. — Let v be the value at any instant of the potential drop from any point 1 to any other point 2, and let i be the instantaneous value of the current from 1 to 2 at this same instant; then the power input at this instant is

$$p = vi. \tag{6}$$

When v and i are *both* positive (i.e., in the direction from 1 to 2, say) or when they are *both* negative, the power input is positive, but when v is positive and i negative or vice versa, the power input is negative, i. e., there is an actual power output.

The average value of the product vi over a complete period for both v and i (or over any whole number of periods) is the average power input or output, usually called simply the power input or output (input when the average of vi is positive, output when the average of vi is negative), the word average being understood. That is, the average power input is

$$P = \frac{1}{T}\int_0^T p\,dt = \frac{1}{T}\int_0^T vi\,dt, \tag{7}$$

T being a complete period. For the actual measurement of alternating-current power see *Wattmeters*.

Power Factor. — Only in certain special cases (*see below*) is the average power input P equal to the product of the r.m.s. value V of the potential difference by the r.m.s. value I of the current; it can never be greater and as a rule is less. The ratio of the average power P to the product of the r.m.s. value V of the

potential difference by the r.m.s. value I of the current is called the power factor of the circuit between the terminals considered, i.e.,

$$\text{Power factor} = \frac{P}{VI}. \tag{8}$$

When V is expressed in volts and I in amperes then P must be in watts; when V is expressed in kilovolts and I in amperes P must be in kilowatts.

Volt-Amperes, Kilovolt-Amperes (kv-a.) — The product of the r.m.s. volts across the terminals of a circuit by the r.m.s. amperes through it is called the volt-amperes taken by the circuit; this product divided by 1000 is called the kilovolt-ampere input. Or, when V is in volts and I in amperes

$$\text{volt-amperes} = VI, \tag{9}$$

$$\text{kilovolt-amperes} = \frac{VI}{1000}. \tag{9a}$$

Kilovolt-amperes are usually abbreviated kv-a. or K.V.A., the former abbreviation being that recommended by the American Institute of Electrical Engineers and used in this book.

Effective Resistance (r) **and Conductance** (g). — The effective resistance of any portion of a circuit to an alternating current is the quotient of the average rate P_h at which heat is developed by this current, either directly in the substance through which it passes or indirectly as a consequence of the hysteresis and eddy-current losses produced by its magnetic field (*see Magnetic Properties of Iron*), divided by the square of the r.m.s. value I of the total current (conduction plus displacement or charging current) through this portion of the circuit, viz.,

$$r = \frac{P_h}{I^2}. \tag{10}$$

Similarly, calling V the r.m.s. value of the potential difference across the given portion of the circuit the effective conductance g of this portion of the circuit is defined by the relation

$$g = \frac{P_h}{V^2}. \tag{11}$$

In general, both r and g depend upon both the frequency and the wave-shape (*see below*) of the current and voltage but in many instances they may be considered as practically constant irrespective of the frequency or wave-shape. See the articles on *Resistance and Conductance* and *Skin Effect* for further discussion.

Impedance (z) **and Admittance** (y). — Let V be the r.m.s. value of the potential drop through any portion of a circuit due to its effective resistance, self-inductance and capacity (*see Electricity and Magnetism, Principles of*), i.e., if there is any other source of e.m.f. in the given portion of circuit (e.g., a generator or motor) V is the r.m.s. value of the potential drop which the same current would produce through this portion of circuit were this external source of e.m.f. removed. Then the quotient of the potential drop V by the r.m.s. value of the current I in this portion of the circuit, viz.,

$$z = \frac{V}{I}, \tag{12}$$

is defined as the impedance of this portion of the circuit.

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The reciprocal of the impedance, viz.,

$$y = \frac{1}{z} = \frac{I}{V}, \tag{13}$$

is defined as the admittance of the given portion of the circuit.

Impedance and admittance, as thus defined, both depend upon the frequency and wave-shape. Impedance is expressed in the same units as resistance (e.g. ohms), and admittance in the same units as conductance (e.g. mhos); see *Units and Conversion Factors*.

Reactance (x) and Susceptance (b). — The square root of the difference between the square of the impedance and the square of the effective resistance of a given portion of an electric circuit is defined as the reactance x of this portion of the circuit, viz.,

$$x = \sqrt{z^2 - r^2}. \tag{14}$$

The reactance of a coil of inductance L to a sine-wave current of frequency f is

$$x = 2\pi fL. \tag{14a}$$

Similarly, the susceptance b of the given portion of the circuit is defined by the relation

$$b = \sqrt{y^2 - g^2}. \tag{15}$$

The susceptance of a condenser of capacity C to a sine-wave voltage of frequency f is

$$b = 2\pi fC. \tag{15a}$$

The simple relations expressed by (14a) and (15a) hold only for *sine-wave* currents and voltages; see Pender, H., *Electricity and Magnetism for Engineers, Part II*, N. Y., 1919. See also the articles in this book on *Capacity and Charging Current* and *Inductance and Inductive Reactance*.

Inductive and Condensive (or Capacity) Reactance and Susceptance. — The reactance of a circuit may be due either to the back e.m.f. set up as a consequence of the varying magnetic field of the current or to a back e.m.f. set up by a condenser or its equivalent, or to both. In the first case the reactance and susceptance are said to be "inductive" and in the second case "condensive." A condensive reactance or susceptance is equivalent to a *negative* inductive reactance or susceptance; e.g., the inductive susceptance of a condenser to a sine-wave voltage is $-2\pi fC$.

Equivalent* Resistance, Impedance and Reactance. — Sometimes in calculating alternating-current circuits it is convenient to consider a motor or other load developing a back e.m.f. as equivalent to a single resistance and reactance. Let P be the total power taken by the load, V the voltage between its terminals, I the current; then the equivalent resistance is defined as

$$R = \frac{P}{I^2}, \tag{16}$$

the equivalent impedance as

$$Z = \frac{V}{I} \tag{16a}$$

and the equivalent reactance as

$$X = \sqrt{Z^2 - R^2}. \tag{16b}$$

The difference between the *effective* resistance and the *equivalent** resistance is

* The distinction here made between equivalent and effective is not always observed; the term equivalent resistance is frequently used in the same sense as effective resistance.

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that the first takes into account only the power dissipated as heat, whereas the latter takes into account the total power, of which only a part is heat, the rest being converted into some other form, e.g. mechanical power.

SIMPLE HARMONIC OR SINE-WAVE CURRENTS AND VOLTAGES. — A simple harmonic or sine-wave current is one which varies with time according to the sine formula

$$i = I_m \sin(\omega t + \theta),$$

where t represents time in seconds, measured from any arbitrarily chosen instant, I_m the maximum value of the current, $\omega = 2\pi f = \frac{2\pi}{T}$, where f is the frequency in cycles per second and T the period as a fraction of a second, and θ a constant, called the "phase angle," which depends upon the instant chosen as the zero of time. See the section on *Harmonic Motion* in the article on *Mechanics, Principles of*, for a full discussion of this equation and its physical significance.

Difference in Phase Between a Sine-wave Current and a Sine-wave Voltage of the Same Frequency. — In general, when a sine-wave electromotive force is impressed on a circuit the resulting current is likewise a sine function of time (after a very brief interval, see *Transient Electric Phenomena and Oscillations*) having the same frequency, but the e.m.f. and current do not reach their maximum values simultaneously. Let the current and the potential drop in the direction of the current be represented respectively by the two equations

$$i = I_m \sin \omega t,$$
$$v = V_m \sin(\omega t + \theta),$$

where t is the time measured from the instant when $i = 0$ and is increasing in the *positive* direction. The current reaches its maximum value when $t = \frac{\pi}{2\omega}$, while the potential drop reaches its maximum value when $t = \frac{\pi}{2\omega} - \frac{\theta}{\omega}$. Hence when θ is positive the potential drop reaches its maximum value $\frac{\theta}{\omega}$ seconds *before* the current reaches its maximum, or the current reaches its maximum value $\frac{\theta}{\omega}$ seconds *after* the potential drop reaches its maximum; when θ is negative the current reaches its maximum value $\frac{\theta}{\omega}$ seconds *before* the potential drop reaches its maximum. In the first case the current is said to "lag" the potential drop, and in the second case the current is said to "lead" the potential drop. The angle θ is called the "difference in phase," or simply the phase angle, between the current and potential drop.

In general, when i and v are expressed by the formulas

$$i = I_m \sin(\omega t + \theta_i),$$
$$v = V_m \sin(\omega t + \theta_v),$$

i reaches its first maximum at an interval of time $\frac{1}{\omega}(\theta_i - \theta_v)$ ahead of v, and therefore i leads v by the angle $\theta_i - \theta_v$. Note the order of the subscripts: *i leads v* by the angle $\theta_i - \theta_v$; or *v leads i* by $\theta_v - \theta_i$. A negative lead is of course equivalent to an actual lag, and a negative lag is equivalent to an actual lead.

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Currents and Voltages in Phase, in Quadrature and in Opposition. — When the phase difference is zero the current and potential drop are said to be "in phase"; when the phase difference is $\frac{\pi}{2}$ radians or 90° the current and potential drop are said to be "in quadrature"; when the phase difference is π radians or 180° the current and potential drop are said to be "in opposition."

R.M.S. and Average Values, Form Factor and Crest Factor. — For a *sine wave*:

$$\text{R.m.s. value} = \frac{\text{Maximum value}}{\sqrt{2}}; \tag{17}$$

$$\text{Average value} = \frac{2}{\pi} \times (\text{maximum value}); \tag{17a}$$

$$\text{Form factor} = \frac{\pi}{2\sqrt{2}} = 1.11; \tag{17b}$$

$$\text{Crest factor} = \sqrt{2} = 1.414. \tag{17c}$$

For any other relation between the instantaneous values of the current or voltage and time, i.e., for any other shape of current or voltage wave, *these relations do not hold*. The form factor of a rectangle is 1.00; of an isosceles triangle, 1.15; of a semi-circle or semi-ellipse, 1.04. The corresponding crest factors are 1.00, 1.73 and 1.22. See also article on *Wave Analysis*.

Power and Power Factor for Sine-wave Current and Voltage. — Let the voltage drop from terminal No. 1 to terminal No. 2 through any piece of apparatus be $v = \sqrt{2}\,V \sin(\omega t + \theta_v)$ and the current from terminal No. 1 to terminal No. 2 be $i = \sqrt{2}\,I \sin(\omega t + \theta_i)$, where V and I are the r.m.s. values and therefore $\sqrt{2}\,V$ and $\sqrt{2}\,I$ are the maximum values. Then the *instantaneous* power input is

$$p = vi = VI[\cos(\theta_v - \theta_i) - \cos(2\omega t + \theta_v + \theta_i)]. \tag{18}$$

A study of Fig. 1 will show the physical meaning of this expression. The *average* power input is

$$P = VI \cos(\theta_v - \theta_i), \tag{18a}$$

where $(\theta_v - \theta_i)$ is the difference in phase between the current and voltage. Putting θ for this difference in phase, viz., $\theta = \theta_v - \theta_i$, equation (18a) may be written

$$P = VI \cos\theta. \tag{18b}$$

Whence the power factor of the load supplied to the apparatus is, from equation (8),

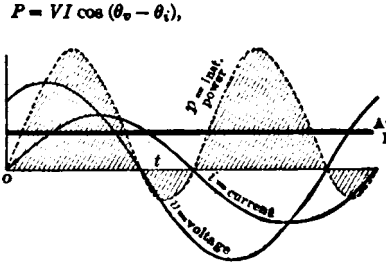


Fig. 1.

$$\cos\theta = \frac{P}{VI}. \tag{19}$$

Power-factor Angle. — Since in the case of sine-wave currents and voltages the power factor is equal to the cosine of the angle which expresses the difference in phase between them, this difference in phase is frequently called the "power-factor angle." When the wave shape is not a pure sine

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urve, the power factor cannot be interpreted as the cosine of the phase difference, for phase difference has no definite meaning except in reference to sine waves; see definitions above. A non-sinusoidal voltage and current may both reach their zero values at the same instant, as in the case of an arc (*see Arc, Electric*), and in a sense may be said to be "in phase," but the power factor as defined by equation (8) may be far from unity.

Leading and Lagging Power Factor. — The power factor is always a positive quantity, but the power-factor angle may be either positive or negative, i.e., the current may lag or lead the voltage drop by any angle between 0° and 90°, or lag or lead the potential drop by any angle between 0° and 90°.* When the current lags the reference voltage by an angle between 0° and 90° the power factor is stated as such a fraction or percentage, *lagging*, e.g., a power factor of 80% lagging, and when the current leads the power factor is stated as such a fraction or per cent, *leading*. In the first case the power-factor angle is taken as positive, and in the second case negative.

Equivalent Sine-wave Currents and Voltages. — In very few instances are the actual currents and voltages in a circuit pure sine-waves, but many of the ordinary calculations of alternating-current circuits may be made with sufficient accuracy by assuming them as sine-waves of the same r.m.s. values as the actual waves, and differing in phase by the angle whose cosine is equal to the actual power factor, i.e., by the angle

$$\theta = \cos^{-1} \frac{P}{VI}, \qquad (19a)$$

where P is the average power, V the r.m.s. value of the actual voltage and I the r.m.s. value of the actual current.

Vector Representation of Sine-wave Currents and Voltages. — Consider any sine function

$$i = I_m \sin \omega t.$$

The value of i at any instant may be represented graphically, see Fig. 2, by the vertical projection (i.e., the vertical distance from P_1 to OX) of a point P_1 at the end of a radius $OP_1 = I_m$ which revolves† at an angular speed ω about a fixed point O, the angle ωt being measured from the horizontal fixed line OX. Similarly, any other sine function

$$v = V_m \sin (\omega t + \theta)$$

may be represented by the vertical projection of the point P_2 at the end of a radius $OP_2 = V_m$ also revolving about O with an angular speed ω, the angle between OP_1 and OP_2, *when the frequency of both i and*

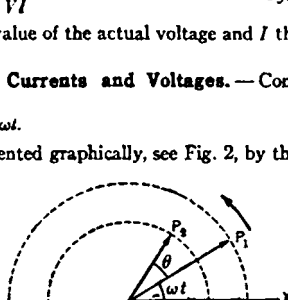


Fig. 2.

* When there is an actual power input into a portion of a circuit (e.g., a motor) it is most convenient to refer the current to the voltage *drop* through this portion of circuit in the direction of the current; when there is an actual power output (e.g., a generator) it is most convenient to refer the current to the voltage *rise* through this portion of the circuit, i.e., to the electromotive force in this portion of the circuit, in the direction of the current. When the potential *rise* is used as the reference, then for a power-factor angle between $-90°$ and 0° and between 0° and $+90°$, the apparatus gives out power, and for a power-factor angle between $-90°$ and $-180°$ and between $+90°$ and $+180°$ the apparatus absorbs power.

† Counter-clockwise rotation has been adopted (1911) as standard by the International Electrotechnical Commission.

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v is the same, remaining fixed in value and equal to the difference in phase θ between v and i. That is, v and i may be represented by rotating vectors (*see article on Vectors*) and when of the same frequency the relative position of the two vectors remains fixed. Similarly any number of currents and voltages of the same frequency may be represented by rotating vectors which remain fixed with respect to one another.

Instead of referring the various rotating vectors to a *fixed* line OX, this line of reference may also be considered as rotating with the same speed ω as the various vectors, or any one of the vectors may be chosen as the line of reference, for example, the vector OP_1 in Fig. 2. The rotating vectors referred to this rotating line of reference are then fixed with respect to this line of reference, and the entire diagram may be considered as fixed, as in Fig. 3, the originally chosen fixed line of reference OX rotating in the opposite direction with an angular speed ω.

Instead of making the vectors equal in length to the maximum values of the sine functions they may be chosen equal in length to their r.m.s. values. This merely introduces a factor $\sqrt{2}$ so that when any vector is considered as rotating the instantaneous value of the quantity which it represents is equal to $\sqrt{2}$ times the perpendicular distance from its end to the fixed line of reference.

Addition of Sine-wave Currents or of Sine-wave Voltages. — Since the r.m.s. values and phase relations of sine-wave currents and voltages may be represented by vectors, sine-wave currents are added in exactly the same manner as vectors, or forces, are added, and similarly for sine-wave voltages. The addition of vectors is fully treated in the article on *Vectors*, q.v. To add any two sine-wave currents or voltages not only must their effective values be known but also their phase relation; *the resultant of two alternating voltages of r.m.s. values V_1 and V_2 is never the arithmetical sum of V_1 and V_2*, except when the two voltages are exactly in phase, and similarly for alternating currents.

In-phase and Quadrature Components. — In Fig. 3, considering OP_1 as equal to the r.m.s. value I of the current and OP_2 as representing the r.m.s. value V of the voltage, the voltage V may be considered as made up of two components, viz.:

$V_1 = V \cos\theta$ in phase with I,

$V_2 = V \sin\theta$ in quadrature with I.

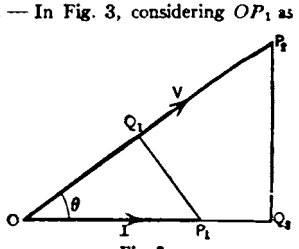


Fig. 3.

The average power corresponding to the component $V_1 = V \cos\theta$ is, from equation (18b), $IV_1 = IV \cos\theta$, and is equal to the total power corresponding to V and I. The average power corresponding to the component $V_2 = V \sin\theta$, since the angle between the current and this component of the voltage is 90°, is equal to zero. The voltage component $V_1 = V \cos\theta$ is therefore frequently called the "power" component of the voltage, and the component $V_2 = V \sin\theta$ is frequently called the "wattless" component of the voltage. These terms, however, are not recommended. It is preferable to refer to these two components as the in-phase and quadrature components respectively. The terms active and reactive components are also used.

Similarly, the current I may be considered as made up of two components, viz.:

$I_1 = I \cos\theta$ in phase with V,

$I_2 = I \sin\theta$ in quadrature with V.

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The first component is called the in-phase component of the current and the second the quadrature component of the current.

Resistance Drop and Reactance Drop. — When a sine-wave current of r.m.s. value I is established in a coil which has an effective * resistance r and inductance L, the drop of voltage V through the coil is represented by the vector diagram shown in Fig. 4. The reactance of such a coil, from the definition given by equation (14a), is then $x = 2\pi fL$. The voltage drop rI, due to the resistance of the coil, is in phase with the current I, whereas the voltage drop $2\pi fLI = xI$, due to the reactance of the coil, is 90° ahead of the current. A "resistance drop" i.e., the drop of potential due to a current through a resistance, is always in phase with the current which causes it, and an *inductive* reactance drop is always 90° ahead of the current which produces it. (A *condensive* reactive drop is always 90° behind the current which causes it, and is therefore directly opposite in phase to an inductive reactance drop produced by the same current.)

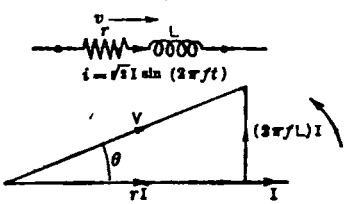


Fig. 4.

Impedance of a Coil to a Sine-wave Current. — From Fig. 4 and the definition of impedance, equation (12), it is evident that the impedance of a coil of resistance r and inductance L is

$$z = \sqrt{r^2 + (2\pi fL)^2}. \qquad (20)$$

Leakage Current and Charging Current of a Condenser. — When a sine-wave voltage of r.m.s. value V is established across a condenser which has an effective† conductance g and capacity C, the total current I through it is represented by the vector diagram shown in Fig. 5. The *condensive* susceptance of a condenser from the definition given in equation (15a) is then $b = 2\pi fC$, or the *inductive* susceptance is $b' = -b = -2\pi fC$. The conduction or leakage current gV is in phase with the voltage drop through the condenser, whereas the charging or capacity current (or displacement current) $2\pi fCV = bV$ is 90° ahead of the voltage.

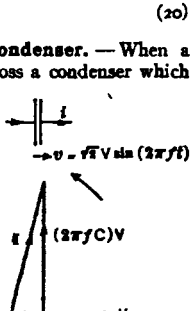


Fig. 5.

Admittance, Impedance, Effective Resistance and Reactance of a Condenser. — From Fig. 5 and the definitions given by equations (12) to (15) it follows that the admittance of a condenser to a sine-wave voltage is

$$y = \sqrt{g^2 + (2\pi fC)^2}; \qquad (21)$$

the impedance is

$$z = \frac{1}{y} = \frac{1}{\sqrt{g^2 + (2\pi fC)^2}}; \qquad (21a)$$

* When the coil has a non-magnetic core and the frequency is low, say 60 cycles or less, the effective resistance is practically equal to its ohmic or d-c. resistance; see article on *Skin Effect*.

† Even for moderate frequencies, 25 cycles or more, the effective conductance of a condenser is in general many times its ohmic conductance; see article on *Condensers, Electric*.

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the effective resistance is

$$r = \frac{g}{g^2 + (2\pi fC)^2}; \tag{21b}$$

and the effective *condensive* reactance is

$$x_c = \frac{2\pi fC}{g^2 + (2\pi fC)^2}, \tag{21c}$$

which is equivalent to an *inductive* reactance of

$$x = -x_c = \frac{-2\pi fC}{g^2 + (2\pi fC)^2}. \tag{21d}$$

Only when the effective conductance g is zero is the reactance of a condenser equal to $-\frac{1}{2\pi fC}$, but in many instances the value of g is so small compared with $2\pi fC$ that the inductive reactance may be taken as $-\frac{1}{2\pi fC}$; the error in this approximate expression is less than 1 per cent for g less than 10 per cent of $2\pi fC$.

Relations between Effective Resistance, Reactance and Impedance and Effective Conductance, Susceptance and Admittance for Sine-wave Currents and Voltages. — From the definitions given above, equations (12) to (15), it may be shown that for sine-wave currents and voltages of a given frequency the following relations hold for any portion of a circuit:

$$\left.\begin{array}{ll} z = \sqrt{r^2 + x^2}, & y = \sqrt{g^2 + b^2}, \\ z = \frac{1}{y}, & y = \frac{1}{z}, \\ r = \frac{g}{y^2}, & g = \frac{r}{z^2}, \\ x = \frac{b}{y^2}, & b = \frac{x}{z^2}, \end{array}\right\} \tag{22}$$

where r = effective resistance, x = reactance (taken positive when inductive), z = impedance, g = effective conductance, b = susceptance (taken positive when inductive) and y = admittance, all for the given portion of circuit. Equations (20) to (21d) are special cases of equation (22).

Impedances in Series. — Let z_1, z_2, z_3, etc., be the impedances of the several portions of a circuit all connected in series (same current through each). Then the resultant impedance is

$$\left.\begin{array}{ll} & Z = \sqrt{R^2 + X^2}, \\ \text{where} & R = r_1 + r_2 + r_3 + \text{etc.}, \\ \text{and} & X = x_1 + x_2 + x_3 + \text{etc.}, \end{array}\right\} \tag{23}$$

where r_1, r_2, r_3, etc., are the effective resistances and x_1, x_2, x_3, etc., the reactances (condensive reactances to be considered as negative) of the several impedances. When there is no external source of e.m.f. in any portion of the circuit, then the resultant power factor is $\cos\theta$ where

$$\tan\theta = \frac{x_1 + x_2 + x_3 + \text{etc.}}{r_1 + r_2 + r_3 + \text{etc.}}. \tag{23a}$$

Example. — An alternating current of 100 amperes is to be supplied to a receiver which has an equivalent resistance r_1 of 2 ohms and an equivalent

reactance x_1 of 0.5 ohm. The line has a resistance r_1 of 0.1 ohm and an inductive reactance x_2 of 1.5 ohms. The equivalent resistance of the line and receiver is then $R = 2 + 0.1 = 2.1$ ohms and the equivalent reactance of the line and receiver is $X = 0.5 + 1.5 = 2.0$ ohms. Hence the equivalent impedance of the line and receiver is $Z = \sqrt{(2.1)^2 + (2.0)^2} = 2.90$ ohms. The impedance of the receiver alone is $z_1 = \sqrt{(2)^2 + (0.5)^2} = 2.06$ ohms and the impedance of the line alone is $z_2 = \sqrt{(0.1)^2 + (1.5)^2} = 1.50$ ohms. The arithmetical sum of z_1 and z_2 is 3.56, which is 23 per cent greater than the true impedance of the line and receiver.

When the current supplied to the receiver is 100 amperes, the voltage at the receiver is $V = 100 \times z_1 = 100 \times 2.06 = 206$ volts and the voltage at the generator is $V_0 = 100 \times Z = 100 \times 2.90 = 290$ volts, see Fig. 6, that is, the voltage at the receiver is 290 — 206 = 84 volts less than at the generator. The total potential drop in the two wires forming the line, however, is $100 \times z_2 = 100 \times 1.50 = 150$ volts, which is 79 per cent greater than the true difference between the potential drops across the generator and across the receiver terminals.

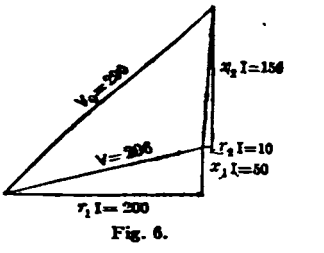


Fig. 6.

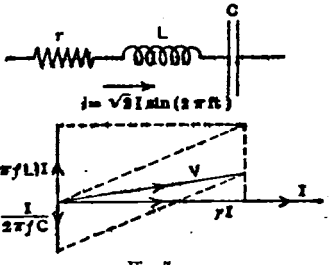


Fig. 7.

Resonance of a Coil and Condenser in Series. — Consider the circuit shown in Fig. 7. When a sine-wave current of effective value I is established in such a circuit the voltage drop across the resistance is $V_r = rI$ and is in phase with I. The voltage drop across the inductance is $V_L = (2\pi fL)\, I$ and *leads* I by 90°. The voltage drop across the capacity (a condenser with *negligible* conductance) is $V_C = \frac{I}{2\pi fc}$ and *lags* I by 90°. Hence the resultant voltage across the entire circuit is

$$V = \sqrt{V_r + V_L + V_C} = I\sqrt{r^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}. \qquad (24)$$

The reactance is therefore

$$x = \sqrt{z^2 - r^2} = \left(2\pi fL - \frac{1}{2\pi fC}\right).$$

When the inductance L, capacity C and frequency f are so related that

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (25)$$

the reactance of the circuit is zero, the impedance is equal to the resistance, the power factor is unity and the current corresponding to a given voltage V is $I = \frac{V}{r}$; that is, the current is a maximum and depends only upon the resistance

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of the circuit. The frequency corresponding to this condition is the same as the frequency with which the current and p.d. would oscillate were the condenser short-circuited by the inductance; i.e., this frequency corresponds* to the free period of such a circuit (*see Transient Electric Phenomena and Oscillations*). In general, a condenser and coil in series are said to be in resonance with the impressed frequency when the current for a given impressed voltage is a maximum, and the power factor therefore unity. When the conductance of the condenser is negligible the resonant frequency is given by equation (25).

When resonance obtains in a series circuit the voltage across the coil and that across the condenser may be many times the impressed voltage. For example, when the inductance L is 1 henry, the capacity C is 7.04 microfarads, and the frequency is 60 cycles, the inductive reactance is $x_L = 2\pi \times 60 \times 1 = 377$ ohms, the condensive reactance is $x_c = \frac{1}{2\pi \times 60 \times 7.04 \times 10^{-6}} = 377$ ohms, and the circuit is in resonance. For a resistance of 1 ohm in the coil and an impressed e.m.f. of 100 volts, the voltage across the coil is $\sqrt{(100)^2 + (377 \times 100)^2} = 37{,}700$ volts and the voltage across the condenser is $377 \times 100 = 37{,}700$ volts.

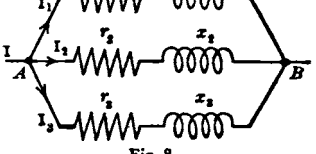


Fig. 8.

Impedances in Parallel.— Let z_1, z_2, z_3, etc., be the impedances of several branch circuits as shown in Fig. 8, and let the resistances and reactances constituting these impedances be r_1, r_2, r_3, etc., and x_1, x_2, x_3, etc., respectively.† First calculate the corresponding conductances g_1, g_2, g_3, etc., and susceptances b_1, b_2, b_3, etc., using equations (22). Then the resultant admittance, *provided there are no external sources of e.m.f. in any of the branches*, is

$$\left.\begin{aligned} Y &= \sqrt{G^2 + B^2}, \\ G &= g_1 + g_2 + g_3 + \text{etc.}, \\ B &= b_1 + b_2 + b_3 + \text{etc.}, \end{aligned}\right\} \quad (26)$$

where

and the resultant power factor is $\cos\theta$ where

$$\tan\theta = \frac{b_1 + b_2 + b_3 + \text{etc.}}{g_1 + g_2 + g_3 + \text{etc.}}. \quad (26a)$$

Resonance of a Coil and Condenser in Parallel. — When a coil of negligible resistance and a condenser of negligible conductance are connected in parallel, the resultant current established through the circuit by a given impressed voltage will be *zero* (infinite impedance) when the inductance L, capacity C and frequency f bear the following relation:

$$f = \frac{1}{2\pi\sqrt{LC}}. \quad (27)$$

Compare with equation (25). Under these conditions the coil and condenser are said to be in resonance with the impressed frequency. When the coil has an appreciable resistance and the condenser an appreciable conductance they are said to be in resonance when the resultant current is a minimum for a given impressed voltage, and the power factor therefore unity.

* Approximately only when r is large; see *Transient Electric Phenomena and Oscillations*.

† Condensive reactances to be considered negative.

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NON-SINUSOIDAL CURRENTS AND VOLTAGES. — The general expression for any alternating current, or in fact of any continuous periodic function, is

$$i = \sqrt{2}\, I_1 \sin(\omega t + \theta_1) + \sqrt{2}\, I_2 \sin(2\,\omega t + \theta_2) + \sqrt{2}\, I_3 \sin(3\,\omega t + \theta_3) + \ldots,$$

where I_1, I_2, I_3, etc., represent the r.m.s. values of each of the terms. That is any current or voltage wave may be considered as made up of a "fundamental" sine-wave, having the same frequency as that of the actual wave, and "harmonic" sine-waves having frequencies which are integral multiples of the frequency of the fundamental. Alternating currents and voltages in practice usually contain one or more of the *odd* harmonics; *even* harmonics practically never occur in ordinary electric circuits supplied from commercial forms of generators. However, as noted above, it is permissible in most instances to assume sine-wave currents and voltages, since the harmonics present are usually relatively weak compared with the fundamental. In certain instances, however, it is necessary to analyze a wave into its fundamental and harmonics. For methods of experimentally determining the shape of current and voltage waves see the articles on *Oscillographs* and *Braun Tube;* for the analysis of the curves themselves see the article on *Wave Analysis*.

R.M.S. Value of a Non-sinusoidal Wave. — The r.m.s. value of such a wave can be obtained directly from equation (3), or if the r.m.s. values I_1, I_2, I_3, etc., of the harmonic and fundamentals are known the r.m.s. value of the resultant wave is

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots} \qquad (28)$$

A like relation holds for the r.m.s. value of a voltage wave. Similarly, if for example a 25-cycle e.m.f., say E_{25}, and a direct e.m.f., say E_d, are acting in series in the same circuit, the resultant e.m.f. of the combination is

$$E = \sqrt{E_{25}^2 + E_d^2}.$$

Power Corresponding to Non-sinusoidal Currents and Voltages. — Let I_1 be the r.m.s. value of the fundamental (first harmonic) of the current, V_1 the r.m.s. value of the fundamental of the voltage and θ_1 the difference in phase between these two fundamentals, both being of the same frequency; let I_2, V_2 and θ_2 be the corresponding quantities for the second harmonic; let I_3, V_3 and θ_3 be the corresponding values for the third harmonic, etc. Then the average power is

$$P = V_1 I_1 \cos\theta_1 + V_2 I_2 \cos\theta_2 + V_3 I_3 \cos\theta_3 + \text{etc.}$$

That is, each harmonic contributes an amount to the total power equal to the power it would develop were the other harmonics not present. If, for example, the third harmonic is not present in the current wave, then this harmonic contributes nothing to the average power even though there may be a large third harmonic in the voltage wave. Again, when a 25-cycle alternating electromotive force E_{25} and a direct electromotive force E_d are acting in series on the same circuit the power developed is the sum of the powers which each would develop if they acted separately, but the resultant e.m.f. of the combination is not $E_{25} + E_d$, but, as noted above, is $\sqrt{E_{25}^2 + E_d^2}$.

Calculation of Networks when the Currents and Voltages are Non-sinusoidal. — See below under *Symbolic Notation*, equations (31) and (32)), and the accompanying text.

SYMBOLIC NOTATION FOR EXPRESSING SINE-WAVE CURRENTS AND VOLTAGES. — Since sine-wave currents and voltages may be represented by vectors equal in length to the r.m.s. values of these quan-

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tities and making definite constant angles with one another, two mutually perpendicular axes of references may be chosen, and each current and voltage resolved into two components, one along the X-axis or horizontal axis and one along the Y-axis or vertical axis. The component along the X-axis may be expressed as an ordinary algebraic quantity, and the component along the Y-axis may also be expressed as an algebraic quantity with the symbol "j" written in front of it to indicate that it is perpendicular to the X-component. That is, any current may be written

$$\underline{I} = I_1 + jI_2,$$

where I_1 is the horizontal or X-component of the current and I_2 the vertical or Y-component. Until one gets familiar with this notation it is best to indicate the symbolic nature of the currents, voltages, impedances, etc., by writing dots under them; but these dots may be dispensed with in the actual solution of problems by this method when one keeps clearly in mind that in all operations the various quantities are to be treated as *complex* quantities throughout.

A voltage drop in symbolic notation is expressed in a similar manner, viz.,

$$\underline{V} = V_1 + jV_2,$$

and an electromotive force as

$$\underline{E} = E_1 + jE_2,$$

the *same* axis of reference being used for the currents, voltage drops and electromotive forces.

Impedance and Admittance in Symbolic Notation. — In this notation an impedance of resistance r and reactance* x is represented by the complex quantity

$$\underline{z} = r + jx, \qquad (29)$$

and an admittance of conductance g and susceptance* b by the complex quantity

$$\underline{y} = g - jb. \qquad (29a)$$

These expressions are independent of the axes of reference chosen.

Currents, Voltages, Impedances and Admittances as Complex Numbers. — In all operations involving the addition or subtraction of currents or voltages and in all operations involving products of currents and impedances or products of voltages and admittances, these quantities when written in symbolic notation may be treated as complex quantities (*see article on Complex Quantities*), *provided all the currents and voltages are referred to the same axis of references*. In all such operations the symbol "j" may be considered as mathematically equivalent to $\sqrt{-1}$. Hence when a term of the form $A_1 + jA_2$ occurs in the denominator of any fraction, the fraction may be "rationalized" by multiplying numerator and denominator by $A_1 - jA_2$, which gives

$$\frac{1}{A_1 + jA_2} = \frac{A_1 - jA_2}{A_1^2 + A_2^2}. \qquad (30)$$

In any resulting expression for a current or voltage when thus rationalized the "real" part represents the actual component of the current or voltage in the direction of the X-axis and the "j" part, i.e., the sum of the terms which are multiplied by j, represents the actual component of the current or voltage along the Y-axis.

* Taken positive when inductive, negative when condensive, e.g., the admittance of a condenser is $g + j\,(2\pi fC)$.

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Solution of Alternating-current Networks. — When all the currents, voltages, impedances and admittances are expressed in symbolic notation, the following relations hold:*

1. The sum of all the currents flowing to any point in any network of conductors is zero. That is, at any point

$$\dot{I} + \dot{I}' + \dot{I}'' + \ldots = 0, \tag{31}$$

where the currents are all expressed in symbolic notation and are all referred to the *same* line of reference.

2. The sum of all the impedance drops in a given direction around any closed loop in any network of conductors is equal to the sum of all the *externally induced e.m.f.'s* acting in this loop in this direction. That is, around any closed loop

$$\dot{z}\dot{I} + \dot{z}'\dot{I}' + \dot{z}''\dot{I}'' + \ldots = \dot{E} + \dot{E}' + \dot{E}'' + \ldots, \tag{32}$$

where the currents, impedances and electromotive forces are all expressed in symbolic notation, and the *currents and e.m.f.'s are all referred to the same axis of reference*. That is, the currents are to be expressed as $\dot{I} = I_1 + jI_2$, $\dot{I}' = I_1' + jI_2'$, etc., and the e.m.f.'s as $\dot{E} = E_1 + jE_2$, $\dot{E}' = E_1' + jE_2'$, etc., where all the components of the currents and e.m.f.'s with the subscript 1 are parallel to one another and all those with the subscript 2 are parallel to one another and lead the first set of components by 90 degrees.

The electromotive forces due to inductance and capacity are taken account of by the impedance; the electromotive forces represented by the $\dot{E}$'s in equation (32) are the externally induced electromotive forces such as those due to generators or motors or to the mutual inductance of the two windings of a transformer.

In applying equations (31) and (32) to the calculation of the currents and potential drops in any network of circuits, care must be taken to designate clearly the sense of the vectors representing the currents and e.m.f.'s. This is most conveniently done by numbering all the junction points in the network, and designating each current and e.m.f. by a double subscript written in the order corresponding to the assumed direction of the current or e.m.f. vector. For example, in Fig. 9, the e.m.f. from 0 to 1 is represented by $\dot{E}_{01}$ while the e.m.f. from 1 to 0, which is equal to $-\dot{E}_{01}$, is represented by $\dot{E}_{10}$. In the figure, then, the net electromotive force from 1 to 2 is

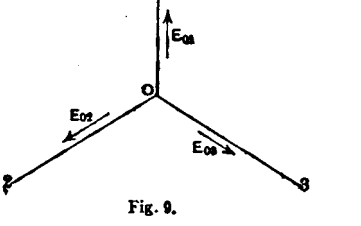


Fig. 9.

$$\dot{E}_{12} = \dot{E}_{10} + \dot{E}_{02},$$

or

$$\dot{E}_{12} = -\dot{E}_{01} + \dot{E}_{02}.$$

Each equation of the form (31) or (32) is in reality equivalent to two equations, since the sum of all the "real" terms on one side must be equal to the sum of all the real terms on the other side, and similarly, the sum of all the "j" terms on one side must be equal to the sum of all the "j" terms on the other side, the denominators of all fractions having been cleared of "j" terms by the transformation given by equation (30). This is merely another way of stating the fact that the component in any direction of the *resultant* of any number of vectors

* These relations are simply Kirchhoff's Laws (*see Electricity and Magnetism, Principles of*) expressed in a convenient form for alternating currents.

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must be equal to the algebraic sum of the components in this direction of all the individual vectors. Applying these two laws to any network enables one, therefore, to calculate both components of every p.d. and every current, when the impedances and the electromotive forces are known.

These equations hold only when *the currents and e.m.f.'s are all simple harmonic functions* of the *same* frequency *and the resistances and reactances are constant.* When, however, the resistances, inductances and capacities are constant, a similar set of equations holds for each frequency that may be present. Since the equations are all linear in the I's and E's, the currents and e.m.f.'s of any given frequency will be uninfluenced by the presence of currents or e.m.f.'s of any other frequency. Hence, when the harmonics present in each e.m.f. are known, the harmonics present in each current may be calculated by solving the equations corresponding to the frequency of this particular harmonic, these equations being exactly the same as would hold were all the other harmonics absent.

Network problems can often be simplified by various expedients, see for example, *Analytical Solutions of Power-Circuit Network Problems*, by R. D. Evans, in the *Electric Journal, Vol. 16, pp. 345–349, 1919.*

Difference in Phase between a Current and Voltage in Symbolic Notation. — Let the current be represented by

$$\underline{I} = I_1 + jI_2$$

and the voltage drop in the same sense as the current be represented by

$$\underline{V} = V_1 + jV_2.$$

Then the current lags behind the voltage drop by the angle θ, where

$$\tan\theta = \frac{V_2I_1 - V_1I_2}{V_1I_1 + V_2I_2}. \qquad (33)$$

Power Corresponding to a Current and Voltage in Symbolic Notation. — Let the current and voltage drop be represented by the same expressions as in the preceding paragraphs. Then the average power is

$$P = V_1I_1 + V_2I_2. \qquad (34)$$

Note that this expression is equal to the real part of the product of the complex numbers $V_1 + jV_2$ and $I_1 + jI_2$ *with the sign between the two terms reversed.*

Example of the Use of the Symbolic Method. — An impedance z_1 has a resistance of 3 ohms and an inductive reactance of 4 ohms; a second impedance z_2 has a resistance of 8 ohms and a condensive reactance of 6 ohms. z_1 is then represented symbolically as $z_1 = 3 + j4$ and z_2 as $z_2 = 8 - j6$.

Let these two impedances be connected in series, and let an e.m.f. of 100 volts be impressed across them. Choosing the vector representing the over-all potential drop as the axis of reference, and calling the current I, then $(3 + j4 + 8 - j6)\,\underline{I} = 100 + j0$, whence

$$\underline{I} = \frac{100}{11 - 2j} = \frac{1100 + j200}{121 + 4} = 8.8 + j1.6.$$

Hence the effective value of the current is

$$I = \sqrt{(8.8)^2 + (1.6)^2} = 8.94 \text{ amperes}$$

and the current leads the over-all potential drop by the angle

$$\tan^{-1}\frac{1.6}{8.8} = 10.3°.$$

The potential drop across the first impedance is

$$\underline{V}' = (3 + j4)\,(8.8 + j1.6) = 26.4 - 6.4 + j\,(35.2 + 4.8) = 20 + j40,$$

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which has the effective value

$$V' = \sqrt{(20)^2 + (40)^2} = 44.7 \text{ volts},$$

and leads the over-all potential drop $\mathfrak{V}$ by the angle

$$\tan^{-1}\frac{40}{20} = 63.5°.$$

The potential drop across the second impedance is

$$\mathfrak{V}'' = (8 - j6)(8.8 + j1.6) = 70.4 + 9.6 - j(52.8 - 12.8) = 80 - j40,$$

which has the effective value

$$V'' = \sqrt{(80)^2 + (40)^2} = 89.4 \text{ volts},$$

and lags behind the over-all potential drop $\mathfrak{V}$ by the angle

$$\tan^{-1}\frac{40}{80} = 26.5°.$$

The power input into the first impedance is

$$W' = 8.8 \times 20 + 1.6 \times 40 = 240 \text{ watts}.$$

The power input into the second impedance is

$$W'' = 8.8 \times 80 - 1.6 \times 40 = 640 \text{ watts}.$$

The total power input is

$$W = 8.8 \times 100 + 1.6 \times 0 = 880 \text{ watts},$$

which of course is the sum of W' and W''.

POLYPHASE SYSTEMS. — A polyphase alternating-current system is a network (i.e., combination of circuits) supplied from a generator or generators which develop two or more electromotive forces differing in phase from one another by a constant angle; see *Distribution of Electric Energy; Generators, Alternating-current; Transformers*. The two kinds of polyphase circuits commonly employed are the two-phase and three-phase circuits.

Star and Mesh Connections. — Consider n separate coils or windings, which may be mounted on a common armature or be entirely distinct, as for example n groups of lamps. When these n windings are connected end to end so that they are all in series, forming a closed chain, as in Fig. 10, and terminals

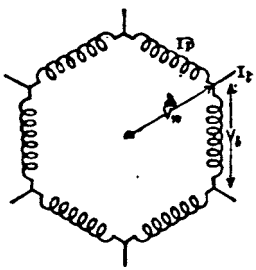


Fig. 10.

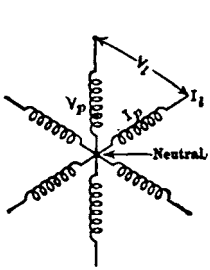


Fig. 11.

are brought out from the n junctions, they are said to be connected in "mesh." When one terminal of each of these windings is connected to a common junction point, as in Fig. 11, and terminals are brought out from the free ends, the windings are said to be connected in "star," and the common point is called the "neutral point."

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n-Phase System. — When such a group of n windings, as shown in Fig. 10 or 11, is connected to a generator or other source of e.m.f., having n separate windings and therefore developing n different e.m.f.'s which differ in phase from one another, the system is called an n-phase system, each winding being called a "phase." For example, when there are three separate windings on the generator, three line wires and three windings constituting the load, the system is a three-phase system.

Balanced Systems. — When the e.m.f.'s, if any, in the n-phases of any system of connection are all equal in r.m.s. value and differ successively in phase by $360/n$ degrees and if the currents in these windings are also equal in r.m.s. value and differ successively in phase by $360/n$ degrees, the system is said to be a "balanced" n-phase system. When the e.m.f.'s in the various parts of a system are equal in r.m.s. value and differ successively in phase by $360/n$ degrees, and the impedances in the various windings or phases are all equal, both as regards resistance and reactance, then the currents are necessarily equal in r.m.s. value and differ successively in phase by $360/n$ degrees, and the system is balanced.

Phase and Line Currents and Voltages. — The current in any winding or phase of an n-phase system, see Figs. 10 and 11, is called the "phase current," and the drop (or rise) of potential *through* this winding is called the "phase voltage." The current in the line leaving any terminal of an n-phase system is called the "line current" and the voltage between *adjacent* line wires or terminals is called the "line voltage," except in the special case of a two-phase connection, see below, when the voltage between diametrically opposite terminals is called the line voltage. In the case of a star-connection the voltage between any terminal and the neutral point is called the "voltage to neutral"; in the case of a balanced mesh connection by voltage to neutral is meant the voltage which would exist between any terminal and the neutral of a star-connection connected to the terminals of the actual device, the impedance of all the legs of the star-connection forming this "artificial neutral" being equal and sufficiently large not to take an appreciable current.

The relations between these various currents and voltages for a balanced n-phase system are as follows:

	Mesh	Star
Number of phases	n	n
Line current	I_l	I_l
Line voltage	V_l	V_l
Phase current	$I_p = \frac{1}{2 \sin \frac{\pi}{n}} I_l$	$I_p = I_l$
Phase voltage	$V_p = V_l$	$V_p = \frac{1}{2 \sin \frac{\pi}{n}} V_l$
Voltage to neutral	$V_n = \frac{1}{2 \sin \frac{\pi}{n}} V_p$	$V_n = V_p$
Total volt-amperes	$nV_pI_p = \frac{n}{2 \sin \frac{\pi}{n}} V_lI_l$	$nV_pI_p = \frac{n}{2 \sin \frac{\pi}{n}} V_lI_l$

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Two-phase or Quarter-phase System. — Strictly, the so-called single-phase system is a star-connected two-phase system, since the currents *from* the two terminals are in opposite directions at any instant, the current leaving by one and entering by the other. However, in practice the name two-phase system is used for a system supplied from a generator or other source of e.m.f. having two windings in which are developed two e.m.f.'s differing in phase by 90°; i.e., a two-phase system is in reality two distinct single-phase systems each with two terminals. Two of the four terminals may be connected to each other, in which case but three line wires are required. Or, the two single-phase systems may be connected at their middle points; in this case the two-phase system may be considered as a four-phase, or, as it is usually called, a "quarter-phase" system. See the articles on *Distribution of Electric Energy* and *Transformers*.

Three-phase System. — Delta and Y-Connections. — For a three-phase system the generators and motors are designed with three windings or phases which may be connected either in mesh, usually called a "delta-connection" in this case, since the diagram of the three windings forms a Greek delta, or the three windings may be connected in star, usually called a "Y-connection" in this case, since the diagram of the three windings forms a Y. The relations between line and coil currents and voltages for a *balanced* three-phase system are as follows:

	Delta	Y
Line current	I_l	I_l
Line voltage	V_l	V_l
Phase current	$I_p = \frac{I_l}{\sqrt{3}}$	$I_p = I_l$
Phase voltage	$V_p = V_l$	$V_p = \frac{V_l}{\sqrt{3}}$
Voltage to neutral	$V_n = \frac{V_l}{\sqrt{3}}$	$V_n = V_p$
Total volt-amperes	$3V_pI_p = \sqrt{3}V_lI_l$	$3V_pI_p = \sqrt{3}V_lI_l$

Calculation of Balanced Three-phase Circuits. — Any problem in regard to a *balanced* three-phase circuit may be solved by reducing all parts of the circuit to an equivalent Y-connection, provided the currents and e.m.f.'s are sine-waves. The transformations are made as follows:

Any Δ-connected motor or generator is considered as equivalent to a Y-connected generator or motor in which

$$E_y = \frac{E_\Delta}{\sqrt{3}}, \qquad r_y = \frac{r_\Delta}{3}, \qquad x_y = \frac{x_\Delta}{3},$$

where the quantities E_y, r_y and x_y are the e.m.f., resistance and reactance per phase of the Y-connected machine equivalent to the e.m.f., resistance and reactance per phase of the actual Δ-connected machine.

Each of the line wires is in series with a corresponding phase of the equivalent Y-connected machine.

When all parts of the circuit have thus been reduced to equivalent Y's, each of the three-phases may be treated as a single-phase circuit, each circuit considered completed by a wire having *zero* impedance connecting all the neutrals together, since all the neutrals are at the same potential.

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The voltages thus calculated are the voltages to neutral and the currents are line currents. To find the line voltage multiply the calculated voltage by $\sqrt{3}$; similarly, to find the actual phase current in the Δ-connected generator or load divide the calculated current by $\sqrt{3}$.

Example of Three-phase Calculation. — Energy is supplied from a generating station to a substation 50 miles away at a rate of 20,000 kilowatts. The system is a balanced three-phase system and operates at a frequency of 25 cycles. The transmission line consists of three No. 0000 B. & S. copper wires spaced six feet between centers. It is desired to find (1) the voltage between wires at the generating station when the voltage between wires at the substation is 60,000 volts, and the power factor at the substation is 80 per cent, with the current *lagging*, (2) how much power is lost in the transmission line and (3) what is the power factor at the generating station. The electrostatic capacity of the line may be neglected.

The current per wire is

$$I = \frac{20{,}000{,}000}{\sqrt{3} \times 60{,}000 \times 0.8} = 241 \text{ amperes.}$$

The voltage to neutral at the substation is

$$V_n = \frac{60{,}000}{\sqrt{3}} = 34{,}600.$$

The component of this voltage in phase with the line current is $0.8 \times 34{,}600 = 27{,}700$ volts and the component 90° ahead of the line current is $0.6 \times 34{,}600 = 20{,}800$ volts, since $\cos\theta = 0.8$ and $\sin\theta = 0.6$.

The resistance per mile of a No. 0000 wire is 0.258 ohm; its reactance per mile at 25 cycles is 0.303 ohm. Hence the total resistance of each wire is 12.9 ohms and the total reactance of each wire 15.2 ohms. The resistance drop in each wire is then $12.9 \times 241 = 3110$ volts and is in phase with the line current and the inductive drop in each wire is $15.2 \times 241 = 3660$ volts and is 90° ahead of the line current.

At the generator end the voltage to neutral in phase with the line current is then $27{,}700 + 3110 = 30{,}810$ volts and the voltage to neutral 90° ahead of the current is $20{,}800 + 3660 = 24{,}460$ volts. The resultant voltage to neutral at the generator end is then $\sqrt{(30{,}810)^2 + (24{,}460)^2} = 39{,}300$ volts, and therefore the line voltage at the generating station is

$$V_l' = \sqrt{3} \times 39{,}300 = 68{,}000.$$

The power lost in the line is equal to $3RI_l^2$, where R is the total resistance of each wire and I_l the line current. Hence the power lost in the line is

$$3 \times 12.9 \times (241)^2 \text{ watts} = 2250 \text{ kilowatts.}$$

The total power delivered to the line and substation is then 22,250 kilowatts. Hence the power factor at the generating station is

$$\frac{22{,}250{,}000}{\sqrt{3} \times 68{,}000 \times 241} = 0.784 = 78.4 \text{ per cent.}$$

Measurement of Power in Three-phase Circuits. — See *Wattmeters*.

Calculation of Unbalanced Three-phase Circuits. — When a three-phase system is unbalanced, the currents and voltages can always be calculated by applying Kirchhoff's laws to the junctions and loops formed by the various parts of the system. For example, referring to Fig. 12, what will be the currents in each line wire and what will be the readings of the two watt-meters connected as shown when the three impedances forming the unbalanced star

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ive the values $z_1 = 1 + j2$, $z_2 = 3 - j4$ and $z_3 = 5 + j6$, and the voltages tween the terminals 1, 2 and 3 are balanced and numerically equal to 100 lts? What is the voltage from each terminal to the neutral?

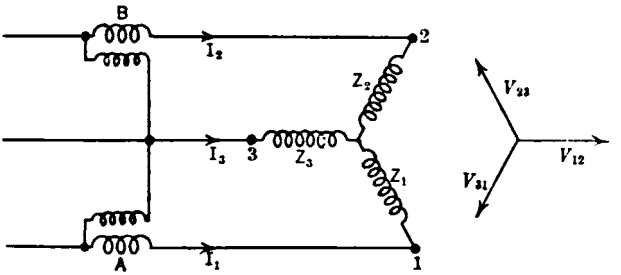


Fig. 12.

The following relations then hold, taking V_{12} as the reference vector:

$$\dot{V}_{12} = 100, \tag{a}$$

$$\dot{V}_{23} = -50 + j86.6 \tag{b}$$

$$\dot{V}_{31} = -50 - j86.6 \tag{c}$$

$$\dot{I}_1 + \dot{I}_2 + \dot{I}_3 = 0 \tag{d}$$

$$100 = (1 + j2)\dot{I}_1 - (3 - j4)\dot{I}_2 \tag{e}$$

$$-50 + j86.6 = (3 - j4)\dot{I}_2 - (5 + j6)\dot{I}_3 \tag{f}$$

Substituting in (f) the value of $\dot{I}_3$ from (d) there results.

$$-50 + j86.6 = (8 + j2)\dot{I}_2 + (5 + j6)\dot{I}_1 \tag{g}$$

Substituting in (g) the value of $\dot{I}_2$ from (e) and solving for $\dot{I}_1$ there results,

$$\dot{I}_1 = 25.36 + j5.90. \tag{h}$$

Substituting this value of $\dot{I}_1$ in (e) there results,

$$\dot{I}_2 = -19.43 - j7.04 \tag{i}$$

Substituting (h) and (i) in (d) there results,

$$\dot{I}_3 = -5.93 + j1.14 \tag{j}$$

The r.m.s. values of these three currents are respectively,

$$I_1 = 26.04; \quad I_2 = 20.64; \quad I_3 = 6.04.$$

Wattmeter A indicates the power P_A corresponding to the voltage V_{13} and the current I_1, and wattmeter B indicates the power P_B corresponding to the voltage V_{23} and the current I_2. Note that from (b) and (c) and (h) and (i),

$$\dot{V}_{13} = 50 + j86.6, \qquad \dot{V}_{23} = -50 + j86.6,$$

$$\dot{I}_1 = 25.36 + j5.90, \qquad \dot{I}_2 = -19.43 - j7.04.$$

Whence, from equation (34),

$$P_A = 1779 \text{ watts} \quad \text{and} \quad P_B = 362 \text{ watts}.$$

Note that $(P_A + P_B)$ is equal to the total power in-put to the three phases, viz., to $(r_1I_1^2 + r_2I_2^2 + r_3I_3^2)$, and compare with the article on *Wattmeters*.

The r.m.s. voltage from each terminal to the neutral is the product of t current in that particular phase of the Y by the impedance of that phase, viz.,

$$V_{10} = 26.04 \times \sqrt{(1)^2 + (2)^2} = 58.23 \text{ volts},$$

$$V_{20} = 20.64 \times \sqrt{(3)^2 + (4)^2} = 103.20 \text{ volts},$$

$$V_{30} = 6.04 \times \sqrt{(5)^2 + (6)^2} = 47.17 \text{ volts}.$$

Unbalanced Polyphase System Equivalent to Two Balanc Polyphase Systems of Opposite Phase-rotation. — In many cases it advantageous, for the purpose of calculation, to consider an unbalanced pol phase system as the superposition of two balanced polyphase systems of opposi phase rotation. The procedure and a number of applications are given b Fortescue in the *A.I.E.E. Proc., June 18, 1918, p. 629.* See also Lyon, W. V *Elec. World, 75, p. 1304, June 5, 1920.*

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ALUMINUM. — (*See also Electrochemical Processes, Industrial; Lightning Protectors; Wires and Cables, Bare.*) The method of manufacturing aluminum wire is similar to that employed in making copper wire (*see Copper*).

MECHANICAL PROPERTIES. — The more important mechanical properties of aluminum are discussed below.

Necessity of Stranding Aluminum Wire. — Aluminum wire (i.e., solid wire) is little used for aerial spans owing to the danger of failure where accidental abrasions have occurred. Cables not only reduce the above danger, but have greater breaking load, owing to the superior tensile strength of small wires.

Tensile Strength. — The tensile strength of aluminum has not been studied as thoroughly as that of copper, but it is well known that, like copper, aluminum is much stronger in small, than in large, wires. The following table by H. M. Hobart, which is for solid wires, illustrates this point.

Diameter, inches	0.05	0.10	0.15	0.20	0.25	0.30	0.35
Tensile strength, lb. per sq. in.	33,300	28,800	26,200	24,800	23,800	23,200	23,000

The Standard Electric Co., of California, uses a solid aluminum wire, 0.294 inch diameter, having a tensile strength of 22,800 pounds per square inch, and a conductivity of 59.9 per cent.

Elongation. — The ultimate elongation of hard-drawn aluminum wire varies from 2.0 per cent to 3.7 per cent (in 1 meter length) as the diameter is increased from 1 to 4½ mm. (*H. M. Hobart.*)

Modulus of Elasticity. — Different authorities give values from 9×10^6 to 10×10^6 in pounds per square inch, the former being given by the Aluminum Company of America.

Elastic Limit. — The Aluminum Company of America in their booklet on "Properties of Aluminum," give the following figures for elastic limit in tension, the metal being 99 per cent pure.

	Lb. per sq. in.
Castings	8,500
Sheet	12,500 to 25,000
Wire	16,000 to 33,000
Bars	14,000 to 23,000

Density. — A density of 2.70 grams per cubic centimeter is given by the U. S. Bureau of Standards (*Circ. No. 31*) as a good average value for commercial hard-drawn aluminum. This is equivalent to 0.0975 pound per cubic inch. Hobart gives 2.71 for the density. F. J. Brislee (*Lond. Elec. Review, Jan. 5, 1912*) gives 2.708 as the density of cast aluminum and 2.705 for hard-drawn rod.

THERMAL PROPERTIES. — See article on *Heat and Thermal Properties*.

CONDUCTIVITY AND RESISTIVITY. — The Aluminum Company of America give as the average of many thousands of separate determinations, the figure of 2.828 microhms per centimeter cube at 20° C. as the resistivity of commercial aluminum wire. This corresponds to a conductivity of 61 per cent of the annealed copper standard (see *Resistance and Conductance, Electric*).

Effect of Hardness on Conductivity. — The resistance of aluminum depends upon its hardness; for example, the resistance of aluminum wire of hard-

ness corresponding to a tensile strength of about 20 kg. per mm. is approximately 2 per cent greater than that of the same wire when thoroughly annealed and consequently soft. (*H. M. Hobart.*)

Temperature Coefficient of Resistivity. — From the data given by G. Grassi (*Elletrotecnica, 6, p. 10, Jan. 5, 1919*), the 20° C. temperature coefficient of 61 per cent conductivity annealed aluminum wire is 0.00408, per degree centigrade, corresponding to a 0° C. coefficient of 0.00444. Grassi also found that the temperature coefficient of aluminum is proportional to its per cent conductivity (as is also the case with copper; see article on *Copper*). American investigators have found a lower coefficient, the figure 0.0039 being most commonly used.

COMPARISON OF ALUMINUM AND COPPER. — Aluminum is usually cheaper than copper of the same length and resistance and is said to be cheaper to install (*C. B. Smith, El. W., 1912, Vol. 59, p. 96*). It is, however, subject to the disadvantage of lower tensile strength which often makes it more expensive than copper, except for very high voltages.

The table below compares the various items for wires having the same length and same resistance and is based on the following assumptions:

	Copper	Aluminum
Per cent conductivity	98	61
Tensile strength, lb. per sq. in.	55,000	25,000
Density	8.89	2.70
Price per pound	P	p

COMPARISON OF COPPER AND ALUMINUM WIRES FOR EQUAL RESISTANCES PER UNIT LENGTH

Item	Copper	Aluminum
Cost	1	$0.488 \times \frac{p}{P}$
Cross-section	1	1.63
Diameter	1	1.28
Weight	1	0.488
Breaking strength	1	0.731
Carrying capacity	1	1.13

Disadvantage of Low Tensile Strength. — The lower tensile strength of aluminum for equal length and conductance as compared with copper affects the cost of an aerial line in two ways: 1st, by making it necessary to erect the spans with a greater sag or less length in order to reduce the stresses, thereby either increasing the height or the number of poles, and 2nd, by making it necessary to increase the distance between wires on account of the increased sag. The increase in the height of poles for the same spacing amounts to about 10 per cent. (*C. L. Johnson*). Aluminum cables with steel core are now used and overcome these difficulties. See article on *Wires and Cables, Bare.*

Effect of Large Elongation of Aluminum. — The extraordinarily great elongation of aluminum enables it to withstand severe mechanical overloads by stretching and thus increasing the sag. However, in dealing with a single

solid wire this cannot be relied on, as a scratch or a single imperfection will often cause the wire to break without any appreciable elongation. This is one reason why cables are to be preferred to single-wire conductors.

Effect of Low Melting Point of Aluminum. — The distance between aerial wires is also influenced by the fact that aluminum has a lower melting-point than copper, making it necessary to keep wires at different potentials well separated in order to avoid the danger of short-circuits through foreign bodies. This danger has, perhaps, been exaggerated in the past as the author has the record of a case where a copper wire was thrown across two aluminum cables with 60,000 volts difference of potential between them and an arc was formed between the cables forming an arch 12 to 15 feet high, but with no injury to the cables except the formation of a few minute beads on their surface.

Formation of Sleet. — While for equal length and resistance, aluminum wires are larger than copper wires, they do not necessarily collect a proportionally greater load of sleet, as it is found that a film of grease left over from the drawing process often entirely prevents the adhesion of sleet. Conclusive information on this subject is, however, lacking, especially with regard to wire that has been in use for several years.

Corona Formation. — At very high potentials, such as 100,000 volts, aluminum conductors possess a marked advantage over copper in the lower corona loss due to their greater diameter for the same conductance.

Corrosion. — E. Huber-Stockar gives the results of a number of tests on the corrosion of aluminum in moist air, salt air, salt water, various gases, acids, etc., which indicate that, in respect to its chemical stability, aluminum is in general the equal of copper. There has been much said about the tendency of electrostatic repulsion to reduce impure condensation on aluminum conductors, but this author rejects such statements as unworthy of the slightest credence.

Aluminum wire exposed to the atmosphere increases in resistance. E. Wilson (*Electrician, 75, p. 886, Sept. 17, 1915*), reports a case where commercial aluminum increased in resistance 17.2 per cent in 13 years. Wilson also gives the results of tests on various aluminum alloys.

Bare aluminum conductors laid in the earth have been tried for railway return feeders, with the result that they were rapidly corroded by galvanic action.

Mr. Dusaugey says that aluminum containing over 4 per cent of impurities is very liable to corrode rapidly. This is especially the case if sodium is present.

At ordinary temperatures aluminum is covered with a layer of oxide which protects it against the influence of the weather and of many chemicals.

Example of Relative Cost. — According to the official publications of the Ontario Hydro-Electric Commission on a line consisting of two three-phase circuits, each comprising three 0000 A.W.G. cables, the six cables cost $1450 per mile as compared with $2050 per mile for copper cables (copper being at 16 cents per pound and aluminum at 23.5 cents per pound), showing a saving of nearly 30 per cent on the cables alone. This saving was reduced to 5.6 per cent only on the total cost of the line, partly because the actual towers weighed 1.72 tons against 1.57 tons for towers for an equivalent copper line, and partly because the cost of cables was only 30 per cent of the total cost of the line, including erection but excluding rights-of-way. (*C. L. Johnson.*) Owing to a tariff of 3 ½ cents per pound the price of aluminum is higher in the United States than in Canada and Europe, so that the saving would have been considerably less at United States prices.

SOLDERS FOR ALUMINUM. — (*Bureau of Standards, Circ. No. 78*, Washington, D. C., 1919). Aluminum can be welded in a satisfactory manner by the oxyacetylene blowpipe flame, but soldering is often desirable. Alumi-

num solders consist usually of mixtures in varying proportions of Zn and Sn or of Zn, Sn and Al. The surfaces to be soldered are carefully cleaned and "tinned" or coated with a layer of the solder by heating the surface and rubbing the solder into it. The joint between the tinned surfaces may then be made in the usual way with a soldering iron and the solder, no flux being used. A soldered joint is rapidly attacked when exposed to moisture. The joints should never be made by soldering unless they are to be protected against corrosion by a paint or varnish or unless they are heavy, as in the case of repairs in castings.

The composition of the solder may vary within wide limits. For tin-zinc solders, zinc 15 to 50 per cent, the remainder Sn, is recommended. The higher the temperature at which the tinning is done the better is the adhesion of the tinned layer, therefore the solders high in Zn and Al give better results. The joint between previously tinned surfaces may be made by ordinary methods by ordinary soft solders; only the tinning mixture need be special for Al. The tensile strength of a good solder is about 7000 pounds per square inch. The strength of a joint depends on the type and on the workmanship, but much dependence should not be placed upon it.

SPREE-ALUMINUM. — E. Huber-Stodkar gives considerable data on an aluminum alloy, known under the name of spree-aluminum. It has nearly double the strength of pure aluminum. Its breaking length is 10.7 kilometers, as compared with 10.3 kilometers for steel, 6.7 kilometers for aluminum and 5.1 kilometers for hard copper. The use of spree-aluminum cable shows a saving in cost of about 7.3 per cent as compared with copper cable of equal conductance.

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AMMETERS. — (*See also Balances, Current; Electricity and Magnetism, Principles of; Electrodynamometers; Galvanometers; Voltmeters.*) An ammeter is essentially a galvanometer (q.v.) or electrodynamometer (q.v.) of rugged construction, provided with a pointer moving over a scale forming an integral part of the instrument and calibrated to read directly in amperes. The moving element is usually supported in jeweled bearings.

CLASSIFICATION AND USE OF AMMETERS. — Ammeters which have found general commercial application may be classified as follows:

Moving-magnet Type, in which a permanent magnet or polarised vane is caused to move under the influence of a winding which carries the current to be measured. The principle of operation is similar to that of a Thomson galvanometer (*see Galvanometers*). The restoring force is usually a fixed permanent magnet. This type of instrument measures average values and is therefore suitable for direct currents only.

Moving-iron Type, in which there is relative motion between a piece of soft iron and a fixed coil carrying the current to be measured. There are a number of subclasses which are distinguished chiefly by differences of mechanical construction. In the plunger type a soft iron core is drawn into the coil. The core is usually in the form of a rod, and the length of the coil is several times its diameter. In the repulsion type, as usually constructed, a piece of iron is repelled by a fixed piece of iron, both being within the coil carrying the current to be measured. The Weston moving-iron ammeter is of this type. In the Thomson inclined-coil ammeter, the coil is fixed at an angle of about 45° with the shaft which carries one or more iron vanes, the latter also making the same angle with the shaft. As the current through the coil increases the vanes turn so as to approach the condition of parallelism with the magnetic field within the coil. The restoring force of all these forms of ammeter is usually that of a spring. This type of ammeter measures effective (r.m.s.) values * and may be used for either alternating or direct currents, but such ammeters are subject to slight errors in the latter case, due to the tendency of the vane or plunger to hold its magnetism.

Permanent-Magnet Moving-coil Type, in which a permanent magnet maintains a strong field in a fixed location, and the current to be measured is sent through a moving coil, entering or leaving by springs that furnish the restoring force or through auxiliary spirals. The principle of operation is the same as that of a d'Arsonval galvanometer (*see Galvanometers*). This type of instrument measures average values and is suitable for direct currents only. Precision d-c. ammeters are usually of this type.

Electrodynamic Type, in which the operation depends upon the force exerted by one current-carrying circuit upon another, or by a portion of one circuit upon another portion of the same circuit. (See *Electrodynamometers.*) The usual form of construction includes a pivoted coil which moves in the field of a fixed coil or set of coils. The restoring force is usually due to springs, and the current is led into and out of the moving coil through these springs or through flexible conductors constructed to carry relatively large currents and to have a minimum restoring force. This type of instrument measures effective (r.m.s.)

* Moving iron instruments do not measure r.m.s. values exactly, on account of the lack of exact proportionality between the instantaneous torque and the square of the instantaneous current, but by careful attention to details in the design such instruments can be made nearly perfect in this respect, so that all things considered, they are sometimes to be preferred to electrodynamic instruments. For precise work, calibration of such instruments made with direct current should not be used on alternating current.

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values and may be used to measure either alternating or direct currents. Precision a-c. instruments are usually of the electrodynamic type.

Hot-wire Type, in which the expansion of a wire or strip due to the heat developed within it, caused by the current passing through it, is made to move an indicating pointer. The "thermocouple" ammeter, described below, may also be classified as a hot-wire ammeter, although the principle of operation is quite different. Hot-wire ammeters measure effective (r.m.s.) values and are useful for both alternating- and direct-current measurements.

Induction Type, in which a metal cylinder or disk with pointer attached is caused to rotate under the action of a rotating magnetic field, usually produced from a single-phase source by means of a phase-splitting device. The principle of operation is similar to that of an induction watthour meter (*see Watthour Meters*), the motion of the moving element being opposed by a spring. This type of instrument measures effective values of alternating currents only and generally for only a limited range of frequency and wave form.

Thermocouple Ammeters. — For measuring small alternating currents, particularly when the frequency is high (500 cycles per second or more), a thermocouple (*see Pyrometers*) may be used; the current to be measured is passed through a wire resistor (*see Wires, Resistor*) to which is soldered one junction of the thermocouple, the free ends of which are connected to an ammeter (or galvanometer) of any of the types noted above. The heating of the resistor wire sets up a direct current in the thermocouple circuit which, in turn, depends upon the effective value of the current through the heater wire. The limitations and errors in the use of such ammeters are discussed at length in a paper on *High Frequency Ammeters* in Scientific Paper No. 206, Bull. Bur. Stds., 1913, Vol. 10. See also article in the Gen. El. Rev. 17, p. 981, Oct., and p. 1210, Dec., 1914.

Other Types of Ammeters. — Successful instruments for special needs have been made that would not ordinarily be classed under the above headings, and other instruments might be referred to which combine in a single instrument more than one of the subdivisions.

Portable and Switchboard Instruments. — Switchboard instruments are usually of more rugged construction than portable instruments and are somewhat less precise in their indications. Portable instruments are provided with suitable binding posts on their bases and are generally used in a horizontal position. Switchboard instruments are usually provided with back connections and are used in a vertical position. In the so-called "edgewise" instruments the instrument mechanism is horizontal but the pointer is so designed that it indicates on a vertical scale.

Recording (Graphic) Ammeters. — A continuous record of current may be obtained by using an ammeter provided with a clock mechanism which slowly rotates a chart (disk-shaped or mounted on a drum) or a continuous paper ribbon under the end of the pointer which carries a pen kept continuously inked. The moving element is comparatively heavy since the deflecting force must be great enough to overcome the friction of the pen and prevent "sticking."

INSTRUMENT SCALES. — A uniform scale is usually desirable in any kind of instrument, and with permanent-magnet moving-coil types such a scale is readily obtained, since the deflecting torque is proportional to the current. In moving-iron, electrodynamic and other types in which the deflecting torque depends upon the square of the current, very small deflections are obtained for low values of the current and the scale divisions are crowded for low values.

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DAMPING. — For ordinary purposes it is essential that the pointer of the instrument come quickly to rest. The moving coil of the permanent-magnet moving-coil instrument is usually wound on a light aluminum frame which is mounted between the poles of the permanent magnet, and a soft-iron core fills the air gap between the poles, other than that necessary to allow free motion of the coil. The metal frame moves through a very strong magnetic field and eddy currents are set up in it which effectually damp its motion. Although it is not difficult to make the instruments perfectly aperiodic, a slight underdamping is often preferred because it gives opportunity to observe at all times that the movement of the instrument is perfectly free.

Magnetic (eddy current) damping or air damping by means of light vanes moving in a more or less perfectly closed air chamber is used with the other types of instruments.

ELIMINATION OF EFFECT OF STRAY FIELDS. — Due to the low reluctance of iron compared with air, a soft-iron shield placed around the instrument mechanism will greatly reduce the disturbing effect of an external magnetic field on the readings of the instrument. Many types of switchboard and portable instruments are thus shielded. Permanent-magnet moving-coil instruments are affected by only comparatively strong fields.

Astatic Instruments. — Another means of avoiding errors due to stray fields is by making the moving element astatic. The principle of this construction is to divide the moving element into two parts, so arranged that the deflecting torques acting on the two parts due to the field of the instrument are additive, whereas any stray field will produce equal and opposite torques on these two parts.

Thomson Astatic Instruments. — The Thomson astatic ammeters and voltmeters are unique in that the deflecting torque and the controlling torque are both caused by the same magnetic field. This field is produced by an electromagnet wound for any specified voltage and provided with binding posts separate from the current posts of the instrument, or by means of a permanent magnet. Two moving coils are mounted diametrically opposite each other upon an aluminum disk. The disk and coils cut across the field which is directed parallel to the shaft carrying the disk. Two small pieces of soft iron are rigidly mounted on the shaft, the magnetic field entering these pieces of iron radially tending to hold the shaft and moving coils in their initial position.

When current passes through the coils of the moving element, the lines of force parallel to the shaft produce a torque which tends to turn the shaft and cause the needle to travel across the scale. This action is opposed by the magnetic field at right angles to the shaft acting on the two pieces of soft iron. The instrument has no controlling springs and since both the deflecting and controlling force are due to the same electromagnet, the accuracy is not affected by changes in magnetic strength. These instruments are particularly suited to service where very strong external fields are present.

USE OF SHUNTS AND CURRENT TRANSFORMERS. — *See also articles on Shunts; Transformers, Instrument.*) The current which may be led into the moving element of an ammeter (moving-coil or electrodynamic type) is limited by the current-carrying capacity of the springs or special leading-in wires, which must necessarily be light; this current seldom exceeds 5 or 10 amperes. To increase the range of such instruments, and also to avoid the use of heavy conductors in the instruments, shunts or current transformers (the latter for alternating currents only) are used. Ammeters for use with current transformers are usually designed to take a maximum current of 5 amperes, but

their scales are calibrated to read directly the current in the primary of the transformer.

Millivoltmeter Used as Ammeter. — Direct-current ammeters designed for use with shunts are usually designed to carry but a very small current (about 0.025 ampere). A wire resistor having practically zero temperature coefficient is permanently connected, within the case of the instrument, in series with the moving coil. The combined resistance of the moving coil and resistor is thus made large compared with the resistance of the shunt, and the error, due to resistance variation, is not large for ordinary changes in temperature. The ammeter proper is then essentially a millivoltmeter (*see Voltmeters*) and measures the drop of potential through the shunt to which it is connected; the scale of the ammeter, however, is often calibrated to read directly in amperes for one or more standard shunts designed for use with it.

Voltage Drop Across Shunts. — Shunts for use with switchboard direct-current ammeters of the permanent-magnet moving-coil type are usually designed for a drop of 50 or 60 millivolts at full load, although for some special requirements, where the indicating instrument must be located at a considerable distance from the shunt, double-drop shunts having 120 millivolts are used, and even higher drops are used to meet very special requirements. For precision use with portable instruments the resistance coil is so designed that a drop of 100 or 200 millivolts is required for full-scale reading, the high resistance with zero temperature coefficient practically eliminating temperature errors.

Use of Portion of Bus Bar as Shunt. — Sometimes the shunt is dispensed with altogether and the millivoltmeter is connected directly to a portion of the bus bar or main conductor. This arrangement is usually not desirable, because the variation of temperature in the bus bar due to the current flowing through it causes larger errors than the variation due to changes in room temperatures. Some arrangements have been made to compensate for these, but are not very generally used.

Voltmeter and Shunt for Measuring Alternating Currents. — An a-c. voltmeter with shunt is not in general suitable for measuring an alternating current, since such instruments are not readily constructed to read low voltages and therefore a relatively large drop in the shunt would be required, also the division of current between the shunt and voltmeter depends (1) upon the inductances of the shunt and instrument, (2) upon the "skin effect" (q. v.) in the shunt. However, hot-wire voltmeters with shunts are sometimes used for alternating-current measurements and are satisfactory at commercial frequencies.

PRECAUTIONS IN USE OF PORTABLE AMMETERS. — The following precautions, which in the main also apply to other portable electrical instruments, should be observed:

An ammeter should always be connected in series with the load. Never connect it across the mains.

All contact surfaces of nuts, terminals, etc., must be clean.

Transformers and wires carrying heavy currents should be kept at a safe distance from all instruments.

Portable instruments should be always used in a horizontal position, unless specifically designed for use otherwise.

Tapping an instrument while it is being read is usually unnecessary if it is properly constructed and in good order, but when slight friction is present from any cause its effect can be eliminated by gently tapping the instrument. Hard tapping defeats its object.

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It is a good plan in testing to place a low-resistance jumper or short-circuit ock * or switch around the terminals of the ammeter and to connect a rheostat series with it and the load. The plug of the short-circuit block should be adually withdrawn, or the switch gradually opened, and the needle of the mmeter watched to be sure that the current is in the right direction and does ot exceed the rated current of the instrument.

A heavy short-circuit in nearby conductors, even though of extremely short uration, is liable to demagnetize the magnet of a permanent-magnet instrument. After such a short-circuit the instrument should be recalibrated, even ough the short-circuit causes no mechanical injury.

When it is desired to measure the average value of a pulsating current (e.g., om a rectifier), permanent-magnet moving-coil instruments should be used. he average value is to be used when the current is used for an electrochemical peration, such as plating, or charging storage batteries. Power measurements a rectified-current circuits should in general be made with an electrodynamic attmeter.

The power of a rectified current in a noninductive circuit, such as incandescent amps or electric heating apparatus, may be correctly determined by multiplying the effective current by the effective voltage, both being measured by electrodynamic or hot-wire ammeter and voltmeter. For a discussion of this subject see article by Todd, Elec. Rev. (Chicago) Vol. 77, p. 683, 1920.

Instruments containing iron should not be used for a frequency differing largely from that for which they are designed. For high-frequency measurements (above 500 cycles per second), some type of hot-wire or thermocouple instrument should be used. Instruments containing iron are also subject to errors due to distorted current waves; for precise work on badly distorted waves they should be compared with an electrodynamic or hot-wire instrument, using the same kind of current in the comparison as that to be measured.

CHECKING OF AMMETERS. — The readings of two or more ammeters may be compared by connecting them in series with a rheostat (q.v.) and suitable source of e.m.f. An ammeter may thus be compared with a standard ammeter, and a curve drawn showing the true amperes corresponding to the dial readings. It is usually more convenient to plot the correction to be made to the reading against the actual reading. Corrections to be added to the readings are usually designated as + and corrections to be subtracted from the readings as −.

Instead of using a standard ammeter, a standard millivoltmeter and a standard resistor (*see Resistors, Standard*) may be employed for direct current. The standard resistor is connected in series with the ammeter to be checked and the millivoltmeter is connected across the potential terminals of the resistor. Let V be the reading of the millivoltmeter in volts, R the resistance of the resistor and r the resistance of the millivoltmeter; then the current measured is

$$I = V/R + V/r.$$

The last term V/r is usually negligible.

An accurate and convenient way of checking an ammeter on direct current is to use a potentiometer (q.v.), when such an instrument is available.

Checking of A.-C. Ammeters. — Alternating-current indicating instruments, whose deflections are independent of frequency and wave form, when calibrated on direct current indicate correctly effective values when used on

* For small currents, two blocks of metal mounted on an insulating base with a tapered slot between the two, into which fits a tapered metal plug, make a convenient short circuit block; for heavy currents a switch should be used.

alternating current. Electrodynamic instruments usually give readings of equal accuracy on alternating or direct current at commercial frequencies and wave forms. Eddy currents in the metal supports and conductors, however, may cause slight errors in some makes, even at commercial frequencies, and for high frequencies errors are liable to occur in all types unless special precautions are taken to avoid eddy currents. Moving-iron and induction-type ammeters should be compared with an electrodynamic ammeter which has been previously calibrated on direct current.

ACCURACY OF AMMETERS AND OTHER ELECTRICAL INSTRUMENTS. — Various methods of expressing the accuracy of electrical instruments have been used. A customary and reasonably satisfactory method is to state that the instrument is correct to within a given percentage of the full scale value. This is understood to apply throughout the scale, and in uniform-scale instruments amounts to saying that no division mark is out of its proper position by more than a certain linear distance.

It is difficult to make general statements of the accuracy of electrical instruments, because this depends on many things, such as operating principle, workmanship, range, and conditions of use. It may be said that 0.1 to 0.2 per cent is about the limit of accuracy attainable in d.-c. instruments, and to get it requires high-grade instruments carefully used in connection with calibration curves obtained by regular and sufficiently frequent comparisons with standards of higher class, such as potentiometers. The accuracy attainable in a.-c. instruments is in general less than in d.-c. instruments.

Portable instruments of high grade are obtainable having a stated accuracy of 0.25 per cent of full scale value; intermediate grade instruments, 0.5 per cent; small portable instruments, 1 per cent. Switchboard instruments of the best grade are usually stated to be accurate to within 1 per cent of full scale value.

The accuracy obtainable in service depends not only on the inherent accuracy of the instrument, but also to a very great extent on the conditions of use. This subject is discussed in detail in a paper on "The Accuracy of Commercial Electrical Measurements" by H. B. Brooks, Trans. A.I.E.E., Vol. 39, 1920.

INSTALLATION OF SWITCHBOARD INSTRUMENTS. — The same general considerations apply to all switchboard instruments, i.e., ammeters, voltmeters, wattmeters, etc. Instruments previous to installation should be kept in a dry, cool place. Switchboard instruments should not be put in place until all the work on the boards or in the vicinity of their location has been done, so that they may not be damaged by violent shocks.

During shipment moving parts, etc., are sometimes blocked and instructions furnished with instruments by makers should be carefully followed in unpacking and assembling.

It is not customary to ground the cases of d-c. instruments or of a-c. instruments above 650 volts; these latter are usually protected by insulated covers. The cases of instruments on secondary circuits below 650 volts are usually grounded.

Determination of Capacity of Instruments. — In providing instrument equipment for switchboard service the relation between ammeters, voltmeters, wattmeters and the circuit conditions should be carefully considered so that proper sizes may be provided. The size should be so chosen that a good indication can be obtained under all ordinary load conditions, and at the same time the highest loads can be accurately indicated.

REPAIRS OF INSTRUMENTS. — Most portable and switchboard instruments in use at the present time are constructed with the idea of having

their parts readily accessible for repair. Instruments, however, are usually very delicate in comparison with other apparatus, particularly with reference to the pivots and jewel bearings. Any extended repairs should, therefore, not be attempted unless equipment and experience suitable for the work in hand are available.

COST OF AMMETERS AND VOLTMETERS. — The following figures are approximate only, and should be used only as a rough guide. Shunts and instrument transformers are not included; see articles on *Shunts* and *Transformers, Instrument*.

COST OF AMMETERS AND VOLTMETERS (1920–21)

Type of instrument	Switchboard instruments	Portable instruments
Permanent-magnet moving-coil type:		
Small instruments	$6–$10	$12–$17
Medium-size instruments	$13–$24	.....
Regular-size instruments, high-grade	$23–$34	$43–$100
Polarized-vane type	$2–$4	.....
Moving-iron type:		
Unshielded, portable, single-range	.....	$25–$48
Shielded, portable, two-range	.....	$54–$100
Round pattern	$20–$29	.....
Horizontal edgewise pattern	$36–$51	.....
Electrodynamic type:		
Medium-size instruments	.....	$33–$42
Regular-size instruments, high-grade	.....	$60–$104
Induction type:		
High-grade	$24–$40	$54–$65
Low-grade	.....	$32
Thermocouple type:		
Small instruments	$16–$19	.....
Regular size instruments	$53–$76	.....

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See also an extensive bibliography on electrical instruments and meters in the 1914 report of Meter Committee of the National Electric Light Association.

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AMPERE-HOUR METERS. — (*See also Ammeters; Wattmeters.*) Ampere-hour or quantity (coulomb) meters may be divided into practically two classes, i.e., electrolytic meters and electromagnetic or motor meters. They are used in this country chiefly for storage-battery work; small capacity ampere-hour meters are also used, particularly abroad, as watthour meters, being calibrated in this case to read directly in kilowatt-hours at some definite voltage.

ELECTROLYTIC METERS. — This type of meter is used extensively in Europe, but is rarely used in this country. The meter generally consists of some form of glass container or "U" tube containing an electrolyte, such as water, or an aqueous solution of a salt of mercury, or of caustic soda. The action of the current passing through the solution decomposes it and since the rate of decomposition is proportional to the strength of the current, the deposit of metal or the number of cubic centimeters of gas evolved can be calibrated to measure the quantity of current. (*See Electrochemistry, Principles of.*) Such meters can also be used as watthour meters (q.v.) in which case they are usually calibrated to read directly in kilowatt-hours at some assumed voltage. In some types the entire current to be measured is passed through the electrolyte and in others the main current passes through a shunt and only a very small part of the current passes through the electrolyte. In a satisfactory design of electrolytic meter the drop at full load does not exceed 1½ to 2 per cent on a 200-volt circuit, and the meter is accurate to within 2 per cent or better (depending on the design) at all loads between 10 per cent and 150 per cent load.

MOTOR METERS. — The essential parts of the motor ampere-hour meter are the motor element, the brake or speed-regulating device and the register or gear train which records the integrated current passed through the meter. The motor consists of an armature rotating in a magnetic field produced either by a permanent magnet or by an electromagnet. The meters are generally arranged so that only a shunted portion of the current flows through the armature and when electromagnet fields are used they are connected *in series* with the armature. The construction of these motors is otherwise similar to that of a watthour meter (q.v.). The commutator and other electromagnetic types of motor meters are all designed with the idea of producing a device which will be cheaper and if possible more rugged than the ordinary watthour meter. The absence of a constantly excited potential circuit in the meter also avoids the constant loss of energy which takes place in such a circuit irrespective of the load. In the motor meter the drop across the shunt varies in meters of different manufacture from about 50 to 100 millivolts in the mercury meter, and from 0.8 to 1.5 volts in the commutator meter.

Commutator Ampere-hour Meter. — The commutator type of meter in its simplest form usually consists of one or two permanent magnets which provide a driving field within which rotates an armature with three coils and a three-part commutator. In some designs the armature coils are mounted flat on an aluminum disk which in addition to supporting the armature coils produces the retarding or braking action in connection with the field magnet. In another design there is a stationary iron core between the poles of the field magnet and a drum armature rotating in the gap between the stationary iron core and the pole faces of the field magnet. No braking device is used in this latter type, and the motor runs at a speed proportional to the impressed e.m.f., taking only sufficient power to overcome the friction in the bearings and in the gear train.

To compensate for friction at light loads a slight auxiliary potential difference is sometimes maintained across the brushes by placing the armature in series with a high resistance across the line. This arrangement is adjusted so that the meter will not run with no current through the main shunt, but at light load the

extra potential difference at the brushes will be sufficient to provide a torque which will compensate for the frictional torque of the moving parts. In a recent type of A.E.G. ampere-hour meter the light-load compensation is effected by movable brushes automatically controlled (*Elekt. Zeits. 40 p. 213, May 8, 1919*).

Oscillating Motor Ampere-hour Meter. — A special form of the electromagnetic motor meter differing from all other designs is the oscillating meter. In principle, this meter is a clock which is controlled by the current. The hair spring of the clock is replaced by a disk carrying a few small iron wires. This special balance wheel is supported between two coils which carry the current to be measured or a shunted portion of it. The magnetic field from the coils magnetizes the iron wires and in conjunction with the main spring of the clock causes the special balance wheel to oscillate at a rate proportional to the strength of the magnetic field and therefore proportional to the current passing through the meter. The movement of the clock is transferred to a registering mechanism geared to register ampere-hours, or kilowatt-hours at a constant voltage.

Mercury Ampere-hour Meter. — The motor meter of the mercury type utilizes mercury to carry current to the armature, the mercury really taking the place of the brushes and commutator of the ordinary direct-current motor. One form of the meter consists in principle of a copper disk or copper thimble armature mounted in jeweled bearings and immersed in the mercury. The current is led into the mercury chamber through suitable terminals and since mercury has about fifty-five times the resistance of copper, the greater part of this current goes through the copper (approximately diametrically across the disk) and out the other terminal by way of the mercury. This arrangement applies to meters with permanent-magnet fields. In case electromagnet fields are used, the driving torque is approximately proportional to the square of the current, hence a braking system must be used to produce a retarding force varying with the square of the speed, such as air or fluid friction. When this is done the rate of revolution of the armature when running at a constant speed is proportional to the current passed through the meter. When permanent-magnet fields are used, a device is sometimes used to compensate for the increase of fluid friction with increase of speed; this device takes some such form as an auxiliary coil, in series with the motor element, which produces a flux which augments the flux cutting the driving disk.

The mercury motor meters utilize iron or in some cases moulded compound for the mercury well, and in the design care must be taken to provide non-spillable joints at the point where the spindle of the armature enters the mercury chamber. All metal in the meters should be of such composition as not to be readily affected by mercury even though not in direct contact with it.

SPECIAL FEATURES. — Ampere-hour meters used for showing the state of charge of storage batteries are sometimes provided with special features. For example, a "compensation for overcharge" causes the meter to run more slowly on a given value of charging current than on the same value of current during discharge. The percentage difference in the two cases is chosen to provide for the excess that must be put into the battery because it is not 100 per cent efficient. This is accomplished by a "variable resistor element" in parallel with the main mercury chamber. A pivoted copper bar in this element is immersed in mercury, and is cut by some of the flux from the driving magnets. It will thus change its position with the reversal of current direction, and will vary the resistance of the element. The "compensation for light-load accuracy and internal battery losses" consists of a thermocouple heated by a potential winding and delivering a small current continually to the motor element in the direction corresponding to battery discharge. This action may be adjusted to cause the meter to record the loss of charge when the battery is not in use. The "thermal

shunt method" of compensation for high discharge rates consists in making the shunt to the motor element of iron or other material of high temperature coefficient, and so designing it that it will heat up at the heavier loads. This causes the ampere-hour meter to have a higher percentage registration as the load increases.

Ampere-hour meters are sometimes provided with contacts which actuate auxiliary devices, such as circuit breakers, bells, or other signaling devices. This feature is used in connection with battery charging and electro-plating.

CALIBRATION OF AMPERE-HOUR METERS.— Ampere-hour meters are adjusted and calibrated as follows:

Electrolytic Meters.— As noted above, in the modern types of electrolytic meters mercury is deposited in a glass tube or water is decomposed, the gases passing off into the atmosphere. In the first type a marked scale is placed beside the registering tube into which the electrolyzed mercury falls. This mercury is run back into the mercury reservoir after the reading is taken, by tipping up the cell which is hinged at the top and held vertical by a removable clip at the bottom. To calibrate the instrument an ordinary ammeter may be placed in series with it and the time that the current passes noted on a watch. In testing the types in which gases are evolved and pass off into the atmosphere, it is only necessary to obtain the number of cubic centimeters of liquid per division of the scale, which can be done with a graduated burette. Only the water is decomposed by the passage of the current. To renew the electrolyte after the reading is taken at the end of a period, it is only necessary to add water.

Motor Meters.— In testing ampere-hour meters several adjustments are necessary, since a shunt, a series adjusting resistance and the gear train are involved. In addition, care must be taken to see that there is no excessive friction in any of the moving parts. The general method is to pass a measured constant current through the meter and to determine the time with a stop watch for a certain number of revolutions. Knowing the shunt constant (ratio of total to shunt current) and the register or gear-train ratio the correct speed at a certain current can be calculated and the shunt or adjusting resistance in series with the motor element adjusted to give the correct speed. To determine the accuracy for any set of readings the following formula can be used.

$$\frac{\text{(No. of rev.)} \times \text{(meter constant)}}{\text{No. of seconds}} = \text{current.}$$

The "meter constant" is marked on each meter; it is the number of ampere-seconds per revolution of the disk

WEIGHTS AND COSTS.— Mercury ampere-hour meters of American manufacture are made in different sizes for different types of services. Exclusive of shunts, the larger meter weighs about 16 lb. and the smaller meter 8 to 10 lb. In small capacities with self-contained shunt, the larger meter sells for $30 to $40, and the smaller meter for $12 to $20. External shunts are furnished with the larger meter above 100 amperes, and above 40 amperes with the smaller meter. These shunts range in price from $25 to $30 for 300 amperes and from $65 to $75 for 3000 or 4000 amperes. These prices are only approximate, and should be used only as a rough guide.

BIBLIOGRAPHY.— See the Bibliographies in the articles on *Ammeters* and *Watthour Meters*.

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ANGLES. — (*See also Trigonometric Functions; Trigonometry.*) Plane angles may be expressed in degrees or in radians. The degree is arbitrarily taken as $\frac{1}{360}$th of the plane angle about a point; the radian is defined as the angle subtended by an arc of unit length in the circumference of a circle having unit radius. The angle in radians subtended by any arc of any circle is

$$\text{Angle in radians} = \frac{\text{arc}}{\text{radius}}.$$

The relation between radians and degrees is

1 radian = 57.30 degrees.
1 degree = 0.01745 radians.

Angle of Curvature. — In railroad practice the angle of curvature is the angle subtended by a chord 100 feet in length, the curve being the arc of a true circle. The relation between degree of curvature D and radius of curvature R is

$$R = \frac{50}{\sin \frac{D}{2}} \text{ feet.}$$

For D small, the chord is very approximately equal to the arc, consequently under these conditions

$$R = \frac{5730}{D} \text{ feet,}$$

where D is in degrees. The error involved in this approximate formula is less than 2 parts in 1000 for D less than 10°, and to less than 1 per cent for D less than 30°. (*See also Railways, Location and Permanent Way for.*)

Solid Angles. — The solid angle at any point P subtended by any surface S is equal to the portion of the surface of a sphere of unit radius which is cut out by a cone having its apex at the point P and its base coinciding with the perimeter of S. The total solid angle about a point is then equal to 4π. The unit of solid angle as thus defined is called a steradian. A solid angle of 2π steradians is called a hemisphere and a solid angle of $\frac{\pi}{2}$ steradians is called a spherical right angle. See table in *Units and Conversion Factors.*

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ARC, ELECTRIC. — (*See also Distribution Systems; Furnaces, Electric; Illumination, Interior and Street; Lamps, Arc; Rectifiers.*) An electric arc is an incandescent vapor bridge consisting of material electrically impelled from a negative to a positive electrode. A spark is also an incandescent vapor bridge, but it differs from an arc, in not depending upon the electrodes for its material medium. The establishment of an arc requires the expenditure of energy for the latent heat of evaporation of the electrode and for the motion of the vapor stream. As no energy can be expended for these purposes until the current flows, an arc cannot start spontaneously. The following expedients are, therefore, adopted to start arcs.

(1) Bringing the conductors into contact with each other and separating them after the current has commenced to flow.

(2) Stressing the dielectric between the conductors until it breaks down electrically and becomes conducting.

(3) Using a subsidiary arc to furnish the initial vapor bridge. The first of these methods is used in carbon-arc lamps and the last in the mercury-arc rectifier.

CARBON ARC. — Until recently the only arc used for illumination was the arc between carbon electrodes, though at the present time there are several materials used, such as magnetite, mercury and the mixtures of various substances with carbon.

Crater. — The vapor column of the carbon arc, impinging on the positive electrode, raises the end of the latter to a very high temperature and volatilizes the carbon. The effect of this is to cause a hollow to be burned in the tip of the positive electrode. This hollow is called the crater.

Temperature. — The maximum temperature of the arc cannot be measured by direct means and the various estimates, which have been made, range from 3200° C. to 6000° C., absl. Using Wien's law connecting temperature and wave length corresponding to maximum radiated energy, Lummer and Pringsheim found that this wave length was 0.7 μ and the corresponding temperature somewhere between 3750° C. and 4200° C., absl., the latter figure being the crater temperature at atmospheric pressure. By raising the pressure to 22 atmospheres, a temperature of 6000° C., absl. may be attained. (*W. Mathiesen, Arcs under Pressure, Elekt. Zeits. 37, pp. 549 and 567, Oct., 1916; 38, p. 573, Dec., 1917.*)

Sources of Luminosity. — The light of the arc is derived either from the vapor column or from a body heated to incandescence by the vapor column.

In the old carbon electrode arc no special effort was made to utilize the luminosity of the vapor column, the incandescent spot or crater on the positive carbon being relied upon for practically the entire light. For this reason the positive carbon was always placed above the negative in order that the crater might better shed its light downward.

The flame arc, on the other hand, owes the greater part of its luminosity to the vapor column and very little or none to the heat of the positive electrode.

Hissing. — When the crater is surrounded by the hot gases constituting the arc, the arc is silent, but if the crater extends over the tip of the carbon and comes into contact with cool air, a peculiar hissing sound is evolved.

Characteristic of Arcs between Carbon Electrodes. — A peculiarity of the solid carbon arc is that, with any particular length of arc, if the current be increased, the difference of potential across the carbons will decrease. This occurs continuously until a certain point, when in the open arc the voltage

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drops quite suddenly. If the current is still increased the voltage will again become steady at a much lower value. Between the values before and after the drop, the arc is unstable and hisses. The beginning of the hissing period is indicated by the dotted line in Fig. 1, and the hissing continues throughout the lower part of the curve.

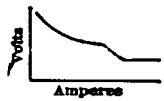


Fig. 1

The hissing point being absent in inclosed arcs, the curve for such arcs is quite continuous.

Steadying Resistance. — In order to maintain a steady current in an electric circuit it is necessary that any decrease in the voltage across the terminals of the circuit shall produce a decrease in the current. Hence, as the arc characteristic shows an increase of current with decreasing voltage there must be placed in circuit with the arc a resistance great enough to compensate for this tendency, if the arc is to be kept in a stable condition. The method of calculating the resistance required to maintain a stable arc for a given current is as follows:

Let e = generator terminal volts = OE,
v = arc terminal volts,
x = resistance in circuit, exclusive of arc and generator resistance,
i = current in amperes,

then, since $e = v + ix$,

the resistance x must be such that

$$x = \frac{e - v}{i}.$$

On the arc characteristic (Fig. 2) find the point P corresponding to the current i and set off $OE = e$ along the vertical axis. Then join EP and continue EP until it cuts the horizontal axis at X. The resistance x is then equal to tan $\angle$ EXO. If EX cuts the curve not only at P, but at S above P, it would appear that the e.m.f. e could support either of two arcs. The point S, although affording a mathematical solution, is not physically possible, as it would involve an increase of voltage, producing a decrease of current, as may be seen by moving EX upward, parallel to its original position. Hence the arc corresponding to P is the only one possible. If EX cuts the curve not only at P, but at some point below P, say T, the same reasoning shows the arc at P to be unstable, while that at T is stable.

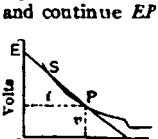


Fig. 2

For any point P, therefore, the arc is stable only if the line EX does not cut the curve below P. Hence, to find the proper value of the resistance x, for a given current i, draw a line tangent to the arc characteristic curve at the point having the abscissa i, then x must be equal to or greater than the tangent of the angle made by this line with the axis of abscissas.

Generator Voltage and Hissing Current. —

Let E = generator voltage,
V = potential difference between carbons just before current is increased to hissing point,
I = maximum amperes which will not produce hissing,
D = drop in volts from silent to hissing,
i = rise of current from silent to hissing,

then $E = V + \frac{I}{i} D$ or $i = \frac{D}{E - V} I$.

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Thus, if the generator voltage is great compared to the arc voltage, and therefore the steadying resistance great, the rise of current at hissing will be less than when the voltage is small.

Resistance of the Arc. — The relation between the drop of potential across the arc and the current flowing through it depends upon whether the arc is in the steady state corresponding to the current flowing or whether the current has been changed without giving time to the vapor column and electrodes to accommodate themselves to the new strength of current. Let V be the drop of potential across a direct-current arc and A the current flowing. If the current be increased by a small amount dA for so short a time that it produces no effect upon the arc itself, it will be accompanied by a rise in potential difference dV, and the ratio $\frac{dV}{dA}$ will be the resistance of the arc. This may be accomplished experimentally by superimposing upon the direct-current arc a small rapidly-alternating current and measuring the value of the alternating p.d. and current. Unless a very high frequency (about 100,000 cycles) is used, the ratio $\frac{dV}{dA}$ will be negative, due to the fact that the power factor of the arc is not unity for low frequencies and this ratio, therefore, does not represent the resistance (*see Duddell's papers in Bibliography*).

Back Electromotive Force of the Arc. — The product of the direct current of an arc and its resistance, measured as described above, is the ohmic drop in the arc. This is usually less than the actual p.d. by 7 to 15 volts, which represent a back electromotive force. This back electromotive force really consists of two, the larger near the positive electrode, opposing the flow of current, and the smaller near the negative, helping the flow. By varying the direct current carried by the arc, the back e.m.f. is not noticeably affected, but the resistance tends to become infinite for very small currents, and small for large currents. A variation in the length of the arc between solid carbons produces no effect upon the back e.m.f., whereas with cored carbons the back e.m.f. decreases with increase of length. The value of the back e.m.f. depends upon the make of carbons employed. In his experiments which established the existence of a true back e.m.f. in the arc, Duddell used an alternating current of about 1 per cent of the strength of the direct current and having a frequency of 100,000 $\sim$ per second.

ARC AS TELEPHONE RECEIVER. — A direct-current arc may be used as a telephone receiver which can be clearly heard in a quiet room at a distance of 10 or 12 feet. The arrangement of apparatus, which gives the best results, is shown in Fig. 3, which is Duddell's improvement of the H. Simon circuit. In Duddell's experiments AB was a solenoid about 30 cm. long, wound with about 1000 turns of No. 18 D.S.C. wire and having an iron core of about 15 mm. diameter. Six hundred turns of the solenoid were connected to the microphone M and battery B and four hundred to the arc and condenser C.

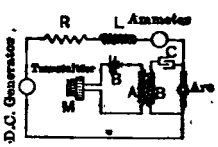


Fig. 3

The arc was between cored carbons of 11 to 13 mm. diameter separated 20 to 30 mm. and took 10 to 12 amperes. The condenser capacity was 2 or 3 microfarads. The resistance R was the usual ballast resistance and the choke coil L served the purpose of confining the telephonic currents to the arc circuit.

ARC AS A TELEPHONE TRANSMITTER. — The arc may be used as a telephone transmitter, but it is unsatisfactory on account of hisses and spits

due to the irregularities of the carbons and to the access of air to the crater. The arrangement of circuits is shown in Fig. 4, the apparatus R, L and C being the same as in the receiver circuit.

MUSICAL ARC. — A direct-current arc of suitable length and current between solid carbons will give a musical note, if it be shunted with a con-

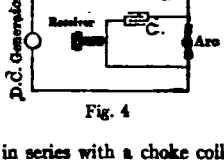


Fig. 4

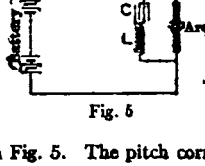


Fig. 5

denser in series with a choke coil, as shown in Fig. 5. The pitch corresponds to the periodic time

$$T = 2\pi\sqrt{LC},$$

where

C = capacity of condenser, farads,
L = inductance of choke coil, henrys.

The choke coil must not have an iron core, or the hysteresis and eddy currents will destroy the effect. A closed circuit, such as a ring of wire placed near the inductance coil, has the same effect. Further details of the musical arc are given below.

THE ARC AS A SOURCE OF HIGH-FREQUENCY CURRENT. — The musical arc owes its pitch to the action of the arc in transforming a part of the direct current into alternating current, the frequency of which can be varied between very wide limits by altering the self-inductance and capacity with which it is shunted. The inclosed arc works just as well as the open arc. In some of Duddell's experiments, the alternating current through the condenser circuit was as large as 5 amperes. Only condensers suitable for high voltages should be used, as, although the arc p.d. may be quite low, the condenser p.d. rises to several hundred volts. Alternating currents of frequencies of from 500 cycles to 500,000 cycles per second are easily obtainable.

Arcs between solid carbons always work well as converters, while those between cored carbons will not work under any conditions. In fact the general conditions under which the arc works as a converter are that $\frac{dV}{dI}$ must be negative and numerically greater than the resistance of the condenser circuit, exclusive of the condenser itself. The expression $\frac{dV}{dI}$ should be taken as referring to small instantaneous changes of the arc voltage and current.

Fig. 6 shows a means of operating several arcs together so as to obtain a greater output than would be possible with a single arc. Direct current is supplied to the arcs from the mains, through the choking coils L_1 and L_2, the ballast resistance R_1 and R_2 and ammeters A_1 and A_2. Alternating current is delivered by the arcs to the circuit containing the capacity C and inductance L. A form of arc used for generating high-frequency currents for use in radiotelephony is the Poulson arc, which is described in this article on *Telephony, Wireless*.

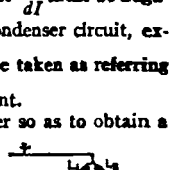


Fig. 6

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OTHER APPLICATIONS OF THE ELECTRIC ARC. — In addition to its application for welding and electrochemical manufactures (q.v.), the thermal effect of the arc is utilized for burning steel. An application of this was made by the contractors of the Pennsylvania Railroad (East River tunnel), who used a carbon rod one foot long and one inch diameter, bolted to a copper rod, provided with an asbestos shield, one foot in diameter. The operators worked with asbestos masks and aprons and dark-colored eye glasses.

Direct-current was used, the carbon electrode being connected to the positive and the steel to be cut to the negative feeders. The current was varied by means of water rheostats, the voltage at the tool varying between 45 and 60 volts. The current varied from 250 to 400 amperes per tool for burning off rivet heads and light section plates and from 600 to 800 amperes for burning plates 4 inches thick. The best results were obtained with 40 volts, 600 amperes and a ¼-inch to ⅝-inch arc. A fair day's work (8 hours) removed 300 rivet heads, although a record of 350 was reached. In the same time 4 feet 6 inches of 4-inch plate could be burned off. (*H. Jappe, Proc. A.S.C.E. 1909, Vol. 35, No. 9, p. 1230.*)

Portable plants, consisting of a gasoline engine-driven generator of about 25 kw. capacity, mounted on a truck, are now in use for wrecking buildings. Such an outfit is capable of burning off a 15-inch I-beam in 20 minutes, using the full-rated output of the generator. The arc has also been used for cutting scrap iron and steel in rolling mills (*G. Kearney, Gen. El. Rev., 20, p. 876, Nov. 1917*).

Experiments on rock removal for tunnel projects have been carried out by the Southern California Edison Co. of Los Angeles. Both direct-current and alternating-current (three-phase) arcs were tried. With direct-current, 500 amperes at 30 volts, 1 pound of rock per minute was removed at a cost of ¼ cent per pound, and with a three-phase arc, 450 amperes per phase with 40 volts between terminals 1 pound of rock per minute was removed at a cost of ¼ cent per pound (*Engineer, 128, p. 57, July 18, 1919*).

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AUTOMOBILES, ELECTRIC. — (*See also Batteries, Storage, Alkaline Type and Lead Type; Batteries, Storage, Applications of; Trucks, Industrial Electric*). There are two types of electric automobiles, namely the battery car and the "gasoline-electric" car. The former type carries a storage battery from which energy is delivered to the driving motor; the latter type, in most instances, carries no battery but electric energy is supplied to the motor by a small generator which is itself driven by a gasoline engine. In other cases storage batteries are used in combination with a motor generator connected to the engine. Thus the machine may be driven by energy from either battery or engine. The battery car only is discussed in this article. A battery car is commonly referred to as "an electric," regardless of whether it belongs to the passenger or the commercial class.

HISTORICAL DEVELOPMENT. — The first battery-driven automobile in this country was built by Fred M. Kimball in Boston in 1888. This machine had 6 cells of lead storage battery and could travel 10 miles on good roads at an average speed of 5 m.p.h. In 1891 there was exhibited at the Mechanics' Fair in Boston an electric surrey built by the Holzer-Cabot Electric Co. Little more was done in the development of electric automobiles until about 1897 when the passenger vehicle was developed in two directions: one for pleasure took the forms of Victoria runabouts, dos-a'-dos and surreys, and the other for business purposes in the form of public taxicabs or vehicles for hire. The latter development expanded during the following four years to the use of fleets of 100 to 400 cabs and broughams in New York, Boston, Philadelphia, Washington, Buffalo and Chicago for public service on a hired basis; these disappeared from use about 1902 or shortly afterwards, largely for financial reasons, but also on account of the fact that large solid or pneumatic tires were not well developed at that date and storage batteries had not progressed beyond the heavy types used for stationary equipment in power stations.

From 1900 to 1903 the commercial type of electric truck began to be employed for merchandise delivery and progressed gradually but steadily until 1910, when the electric light companies recognized in it a desirable "off-peak" power consumer. The Electric Vehicle Association of America with considerable activity materially furthered the use of electric vehicles, both passenger and commercial, until 1914, when there were 37,000 in use; 25,000 passenger cars and 12,000 trucks (*El. World, Jan. 3, 1914*). The average price of the former at that date was $2200 and the latter $2800; this represented $88,000,000 invested by the public in this type of automobile. Following 1914 there was a rapid decline in the rate of production of electric vehicles due largely to general business conditions, but principally to the competitive influence of mass production in the gasoline vehicle industry; although the electric still maintains its superiority in economic operation. In 1920 there were but three manufacturers of each type aggressively conducting production in their respective fields with encouraging reaction, principally in a renewed demand for the commercial type. Another class of the electric vehicle, in the form of indoor industrial material and freight handling trucks, has been in progressive development since 1904; *see Trucks, Industrial Electric.*

APPLICATIONS OF ELECTRIC TRUCKS.— The three types of vehicles which are at present available for urban street haulage are the horse-drawn wagon, the gasoline motor car and the electric battery car. In comparing these three types for use in any given service, the chief factors to be considered are relative speed, distance between stops, length of stops required by the service, expense per vehicle and reliability (i.e., number of days per year upon which

the wagon can be depended for operation). The first three of these factors may be determined by trial or by observation.

In considering the matter of speed it should be remembered that with motor cars the wear and tear on the machine increases approximately as the square of the speed, so that the speed should be such as to give minimum cost of service. The last two of the above factors, namely expense and reliability, can be absolutely determined for any set of operating conditions only by several years of use of each type of vehicle. It is possible, however, to closely estimate the "expected" values of expense from the experience of others in similar kinds of work. See section below on *Costs*.

The electric truck has found its widest commercial application in city services where the hauls are of moderate length, say from two to ten miles, and where the daily service does not exceed 30 miles on the average, with occasional daily mileages of 40 to 50. For very short hauls where the standing time of the wagon is a large proportion of the working time, so that the work per day of each delivery unit is not largely influenced by the speed of the unit, the horse-drawn wagon can perform the work cheaper than any motor vehicle. For the so-called "long hauls" the gasoline truck would be expected to work to better advantage than an electric truck because of higher running speed or greater distance capacity in a day, or both. The rated values of speed and distance on a single battery charge of electric trucks are given in Table V below. The effect of hills or poor pavements would be equivalent to a decrease in the rated values of both speed and mileage. Systems of operating in which discharged batteries are exchanged for charged batteries during the day in order to increase the mileage capacity beyond the rated value have been used with signal success in a few instances, but in general the battery equipment is usually of sufficient capacity to perform the daily service required, or is in some cases supplemented by high-rate boosting charge during the noon hour or other convenient period.

DESIGN. — The necessity of producing cars which would travel at moderate speeds with a low rate of energy consumption has forced the designers of electric automobiles to use equipment which would meet this requirement, even though in some instances less efficient equipment would cost less or might wear longer than that used. Thus tires of low-energy consumption, batteries with large capacity per unit of weight and "anti-friction" bearings in transmission and axles are used almost universally. Consequently an electric automobile is essentially a high-grade machine, for any inefficient equipment directly influences the operating qualities.

Weight and Speed. — In the design of an electric battery car the two primary features are the total weight and the speed under normal conditions. In special cases a car may be built to meet unusual requirements of distance traveled per charge, in which case either the speed or weight must depart from the limitations of common practice. Any decrease in the total weight of the car will result in an increase in either speed or distance capacity or both; or if the weight is brought back to the original value by the use of additional battery capacity, the speed or distance may be still further increased. This has been one of the chief considerations leading to the adoption of lighter batteries, such as the Edison and "thin" paster lead plate, in place of the heavier type lead plate batteries commonly used where their additional weight is not a critical factor. General practice as regards weight and speed for various types of electric automobiles is indicated in Table I.

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TABLE I.—SPEEDS AND WEIGHTS OF ELECTRIC AUTOMOBILES

Class of car or rated capacity of truck	Approximate weight in lb., including empty body	Approximate speed in miles per hour	Weight allowance for body, lb.
2-passenger runabout *	2,200	15 to 25	....
2-passenger Victoria *	2,400	15 to 21	....
2-passenger coupe *	2,600	15 to 20	....
4-passenger brougham	3,780	23 to 25	1010
5-passenger coach	3,860	22 to 24	1060
1,000-lb. truck	3,500	12 to 14	500
2,000-lb. truck	4,500	10 to 12	600
4,000-lb. truck	6,000	8 to 10	800
7,000-lb. truck	8,500	6.5 to 8	1100
10,000-lb. truck	9,500	6 to 7	1400
12,000-lb. truck	11,500	6 to 6.5	1600

* These vehicles are not now (1920) manufactured, but many of them are in use.

Similar data for a representative line of electric trucks are given in Table V below.

Load Efficiency. — By load efficiency of a motor truck is meant the ratio of the load on the machine to the gross weight of the machine, including chassis, body and load. Thus, from the above table, a representative value for the rated load efficiency of a 5-ton capacity electric truck is $\frac{10,000}{10,000+9500} = 0.51$. The rated load efficiencies for gasoline trucks of large capacity, 2 tons or more, are practically the same as the values for electric trucks, but small capacity gasoline cars of good design may have a rated load efficiency as high as 30 per cent as compared to about 24 per cent for electric cars with the customary lead battery equipments.

Motors. — Four-pole series motors are now used almost exclusively for electric automobiles. In the majority of cases but a single motor is used on each vehicle. The field coils are usually arranged in two groups which may be connected first in series and then in parallel. All manufacturers do not rate their motors on the same basis, but good practice is indicated by that of the General Electric Co., whose motors will carry their normal rated load continuously with a maximum temperature rise of 65° C. above the surrounding air at 25° C. or will carry 2½ times their rated load for 1 hour with a maximum temperature rise of 75° C. Ratings are based on bench tests, so that when the motor is installed in a car the overload capacity is usually increased due to the improved ventilation. Large overload capacity is necessary to meet severe street and grade conditions, and unusually good commutating characteristics are required.

An automobile motor must also operate satisfactorily over the varying range in the voltage furnished by the battery in the charged and discharged conditions. The motor speeds which are used with single reduction drives range from 750 to 1000 r.p.m.; the speeds which are used with double reduction drives range from 1000 to 2000 r.p.m.

Number of Motors. — All electric passenger cars and most electric trucks are now being equipped with a single motor. It was formerly common

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practice to use two motors on the larger trucks on account of flexibility in control, but a single motor is now being used on account of space limitations, saving in weight and better electrical efficiency. The peculiar construction of the Couple-gear (*see below*) equipment requires a departure from this practice. Otherwise, either two or four motor equipment is used now only when unusually high tractive effort is required.

Motor Characteristics. — Along with the tendency during recent years to standardize battery equipments at 42 to 44 lead cells and 60 Edison cells, the tendency among motor manufacturers has been to develop a line of motor frames, for each of which two windings could be provided. Thus an 80- or 85-volt motor is usually installed with a 42- to 44-cell lead battery and a 60-volt motor with a 60-cell Edison battery. The windings are so proportioned that a motor has approximately the same speed and torque at both voltage ratings. This development has made it unnecessary to alter either the motor suspension or the mechanical transmission system in changing a car's battery equipment from lead to Edison or vice versa. 24-, 36- and 48-volt motors can also be obtained.

TABLE II.—G. E. STANDARD AUTOMOTIVE MOTOR RATINGS

FOR ROAD VEHICLES

Type	Rated volts	Rated amperes	Speed r.p.m.	Approximate weight
G.E. 1065	60	17	1600	130
G.E. 1065	85	12	1600	130
G.E. 1028	60	28	2000	150
G.E. 1028	85	20	2000	150
G.E. 1043	60	28	1500	218
G.E. 1043	85	20	1500	218
G.E. 1048	60	40	1600	265
G.E. 1048	85	30	1600	265
G.E. 1039	60	40	1200	300
G.E. 1039	85	30	1200	300
G.E. 1022	60	60	1200	425
G.E. 1022	85	40	1200	425
G.E. 1030	60	70	850	530
G.E. 1030	85	50	850	530
G.E. 1027	60	85	900	660
G.E. 1027	85	60	900	660
G.E. 1087	60	160	900	890
G.E. 1087	85	120	900	890

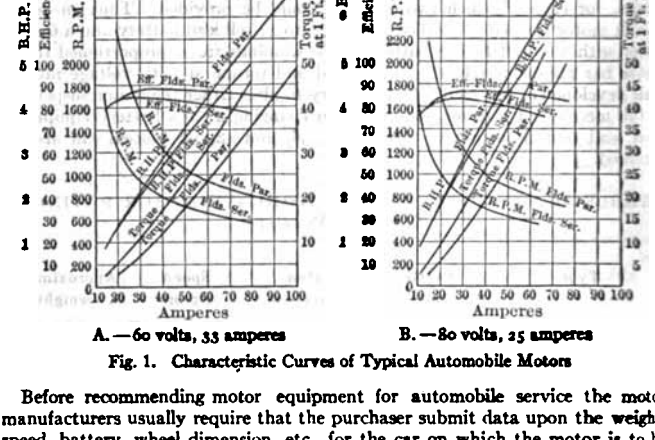
FOR PLEASURE VEHICLES OR INDUSTRIAL TRUCKS

G.E. 1090	24	45	1200	170
G.E. 1090	48	40	2000	170
G.E. 1091	24	65	1750	200
G.E. 1091	48	45	1750	200

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The characteristic curves for a typical Westinghouse motor with the 60-volt and 80-volt windings are given in Figs. 1A and 1B. The relatively small change in efficiency for overload with the field coils in parallel is noteworthy. The "torque ratio" of this motor, i.e., the ratio of torque at 2½ times rated current to torque at rated current, is approximately 5 with both windings.

Table II on page 57 gives a partial list of General Electric automobile motors with their normal ratings.



A.—60 volts, 33 amperes B.—80 volts, 25 amperes

Fig. 1. Characteristic Curves of Typical Automobile Motors

Before recommending motor equipment for automobile service the motor manufacturers usually require that the purchaser submit data upon the weight, speed, battery, wheel dimension, etc., for the car on which the motor is to be used.

Size of Motor Required. — In selecting the size of motor the voltage should be chosen on the basis of 1.9 volts per cell for lead batteries and 1.0 volt per cell for Edison batteries. The average discharge voltages of both types of batteries at their normal rates are higher than these values, but it has been found desirable to install motors on the basis of these values so that at high rates of discharge the terminal voltage may not fall too far below the rated motor voltage.

The current rating of the motor (and also of the battery) should be approximately the value of the current required to drive the car at the rated speed on hard level asphalt. The current input into a vehicle motor when driving a car at constant speed is given by the expression

$$I = \frac{2\,vWr}{E\epsilon},$$

where v = speed of car in miles per hour,
W = total weight of car and load in tons,
r = car resistance in pounds per ton of total car weight,
E = motor terminal voltage,
ϵ = over-all efficiency of motor, controller and transmission.

The value of ϵ at the rated speed is the product of the efficiencies of motor and transmission, usual values falling between 60 and 75 per cent. For value of r see next paragraph.

Car Resistance. — The car resistance depends upon the following conditions: speed, grade, diameter of wheels, load per square inch of tire contact

or per inch of tire width, construction and composition of tire, method of attaching tire to wheel rim, and road surface. The effect of speed is to change r in a manner dependent upon the type of tire, the value of r having a minimum usually at a speed between 6 and 10 m.p.h.; air resistance varies approximately as the square of the speed and need not be considered for speeds of less than 20 m.p.h. The effect of up-grades is to increase r by 20 lb. per ton for each per cent grade. The car resistance with pneumatic tires on hard, level asphalt is given by Churchward (*Soc. of Auto. Eng. Handbook, 1913*) as ranging from 15 lb. per ton for special tires designed for electric runabouts up to 35 lb. per ton for the standard type of tire used on gasoline touring cars; the resistance is greatly affected by the air pressure, increasing rapidly as the air pressure is reduced. Churchward also gives the car resistance with solid tires on hard level asphalt as ranging from 18 to 26 lb. per ton. Other tests have shown a car resistance of 30 lb. per ton for a small capacity electric truck equipped with solid tires (*El. W., May 17, 1913, Vol. 61, p. 1040*).

Effect of Road Surface. — Three sets of values of relative car resistance on various level road surfaces as compared to the value on hard, level asphalt are given in the following table. One set of values is given by Churchward in the *Soc. of Auto. Eng. Handbook* (1913) the set is based on tests conducted at the Massachusetts Institute of Technology in 1913 (*El. W., May 17, 1913, Vol. 61, p. 1040*), and the third set is the result of tests by Kennelly and Schurig, Proc. A.I.E.E., Vol. 35, 1916.

TABLE III.—RELATIVE VALUES OF CAR RESISTANCE

Road surface	Churchward	M.I.T.	Kennelly and Schurig
Asphalt, hard	1.0	1.0	1.0
Wood block	1.15	1.1	1.18
Macadam	1.15 to 3	1.15	1.2
Granite block	1.75	2.0	1.41
Dirt road	1.1 to 2.0	...	1.31
Brick	.....	1.4	1.25
Snow, packed	.....	1.3	....
Snow, fairly hard, without chains	.....	1.7	....
Snow, fairly hard, with chains	.....	1.9	....
Snow, soft, about 3 in. deep	.....	2.1	....
Sand	20	...	....

Transmission Systems. — The transmission systems between motor and wheel which are in common use may be grouped in two classes, known as the "chain" and the "shaft" or gear drives. A single-speed reduction is used in a few makes of cars, but a double reduction is used on a majority of machines. If the first reduction is made by chain and the second by gear, or vice versa, the transmission system is usually designated according to the means employed for the final reduction; e.g., if the final reduction is accomplished by a chain, the system is referred to as a chain drive although the first reduction may be by gears.

Chain Drive. — With chain drive the motor is mounted transversely and a double-speed reduction is used almost without exception. The connection between motor and countershaft is usually by silent chain (Morse or Rey-

nold type, see article on *Chains and Chain Drive*), although spur and herringbo gears are also used; see article on *Gears and Gearing*. The final drive is usua by roller chain, either (*a*) between countershaft and differential in the rear a or (*b*) between countershaft and a sprocket on each of the rear wheels. Cha driven passenger cars are usually equipped with (*a*) and chain-driven commerc cars with (*b*). The chain method of drive possesses the advantages of low i cost and ease of adjustment; its disadvantages are noise, rapid wear due collection of dirt unless properly housed, poor efficiency when not prope adjusted, and unequal wear on the two sides of the car. The chain drive h been losing favor during recent years among both designers and operators a is now (1921) practically abandoned.

Shaft or Gear Drive. — With shaft drive the motor is usually mounte lengthwise of the car, and either a single- or double-speed reduction is used. F single reduction both bevel and worm gears are used as the connection betwee propeller shaft and differential in the rear axle. For double reduction the moto is usually connected to the propeller shaft by spur gear, herringbone gear o silent chain, and the propeller shaft is connected to the differential by a bev gear. The propeller shaft is usually fitted with universal joints. The shaf drive has become standard in passenger cars because it runs quieter than chai drive, and because it can be easily protected from dirt by housing. The shaf drive has the disadvantage of greater weight below the springs than in the cas of the chain drive, which tends to increase the wear on tires.

Worm Drive. — There has recently been a decided tendency among designers of passenger cars and light trucks to use the single-reduction worm gear instead of the double-reduction bevel or chain arrangements, the advantages claimed for the worm being better transmission efficiency and less trouble from adjustment.

Walker Balanced Gear. — In the trucks built by the Walker Vehicle Co. the motor is built into the rear axle, which is made hollow and of a sufficient diameter to contain the motor. The armature shaft is also hollow, so that the drive shafts may extend through from the sockets of the differential to the center of each rear wheel. The wheels are driven by a spur-gear reduction mounted inside the wheels. The wheels have steel-plate sides instead of spokes, so that the gears may run in oil and are thoroughly protected from dirt.

Couple-Gear Wheel. — A device built by the Couple-Gear Freight Wheel Co. has the electric motor mounted inside the wheel. The motor armature carries a pinion on either end which engages with a gear ring on either side of the wheel. The sides of the wheels are dished steel plates. These wheels are being used on both front-wheel-drive and four-wheel drive machines. Being located in the wheels, they do not interfere with the use of the ordinary steering knuckle arrangement.

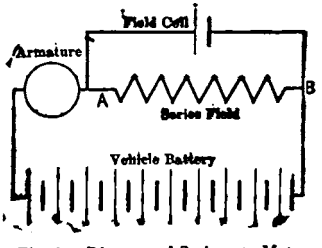


Fig. 2. Diagram of Steinmetz Motor System

Steinmetz System.—A new method of motor excitation consists of connecting a storage battery cell across the field terminals of a series motor employed in vehicle operation. At normal load the drop in voltage between field terminals counterbalances the voltage of battery cell. On starting and heavy grades the current required causes a greater drop in voltage between the field terminals, thus diverting a charging current through

r coil. Similarly if the motor current required in service decreases, the field l will discharge through the field winding. Thus, the field strength varies y within narrow limits and in such a system the coasting of the vehicle down ides and the braking or stopping of the vehicle may be employed to recharge e vehicle storage battery. With this system a motor is used in which both ld and armature rotate; each being connected separately to the two driving eels, no differential being required, and on account of the increased relative ed between field and armature a much lighter motor than the normal type, th stationary field and rotating armature, is required for any given service.

Efficiency of Transmission. — (*See also article on Gears and Gearing.*) aumont gives the following figures on the transmission efficiency of different pes of automobile mechanisms.

Source of loss of power	Efficiency, per cent
One chain, and one and one-half pairs of bearings	89.5
One set of gears, two pairs of bearings	82.0
One set of gears, equivalent of two chains, three pairs of bearings	74.0
Two sets of gears, four pairs of bearings	70.0

The following figures, given by F. Burgess (*Trans. Soc. Auto. Eng., 1912, ol. 7, Part 2, p. 196*), are the results of an efficiency test of a straight type rorm and worm gear for rear-axle drive of electric automobiles. The worm ear was made of phosphor bronze and had 39 teeth; the worm was made of ase-hardened steel and had 4 threads.

R.p.m. of worm	Temperature of worm gear, °F.	Input, trans. dyn., h.p.	Output, brake h.p.	Efficiency, per cent
1383	74	1.64	1.03	61.2
1416	86	3.41	3.17	93.2
1370	90	5.48	5.13	93.7
1389	94	6.72	6.24	93.0
1400	108	9.43	8.5	90.2

Batteries. — There are three types of batteries in general use in electric vehicles, namely, the pasted lead, the "Iron-clad" lead, and the Edison. The performance characteristic (except life) of the first two are identical and are described in the article on *Batteries, Storage, Lead Type;* the characteristics of the Edison battery are described in the article on *Batteries, Storage, Alkaline Type.* The desirable characteristics of a battery for vehicle service are given in the article on *Batteries, Storage, Applications of.*

Number of Cells; Number of Plates. — Practice among electric automobile manufacturers is now practically standardized upon the installation of 42 or 44 cells of lead battery and 60 cells of Edison battery in both passenger and commercial classes of cars, as these numbers permit of charging from a 115-volt circuit with minimum loss in the rheostat. There are, however, in use many old designs of pleasure cars in which from 24 to 38 lead cells are used, and the small capacity delivery wagons in which 48 Edison cells are also employed. A 24-volt to 48-volt battery is used on industrial trucks. For a given watt-hour capacity a battery of a small number of cells is cheaper to buy and

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maintain than one of a large number of cells, but is more expensive to ch from constant-potential d-c. mains on account of rheostat losses.

As pointed out above the rated current output of a vehicle battery f hours should not be exceeded by the current required to drive the car at m speed on hard, level asphalt (*see section above on Size of Motor*). Thus w the current under these normal conditions is known, the number of plates cell can be determined from a knowledge of the discharge rates of the vari types of plates which are under consideration. For A-type Edison batte the normal (5-hr. rate) is 7.5 amp. per positive plate; conservative desig use this rate in applying batteries rather than the value of 9.5 amp. which co be obtained for 4 hours. The discharge rates per positive plate of 5¾ by 8½ for 4 hours and for the so-called "normal" times of discharge for the types vehicle batteries made by the Electric Storage Battery Co. are given in t accompanying table.

Type of plate	"Normal" discharge		Amperes per positive plate discharged during 6 hr.
	Time, hours	Amperes per positive plate	
Exide	4	7	5.12
Hycap	5	5.5	4.8
Thin	6	4.25	4.13
Iron-clad	4.5	7	5.6

It will be noted that the above rule of installing a battery whose 4-hour discharge rate is approximately equal to the current required for running at rated speed under good street conditions will furnish a minimum practicable battery capacity, and that this capacity may have to be increased materially in order that the car may meet the necessary mileage requirements when operating on grades or poor roads. There is a tendency among electric car manufacturers to recommend battery equipment for given conditions which is much more liberal than they recommended a few years ago.

Construction of Battery Box. — In passenger cars a tight wood-lined compartment is usually supplied for carrying the battery. In commercial cars the battery compartment is also wood lined, and provision is commonly made for ventilation to facilitate charging in warm weather. The details of a typical underslung battery box are shown in Fig. 3. With this construction strips may be laid in the spaces between the floor boards in order to make the compartment entirely inclosed, as is frequently desirable in cold weather. A tight covering should be provided with an underslung battery box to prevent dirt and water falling upon the battery from the floor of the car.

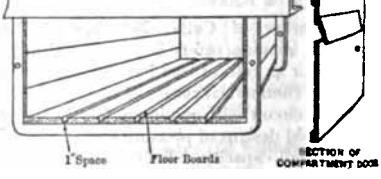


Fig. 3. Typical Underslung Battery Box

Controllers. — Controllers are usually of the drum type with two running positions, known as the "field-series" and the "field-parallel" positions. The motor field coils are arranged in two groups for connection either in series or in parallel.

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cells of the battery are connected permanently in series. In starting, er 2 or 3 resistance notches are used before the "field-series" notch is :hed. A shunt on the fields is frequently used between the "field-series" the "field-parallel" notches. For normal full-speed running the two ups of field coils are in parallel. An emergency speed is obtained by nting a resistance around the fields when connected in parallel. It was nerly customary to split the battery into two groups which could be rated in series-parallel in order to obtain 4 economical running speeds, but uble was experienced from the unequal discharge of the two halves of the tery. In the magnetic type of control which is used to some extent in senger cars the changes in connection are affected by relays operated by auxiliary electric circuit. Some forms of regenerative control have been ed with only moderate success, although in hilly localities regenerative trol may be desirable on account of protecting the mechanical brakes.

Tires. — Tires for use on electric automobiles are generally more resilient an the standard types of tires commonly used on gasoline automobiles. "High iciency" or special electric tires, both solid and pneumatic, have been devel- ed by most of the tire manufacturers in response to a demand by the oper- ors of electric cars for tires with low consumption of energy. Standard types tires may consume as much as 100 per cent more energy than the special ectric tires. Experience has shown that the smooth starting characteristic f an electric motor produces much less abrasion than the uneven acceleration ith a gasoline motor, so that the rubber compounds in tires for electric cars are sually softer than the compounds in tires for gasoline cars and yet the lives of oth types in point of distances traveled are approximately the same. Electric neumatic tires are usually of the cord type; i.e., the "fabric" consists of arallel strands of cotton impregnated with rubber gum. Some types of solid ectric tires, such as the Motz, have the sides undercut at intervals to allow r the "flow" of the r[illegible]er when under compression.

Carrying Capacities of Tires. — In general a tire of small transverse read will consume less energy than a tire of the same compound with large read when operating on a smooth, hard surface; also, a large wheel diameter ives less energy consumption than a small one as well as improving the riding ualities on uneven surfaces. The Society of Automobile Engineers have recom- ended the use of 32-, 36- and 40-in. tires as standard practice. (*See Trans. oc. Auto. Eng., 1914.*) But in selecting tire equipment it should be remem- ered that there is a limit to the load which any size of tire will stand without ermanent injury by disintegration. The maximum carrying capacities per heel at present (1920) recommended by the B. F. Goodrich Co., are given n Table IV, as are also the recommended inflation pressures for pneumatic ires of the fabric type; the recommended inflation pressures for cord tires re approximately 80 per cent of the values in the table.

Examples of Commercial Car Design. — Table V gives data from the standard specifications of a number of the electric trucks.

PERFORMANCE; ENERGY CONSUMPTION. — The energy con- sumed by an electric automobile will depend very largely upon the care of the driver in coasting up to stops instead of braking directly from full speed; other important factors in determining the energy consumption are efficiencies of battery and driving mechanism, tire equipment, nature of roads and grades, number of stops and miles per day, etc. However, for a car which is operated under similar conditions day after day, the energy consumption per mile should be reasonably uniform, so that any considerable increase in energy consumption may indicate either careless driving or poorly adjusted mechanism, as for in- stance a dragging brake. Table VI gives a series of approximate values for

TABLE IV.—MAXIMUM CARRYING CAPACITY OF TIRES

Size of tire, inches	Maximum load, pounds per wheel				Recommended inflation pressure, lb. per sq. in.
	Solid		Pneumatic *		
	Single	Dual	Rear wheel	Front wheel	
2½	700	1400	....	....	..
3	1000	2000	375	450	45
3½	1300	2600	570	600	55
4	1700	3400	815	1200	65
5	2500	5000	1500	1700	85
6	3500	7000	....	....	..
7	4500	9000	....	....	..

* The allowable load per wheel for a given width of tire increases slightly with the wheel diameter. The sizes quoted in the table are 34 × 4½ in., 35 × 5 in., 36 × 6 in. and 38 × 7 in.

TABLE V.—DATA ON ELECTRIC TRUCKS

Rated load capacity, lb.	750	1000	2000	4000	7000	10,000
Speed, miles per hour.	12	15	14	13	12	10
Miles per battery charge, approx....	45	45	45	45	40	35
Lead battery equipment:						
Number of cells....	42	42	42	42	42	44
Number of pasted plates.....	11	11	13	17	23	27
Number of iron-clad plates.....	9	9	11	15	19	21
Edison battery equipment:						
Number of cells...	48	60	60	60	60	60
Designation.....	A-4	A-5	A-6	A-8	A-10	A-12
Tires, front, in.....	32×2½	36×3	36×3½	36×4	36×6	36×7
Tires, rear, in.....	32×3	36×3	36×4	36×4D*	36×5D*	36×6D*
Weight, chassis and lead battery, lb....	2970	3325	4370	6000	8225	9300
Per cent weight on rear wheels †.....	50	50	50	50	50	50
Ampere rating of motor on 80 volts..	20	32	32	45	62	62

* Dual.
† Chassis and battery

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energy consumption per mile which are based upon a large number of reports upon the operation of electric cars in large cities; these reports were collected in connection with the Vehicle Research study conducted during 1912 to 1914 by the Electric Research Laboratory of the Massachusetts Institute of Technology. These figures are representative of experience with modern types of cars under average city conditions; the consumption for a given set of conditions may vary from the figures by as much as 20 per cent, either above or below.

TABLE VI. — ENERGY CONSUMPTION IN WATT-HOURS PER MILE, AT CHARGING BUS BARS

Type of car	Lead battery	Edison battery
2-passenger	300	400
1,000-pounds	550	750
2,000-pounds	650	900
4,000-pounds	830	1150
7,000-pounds	1100	....
10,000-pounds	1400	....

Garage Load Curves. — Fig. 4 shows a typical daily load curve for a public garage handling 75 electric passenger cars; Fig. 5 shows a similar typical daily curve for the private garage of a large department store (*see paper by E. E. Witherby, Proc. N. E. L. A., 1913*). The "off-peak" character of the electric vehicle load is indicated by these curves. In order to attract such off-peak load most light and power companies are now offering special rates for vehicle charging, frequently with the provision that no charging shall be done during the time of the power company's daily peak load.

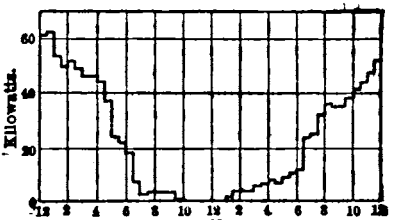


Fig. 4. Daily Load Curves of a Public Garage Handling Passenger Cars

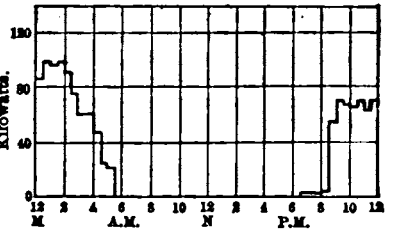


Fig. 5. Daily Load Curves of a Private Garage Handling Trucks

OPERATION.—In the operation of electric automobiles particular attention should be paid to the proper care of the storage batteries. The battery manufacturing companies issue complete instructions for the proper handling of their cells. The manufacturers of the battery, as well as the manufacturers of the car, are usually ready to confer with the operator of a car to the end that he may obtain satisfactory service from his machine. They should be consulted on the first indication of trouble in their respective portions of the equipment, should the cause of the trouble not be understood.

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The following points upon the care and operation of electric cars should be observed:

1. A battery must always be charged with direct current and in the right direction.

2. Never bring an exposed flame near a battery while charging or immediately afterwards.

3. Do not allow the battery temperature to exceed 110° F.

4. Keep the cells filled to the proper level by adding distilled water only. Never put acid in an Edison battery under any circumstances.

5. Keep the outside of the cells free from foreign substances, both solid and liquid.

6. For boosting a lead battery during a specified short period, the maximum current rate I which may be used without reaching the gassing point is the quotient of the ampere-hours Q previously discharged (read from ampere-hour meter), divided by 1 plus the hours H available for boosting, viz., $I = \frac{Q}{1+H}$.

7. The mechanism of a car should be inspected carefully at least once in two weeks.

8. A car should be entirely overhauled at least once each year, in order that worn parts may be located and replaced.

COSTS. — The initial cost of passenger electrics depends so largely upon the character of body and fittings that it is impossible to quote any but the most general figures; prices range from $2800 to $5000, the most popular cars selling at from $4000 to $5000. It is likewise impossible to quote definite figures on the cost of operating pleasure cars; prices for electricity for private charging vary from about 3 cents per kw-hr. upward; the cost of storage in public garages ranges from $15 to $40 per month, plus a charge for electricity at from 4 cents per kw-hr. upward.

The initial cost of commercial electrics ranges from about 60 cents per pound for large trucks to 75 cents per pound for light cars, based upon usual equipment of solid tires, lead batteries and express or stake bodies. (*For typical weights see Tables I and V.*) Special equipment such as winches or dumping bodies is additional. The operating expense will vary widely for different conditions, so that it is impossible to predetermine the total cost of operating a truck of a given rating without knowing the requirements of the service, the nature of the roads, and the general method of handling and caring for the car. The data in the following table are deduced from estimates by Pender and Thomson given in *Vehicle Research Bulletin No. 3*, issued in 1913 by the Massachusetts Institute of Technology. The figures are based upon reports of the operation of a large number of cars during from 1 to 4 years in city trucking and delivery services.

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TABLE VII. — COST OF OPERATING ELECTRIC TRUCKS

(Pre-war figures)

Rated load capacity, lb.	1000	4000	7000	10,000
Miles per year considered	10,500	9100	8850	8000
Cents per mile for:				
Tires, repairs and battery*	6.8	8.3	11.2	14.3
Electricity at 3¢ per kw-hr	1.5	2.2	3.0	3.6
Dollars per year for:				
Garage and lubricants	215	235	255	285
Driver and helper	1,000	1140	1210	1210
Depreciation, interest and insurance	380	464	532	685
Total annual expense, dollars	2,455	2794	3252	3610

* Pasted plate lead battery.

BIBLIOGRAPHY. — Churchward, A., *The Standardization of the Electric Vehicle*, Cent. Sta., 1912, Vol. 11, p. 254, and Vol. 12, p. 166; *Soc. of Auto. Eng. Handbook*; Cushing and Smith, *The Electric Vehicle Handbook*; Schoepf, T H., *The Performance Characteristics of Electric Motors and their Influence on the Operation of Electric Trucks*, Cent. Sta., March, 1914; Pender, H., and Thomson, H. F., *Notes on the Cost of Motor Trucking* and *Observations on Horse and Motor Trucking*, issued by El. Res. Lab. of the Mass. Inst. of Tech., 1911 and 1913; *Operating Cost Commercial Electric Vehicles*, El. World, May 22, 1915; *Tractive Resistance of Roads*, Kennelly and Schurig, Vol. 35, Proc. A.I.E.E., 1916.

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AUTO-TRANSFORMERS AND COMPENSATORS. — (*See also Starters, Motor; Transformers.*) An auto-transformer or single-circuit transformer, also called a "compensator," consists of a transformer having the usual iron core but only one electrical circuit instead of two. This circuit is tapped at various points as shown in Fig. 1, and the primary and secondary circuits, while independent outside the transformer, unite in the same winding in the transformer. If an alternating voltage is impressed across the points *ab*, a magnetizing current will flow in the winding setting up an alternating flux which will link every turn and induce therein an alternating voltage. The voltage between any two taps, as *ac*, is proportional to the number of turns between the taps; thus any ratio of voltages may be obtained. If the secondary *ac* is loaded a current will flow in the primary and the primary and secondary currents will flow in the two parts of the winding as indicated in the figure.

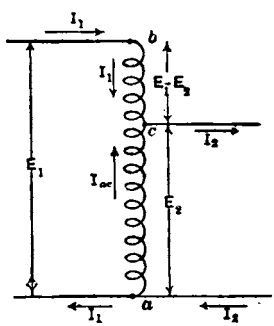


Fig. 1. Auto-transformer

VOLTAGE AND CURRENT RELATIONS. — Let N_1 be the total number of turns between *a* and *b*, N_2 the turns between *a* and *c*, E_1 the voltage across the terminals *a* and *b* and E_2 the voltage across the terminals *a* and *c*. Then, neglecting the resistance and reactance of the winding,

$$E_2 = \frac{N_2}{N_1} E_1.$$

Let I_1 be the current entering the terminal *b*, I_2 the current in the ***external*** circuit connecting *a* and *c*, and I_{ac} the current ***in the transformer winding*** between *a* and *c*. Then, neglecting the resistance and reactance of the winding and the magnetizing current,

$$I_2 = \frac{N_1}{N_2} I_1,$$

$$I_{ac} = I_2 - I_1 = \frac{N_1 - N_2}{N_2} I_1.$$

The current in the turns between *b* and *c* is

$$I_{bc} = I_1.$$

Auto-transformer Versus the Two-circuit Transformer.—For $N_2 = \frac{1}{2} N_1$ the current in the turns between *a* and *c* would be just equal, neglecting the exciting current, to the current in the turns from *b* to *c* (but opposite in direction). Consequently for a 2 to 1 transformation but one winding of an ordinary two-circuit transformer could be used, provided a tap was available at the middle point of this winding, and the rated output of the transformer could be obtained without the current in this winding exceeding its rated value. Since under these conditions there would be no current in the second winding, the heating of the transformer would be less than it would be were the transformer used as an ordinary two-circuit transformer, and therefore a greater output could be obtained without exceeding the nominal temperature rise.

In general, for the same power input into the connected load an auto-transformer requires but $\frac{E_1 - E_2}{E_1}$ of the copper required for a two-circuit transformer,

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here E_1 is the high-tension and E_2 the low-tension voltage. The higher the atio of transformation the less the saving in copper. There is also a serious bjection to an auto-transformer of high ratio of transformation, in that an cidental ground on the high-tension lead, *b* in Fig. 1, would establish a high oltage between the low-tension leads and the ground, which may cause a angerous shock to a person touching either low-tension lead or may cause ther damage. This may be partially prevented by grounding the common oint of the high- and low-tension circuits, the point *a* in Fig. 1, in which case n accidental ground on the high-tension side would produce a short-circuit, hich would open the circuit breaker in the primary circuit, *provided the resistance between the two grounds is low and the circuit breaker operates properly.* hese two provisions, however, may not always be realized even though reasonble care is taken, and it is therefore not considered good practice to use an uto-transformer of high ratio of transformation, except in special cases where conomy of space is an important factor and danger from shock can be guarded gainst, e.g., on a-c. locomotives.

RATING OF AN AUTO-TRANSFORMER. — In commercial practice he rating of an auto-transformer in volt-amperes is taken equal to the differnce between the high- and low-tension voltages multiplied by the rated urrent in that part of the winding, *bc* in Fig. 1, across which this voltage exists. The capacity of an auto-transformer for a given work bears to the capacity of a two-circuit transformer for the same purpose the ratio $\frac{E_1 - E_2}{E_1}$. For example, to step down the voltage of the supply mains from 500 to 400 volts and supply a load of 100 kv-a. would require an auto-transformer having rating of $\frac{500 - 400}{500} \times 100 = 20$ kv-a. as against a two-circuit transformer aving a rating of 100 kv-a. The weight, dimensions and cost of an auto-ransformer are very nearly the same as for an ordinary two-circuit transformer aving the same voltage and kv-a. rating.

APPLICATIONS. — Auto-transformers are used chiefly where the required hange in voltage is small, e.g., for motor starters (*see Starters, Motor*), and for alancing the voltage between two or more circuits. The smaller the ratio of ransformation the greater is the gain in cost and efficiency resulting from the se of an auto-transformer instead of a two-circuit transformer. Auto-transormers are also used to provide a neutral for the Edison three-wire system; see *Distribution Circuits*. In single-phase railway work single-phase auto-transormers are used on the locomotives for transforming the trolley voltage (from 000 to 6000 volts) to the motor voltage (about 500). This is a rather high atio of transformation for an auto-transformer, but as the saving in weight is ery important and as one terminal is grounded, it has proven satisfactory for his service; see *Locomotives, Electric*.

Auto-transformers are frequently constructed three-phase (and occasionally wo-phase). These are generally used for starting polyphase motors by proiding a lower voltage for the starting period. They are also occasionally sed in high-tension distribution. If the voltage applied to an a-c. motor is educed to one-half, the motor starting current will be one-half and the voltmperes one-quarter. Thus the starting current in the line will be onequarter. A three-phase auto-transformer may be either Y or delta-connected. he Y connection is shown under *Motors, Polyphase Induction, Methods of tarting*. The delta connection cannot be made to give a balanced voltage ss than half that of the higher voltage, as may be readily seen from an inspecon of Fig. 2.

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DESIGN. — The design of an auto-transformer is quite similar to that of a two-circuit transformer (q.v.) and the leakage reactance is calculated in the same way. For low-leakage reactance the primary and secondary coils must not be entirely separated, but each must be divided into sections and inter-

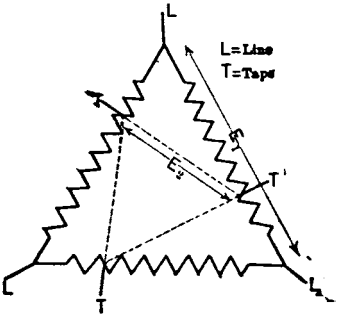


Fig. 2

mixed to as great an extent as possible. Having found the magnetizing current, core-loss, resistance and reactance in the usual manner, the calculations follow the same methods as for power transformers. In general, the efficiency at unity power factor is given by the equation

$$\text{Efficiency} = \frac{E_2 I_2}{E_2 I_2 + (r_1 - r_2) I_1^2 + r_2 (I_2 - I_1)^2 + \text{core-loss}},$$

where r_1 is the total resistance of the winding measured between the high-tension terminals and r_2 the resistance measured between the low-tension terminals. The efficiency is better than that of a two-circuit transformer of the same kv-a. rating.

TESTS, SPECIFICATIONS, ETC. — See *Transformers*.

DIMENSIONS, WEIGHT AND COSTS. — For the same kv-a. rating the dimensions, weight and cost are very nearly the same for auto-transformers as for ordinary two-circuit transformers; see *Transformers*.

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ALANCES, CURRENT. — (*See also Ammeters; Electrodynamometers.*) he Kelvin balance consists of a system of two coils mounted one at each end a rigid beam and free to move between two pairs of field coils. The balance ay be used as an ammeter, voltmeter or wattmeter. It may be used for either c. or d-c. measurements, but for d-c. work it has been practically superseded r laboratory standard voltmeters. For a-c. work it is used only as a laborary standard for calibrating other instruments.

A current balance when carefully constructed may be used for the absolute easurement of electric current, since the force of attraction between the coils n be calculated in terms of their dimensions and the current flowing. It has en successfully used to determine in absolute measure the electrochemical nstant or Faraday (*see Electrochemistry, Principles of*).

Principle of Operation. — The principle of the current balance is similar that of the electrodynamometer. The connections for current measurements e shown in Fig. 1. The current passes through all the coils in series and as a sult of the action of the magnetic fields, the ft-hand end of the beam is depressed and the ght-hand end is elevated. The beam on which he middle coils are mounted has an index pointer nd carries a weight that may be slid along a cale on the beam. With no current on and the liding weight at zero on the scale, a counter eight on the swinging system is so adjusted that he index pointer on the system is opposite a fixed mark and the system is alanced.

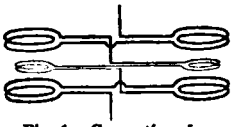


Fig. 1. Connections for Current Balances

Passing current through this system destroys the balance which is restored y sliding the weight along the beam. Since the torque exerted on the moving ystem is proportional to the square of the current, the current flowing will be roportional to the square root of the distance through which the weight has o be moved to balance the beam.

In the case of the wattmeter the current passes through the fixed coils, while he coils on the moving system serve as the potential coils. In this case the ower is directly proportional to the distance through which the weight has to e moved to balance the system.

Range and Cost. — Kelvin balances are built in 5 standard sizes. The seful range and approximate cost of each instrument is given below (**pre-war** rices).

Type	Range, amperes	Approx. cost
Centi-ampere	0.025–1	$150
Deci-ampere	0.25–10	150
Deca-ampere	5–100	150
Hekto-ampere	30–600	150
Kilo-ampere	100–2500	250

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BATTERIES, PRIMARY. — (*See also Cells, Standard; Electrochemistry, Principles of.*) A primary battery or cell is a device for the *direct* transformation of chemical energy into electrical energy. It is becoming common practice, though not yet universal, to use the term "cell" for a single unit, and the term "battery" for a group of two or more units or cells.

For convenience of treatment primary batteries may be classified as wet batteries, dry batteries and standard cells. The latter are treated in the article on *Cells, Standard.* The wet battery at one time was largely used in laboratory testing, for telephones, bells and other devices requiring small amounts of energy. In recent years it has been largely supplanted by the dry battery and small storage battery cells (*see Batteries, Storage*). Dry cells, exclusive of the small flash light cells, are now (1921) used, in this country alone, to the extent of some hundred million a year, chiefly for gas-engine ignition and telephone work (see *Gas Engines* and *Telephone Instruments*).

Poles and Electrodes. — The pole or terminal of a battery which is at the *higher* potential is called the *positive* pole or terminal, the other pole being called the negative pole or terminal. The negative pole is the anode or *positive electrode* or plate and the positive pole is the cathode or *negative electrode* or plate. For example, in a copper-acid-zinc battery the copper is the positive pole but the negative electrode or plate.

THEORY OF PRIMARY CELLS. — The modern theory of primary cells is fully discussed in the article on *Electrochemistry, Principles of.* Only one or two points of practical moment will be mentioned here.

Electromotive Force. — A cell consists essentially of two metallic conductors or poles dipping into an electrolyte. Copper or carbon is commonly employed for the positive pole and zinc for the negative pole. The electrolyte may be sulphuric or nitric acid or sal-ammoniac, caustic soda or other salt. For a cell made of given materials the open-circuit e.m.f. is always the same provided the temperature, degree of concentration of the electrolyte and the purity of the materials are the same. The terminal e.m.f. or potential difference (p.d.) on closed circuit is always less than the open-circuit e.m.f. due (1) to the internal resistance of the battery, (2) to the polarization of the battery and (3) to the exhaustion of the battery.

Internal Resistance. — Let E be the initial open-circuit e.m.f. of the cell and V be the p.d. across its terminals, when it is supplying a given current I, then the "apparent" internal resistance of the cell is

$$r = \frac{E - V}{I}.$$

This is not the true resistance of the cell, for its net e.m.f. when a current I is being drawn from it is less than the initial open-circuit e.m.f. due to polarization (*see below*) and partial exhaustion. If, however, after measuring the p.d. on closed circuit the current is interrupted and the open-circuit e.m.f., say E', is measured *immediately* (i.e., before the polarized condition of the cell has had time to change) then the true internal resistance of the cell is

$$r' = \frac{E' - V}{I}.$$

Polarization. Depolarizers. — Polarization is the name applied to the changes produced in the relative concentrations of the electrolyte at the two poles of a cell or to the production at the poles of new chemical substances (such as hydrogen) as a result of the flow of current through it. A depolarizer is any substance which when placed in the electrolyte or on the poles of the cell will partially or wholly prevent these changes. Polarization always tends to reduce the effective e.m.f. of the cell. When a cell which has been polarized is

open-circuited, the relative changes in concentration gradually disappear, due to diffusion, and any new substances formed also tend to diffuse uniformly through the electrolyte, with the result that the open-circuit e.m.f. returns in time to nearly its original value, provided the active materials are not exhausted.

The chief cause of polarization in a cell is the formation of hydrogen gas at the positive pole or to the transfer of the metal from the negative pole to the positive pole. The depolarizer is usually an oxidizing agent which reduces the hydrogen or metal liberated at the positive pole to a form readily soluble in the electrolyte and thereby prevents its accumulation at the positive plate. This is the principle on which depends the depolarizing action of the various metallic oxides, such as manganese peroxide or cupric oxide. The same result may be obtained by surrounding the positive pole by a solution of a salt of itself which has the same acid radical as the electrolyte surrounding the negative pole, but which is less soluble, the two solutions being kept practically separated by a porous cup which renders the diffusion of one into the other very slow.

TYPICAL WET BATTERIES. — Numerous forms of wet batteries have been used; only some of the more common forms can be described here. The materials used and the e.m.f. developed and approximate range of internal resistance are listed in the following table.

TYPICAL WET BATTERIES

	Daniell	Gravity	Bunsen	Chromic acid	Edison-Lalande	Leclanché type
Positive pole	Cu	Cu (b)	C	C	C	C
Negative pole	Zn (a)	Zn (a)	Zn (a)	Zn (a)	Zn (a)	Zn
Electrolyte	H_2SO_4 or $ZnSO_4$	$ZnSO_4$ or $MgSO_4$	H_2SO_4	H_2SO_4 or NaCl	KOH or NaOH	MnO_2
Depolarizer	$CuSO_4$	$CuSO_4$	HNO_3	CrO_3	CuO	NH_4Cl
Separator	Porous pot	None	Porous pot	With or without pot	None	With or without pot
E.m.f., volts	1.07 to 1.14	1	1.9–1.95	2	0.75	1.5
Resistance, ohms	0.3 to 30	0.1 to 6	Low	0.5 to 4	0.02 to 0.1	1 to 5

a. Amalgamated. b. In the Krüger cell copper-plated lead is used.

Daniell Cell (Fig. 1). — A typical form of this cell is shown in Fig. 1. Other forms, differing in certain details, are Muirheads cell, the Siemens & Halske Daniell cell, Minotto's cell (which may also be classed as a gravity cell, *see below*), etc. *J* is a glass or glazed earthenware jar containing a concentrated solution of copper sulphate, *P* is a porous pot containing dilute sulphuric acid (about 10 per cent by volume) or zinc sulphate solution or both, *C* is the positive copper pole and *Z* the negative zinc pole which is usually amalgamated. The chemical reaction which takes place may be represented by the formula



Fig. 1. Porous Pot Daniell Cell

$$Zn + CuSO_4 = Cu + ZnSO_4.$$

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A current of 1 ampere for 1 hour deposits 1.186 grams of copper and liberates 1.219 grams of zinc. Hence

0.042 oz. copper is deposited per ampere-hour,
0.043 oz. zinc is used up per ampere-hour,
0.164 oz. copper sulphate crystals are used up per ampere-hour,
0.106 oz. zinc sulphate is formed per ampere-hour.

The latter when crystallized out will form 0.189 oz. zinc sulphate crystals. These figures do not include any loss of zinc due to local action, which may amount to 10 per cent or more.

E.M.F. of Daniell Cell. — The e.m.f. of a Daniell cell varies from about 1.07 volts to 1.14 volts, depending on the density of the copper sulphate solution and on the amount of zinc sulphate present in the dilute sulphuric acid. The cell has its highest e.m.f. at the start when the sulphate of copper solution is saturated and no sulphate of zinc has formed. Hence, in order that the e.m.f. shall remain more nearly constant, it is better to start with *both solutions saturated*. The resistance of the cell will be higher and its e.m.f. lower than when dilute sulphuric acid is used, but this lower value of about 1.10 volts will be maintained nearly constant while the cell is sending a current.

Internal Resistance of Daniell Cell. — This depends not only upon the dimensions of the cell but also upon the porosity of the pot or other separating medium. The type of cell shown in Fig. 1, having a pot 7 inches high which is quite porous, has an internal resistance of about 0.3 ohm. The resistance of the Siemens type of Daniell cell is from 10 to 15 ohms, and the resistance of Minotto's modification of the Daniell cell, in which a layer of sawdust or sand is used in place of the porous cup, may be as high as 30 ohms.

The resistance of a Daniell cell, like that of liquids generally, *diminishes* with *increase* of temperature.

Local Action. — Impurities in the zinc form with the zinc small short-circuited voltaic cells, resulting in a wasting away of the zinc without producing a current in the external circuit. This can be largely prevented by amalgamating the zinc, i.e., coating it with mercury, which is readily done by thoroughly cleaning the zinc by dipping it into dilute sulphuric acid and then rubbing mercury over its surface. In the Daniell cell metallic copper also forms in the pores of the porous cup where the zinc touches it; this can be prevented by covering with paraffin those portions of the cup which may come into contact with the zinc.

Care of Daniell Cells. — The type of cell shown in Fig. 1 must be taken to pieces when not in use. If it has to be put to one side for only an hour or two, it will be sufficient to lift the porous pot with the contained zinc rod bodily out of the cell, and to place it in another empty jar, or stand it in a dish while out of use.

Gravity Battery (Fig. 2). — The principle of this cell is the same as that of the Daniell cell, except that no porous pot is used, the copper sulphate and zinc sulphate being maintained separate by gravity. There are various modifications in the form of construction, known as the Meidinger cell, Calland cell, Kelvin tray battery, Krüger cell, etc. The gravity cell is still used in telegraph and telephone work.

The copper electrode is placed at the bottom of the cell, and is then covered with copper sulphate crystals. The zinc electrode is then put in place and the jar either filled with dilute zinc sulphate or with dilute sulphuric acid. With

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Care of Gravity Battery. — The resistance of the cell increases rapidly with decrease of temperature; it should therefore be kept at a reasonably high temperature, say 70° F. A gravity cell must, of course, not be moved about, or if moved great care must be taken to avoid the two liquids being mixed together. To prevent the copper sulphate wandering to the zinc plate, it is well to allow the cell to send a weak current through an external circuit of considerable resistance even when the cell is not in ordinary use. The electrolyte should be renewed when the blue sulphate solution turns brown. The line of separation between the copper and zinc sulphates, or the "blue line," should be about halfway between the two electrodes.



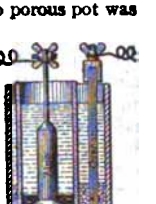
Fig. 2. Gravity Daniell Cell

Bunsen Cell. — In the Bunsen cell a zinc plate is placed in dilute sulphuric acid, as in the Daniell, but the copper plate is replaced by one of carbon and the copper sulphate solution by strong nitric acid, which is generally said to act as the depolarizer. The Grove cell differs from the Bunsen only in the use of platinum in place of carbon. Both cells give a high e.m.f., from 1.9 to 1.95 volts, and have low internal resistances, so they may be used for producing fairly large currents. When working the cells give off dark brown fumes of nitric peroxide, NO_2, and should be placed in the open air or under a chimney.

The chemical reaction which takes place may be represented by the formula $Zn + H_2SO_4 + 2\,HNO_3 = ZnSO_4 + 2\,H_2O + 2\,NO_2$.

Care of Bunsen Battery. — A Bunsen or Grove battery must be taken to pieces at the end of each day's use, since the mixing of the liquids through the walls of the very porous cup used to separate them would render the battery practically useless the next day. The porous pots should be placed in water after use, so that all the zinc sulphate solution may be dissolved out of the pores of the earthenware, for, otherwise, when the pots are dried the zinc sulphate solution will crystallize in the pores and cause the pots to fall to pieces.

Chromic Acid Cell (Fig. 3). — The chromic acid or potassium bichromate cell was devised by Poggendorff. In the original type of cell no porous pot was employed. In the Fuller cell, shown in Fig. 3, a porous pot is used. The depolarizer used is chromium peroxide, popularly called chromic acid, which may be purchased ready prepared, or may be formed by heating potassium or sodium bichromate with sulphuric acid (1 part by weight of the bichromate, 3 parts of acid and 9 parts of water). In the type of cell shown in the figure the wire connected to the zinc rod is well amalgamated or coated with gutta-percha to insulate it. In the porous pot containing the zinc, there is put a quantity of mercury to maintain the amalgamation, and either dilute sulphuric acid or a solution of common salt NaCl. The chromic acid solution is placed in the jar containing the carbon plate.


Fig. 3. Fuller's Mercury Bichromate Cell

The chemical reaction which takes place may be represented by the formula $3\,Zn + 2\,CrO_3 + 6\,H_2SO_4 = Cr_2(SO_4)_3 + 3\,ZnSO_4 + 6\,H_2O$.

This cell has an e.m.f. of about 2 volts, and is suitable for producing a fairly strong current for a short time. When much used the cell becomes saturated with the potassium and chromium sulphates, and a double salt, chrome alum, $K_2Cr_2(SO_4)_4$, crystallizes out and sticks so firmly to the bottom of the cell that it is somewhat difficult to remove.

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Edison-Lalande Cell. — In this type of cell the positive pole is a plate of compressed cupric oxide (CuO), the surface of which is reduced to metallic copper. The cupric oxide acts as the depolarizer. The negative pole is amalgamated zinc and the electrolyte a strong solution (1 to 3 by weight) of caustic potash or of caustic soda.

A layer of heavy oil is poured over the solution to prevent evaporation and "creeping." No local action or polarization takes place in this cell; under normal conditions it is an easy matter to set it up to give any required number of ampere-hours, and to so proportion the constituents that they are all exhausted at the same time. This is a matter of considerable importance where closed-circuit working is employed, as in some systems of telegraphy and in alarm circuits. Although the e.m.f. of the Edison-Lalande cell is low, its resistance is also low, and the cell is capable of producing large currents. The cell may be left set up for months without deterioration.

The chemical reaction which takes place may be represented by the following formula

$$Zn + CuO + 2\,KOH = Cu + H_2O + K_2ZnO_2.$$

Leclanché Cells. — In the original form of this type of cell the positive pole was a plate of carbon embedded in a mixture of solid manganese peroxide and broken carbon contained in a porous pot. The electrolyte is sal ammoniac, NH_4Cl, and the negative pole zinc. The manganese peroxide acts as the depolarizer. The only object of the porous pot was to hold the carbon and manganese peroxide. In the later forms of this cell, such as the "agglomerate," Corsak, etc., the porous pot is dispensed with and a mixture of carbon and manganese peroxide are moulded together with a suitable binder, or the mixture of carbon and manganese peroxide is held together by a wrapping of canvas or sacking.

The chemical reaction which takes place may be represented by the formula

$$Zn + 2\,MnO_2 + 2\,NH_4Cl = Mn_2O_3 + H_2O + 2\,NH_3 + ZnCl_2.$$

If, however, too little sal ammoniac be present, zinc oxide or zinc oxychloride is formed instead of zinc chloride, and the solution becomes milky; hence when this happens, more sal ammoniac should be added.

The e.m.f. of a Leclanché cell is about 1.5 volts, but falls rapidly when the cell is used to send a strong current. It will, however, regain its value if the cell be left for some time unused, and it does not sensibly diminish when the cell is put to one side, even for some months. Hence, while the Leclanché cell is much inferior to the Daniell cell for the purpose of sending a steady current for an hour or two, it is much superior to the Daniell cell for producing intermittent currents at any time during the course of a year or more — for example, such currents as are employed for the ringing of electric bells, for house telephones, and for railway signaling.

Care of Leclanché Cells. — When the sal ammoniac becomes exhausted it should be thrown out and a new solution made. Three or 4 ounces of sal ammoniac for a jar of ordinary size is required, the jar to be filled about one-third with water before putting in the electrodes.

DRY CELLS. — The modern dry cell may be looked upon as a modification of the Leclanché cell, the chief difference being that only enough water is added to the electrolyte to moisten an absorbent layer of pulp-board, blotting paper, cheese cloth or starch paste, this lining separating the positive and negative poles. The negative pole, which also serves as a container, is a hollow zinc cylinder; the bottom of this cylinder is also usually made of zinc. About $\frac{1}{8}$

er cent of the dry cells made in this country have these dimensions. The positive pole is a carbon rod, which may be either cylindrical or fluted. The absorbent layer above mentioned is placed next the zinc and is saturated with a solution f sal ammoniac and zinc chloride. The zinc chloride is necessary to reduce he rapid deterioration which would otherwise take place on open circuit. The pace between this lining and the carbon electrode is filled with a mixture of granulated carbon and manganese peroxide, the latter being the depolarizer. The top of the cell is usually sealed with a pitch composition.

Desiccated Cells, sometimes called reserve cells, are usually constructed he same as the ordinary dry cell. The chief difference is that the cell is assembled without water, provision being made for filling the cells with water before they may be required for use. Desiccated cells will not deteriorate so long as they remain dry. It is necessary to fill them with water several hours before use, and 24 hours may be necessary before the cell will give its maximum current on short circuit.

E.M.F. of Dry Cells. — In new cells of practically all types the open-circuit e.m.f. is between 1.5 and 1.6 volts. The decrease in e.m.f. when the cell stands on open circuit is very slight, being only about 0.1 after the cell has stood many months. An open-circuit e.m.f. materially less than 1.5 volts is generally an indication of serious deterioration or of some other defect. The effect of temperature on the open-circuit e.m.f. is slight, amounting to only a few hundredths of a volt for all ordinary temperature ranges. Due to the relatively rapid polarization and increase of internal resistance with use, the average terminal voltage during the useful life of the cell is only about 1 volt.

Internal Resistance. — The internal resistance of a high-grade dry cell when new is usually less than 0.1 ohm, which may increase to 0.5 ohm within 9 or 12 months, even though the cell is not used during this time. The polarization of the cell in actual service causes a much greater decrease in the terminal e.m.f. than does the internal resistance drop, and therefore the internal resistance test is of little practical value.

Short-circuit Current. — Nine out of every ten users of dry cells consider the short-circuit current, i.e., the current produced through an ammeter having a relatively small resistance connected directly between the poles of the battery, as a direct measure of the value of the cell. There are other factors, however, which must be considered, such as the temperature of the cell, the service for which it is to be used, etc. According to D. L. Ordway (*Trans. Am. Electroch. Soc., 1910, Vol. 17, p. 336*) a standard 2.5 by 6-inch dry cell should give when new a short-circuit current (external resistance not over 0.01 ohm) of from 18 to 25 amperes; a cell giving a short-circuit current much above 25 or below 16 amperes should be looked upon with suspicion. A cell giving a short-circuit current much in excess of 25 amperes is liable to polarize rapidly, whereas if the short-circuit current is much under 16 amperes, it is probable that the cell has been made a long time or that cheap materials have been used.

The effect of temperature on the short-circuit current is pronounced. Between 10 and 80° C. the current increases about 1 ampere for each 10° increase in temperature. This effect is even more pronounced at very low temperatures. The short-circuit current returns to its normal value when the cell is restored to normal temperature.

Shelf-life. — The shelf-life of a dry-cell of the ordinary sizes is usually considered as the time in months that the cell may stand on open circuit without its short-circuit current falling below 10 amperes. This current is about half the short-circuit current when the cell is new, and represents a value which is probably lower than the minimum point at which a dealer could dispose of a

cell to the average consumer. The average shelf-life of high-grade cells is from 10 to 12 months, though the very best cells have a shelf-life of from 12 to 15 months. Many makes of cells have a shelf-life of only 8 to 10 months; and cells are on the market having a shelf-life of only 1 or 2 months.

The shelf-life is increased by storing the cells at a low temperature. Ordway gives the following results on standard dry cells kept in storage at the stated temperatures. These cells give initially a short-circuit current of about 20 amperes.

Temperature at which cells were stored, ° C....	0	25	50	75
Short-circuit current at 25° C. after 5 months....	18.1	17.4	0.5	0.4

Ampere-hour and Watt-hour Capacity. — The short-circuit current, however, is not a measure of the ampere-hours obtainable from the cell, as is indicated in the following table, taken from Ordway's paper. The ampere-hours given are those obtained from the various cells when discharged continuously through a resistance of 16 ohms until the closed-circuit voltage fell to 0.5 volt.

Brand of cell.....	A	D	G	J	M	P	V	X
Short-circuit current.....	33.0	24.5	22.5	20.9	20.1	19.2	11.6	6.6
Ampere-hours.....	24.0	33.5	40.0	18.2	11.7	30.3	13.6	4.5

The letters are arbitrary designations.

Although the short-circuit current falls off with the age of a cell, even though the cell is not used, the ampere-hour capacity does not decrease in the same ratio. Ordway gives the following tests on samples from the same lot.

	Freshly made	9 months after manufacture
Short-circuit current.....	22.4	3.6
Ampere-hour capacity (through 2 ohms to 0.25 volt).....	24.9	20.2

Effect of Rate of Discharge on Capacity. — Ordway gives the following results of tests on standard 2.5 by 6-inch cells, when the cells are discharged continuously through 2, 4, 8, 16, 24, 32 and 40 ohms respectively. By "end point in volts" is meant the terminal voltage per cell at the end of the stated number of hours.

HOURS OF CONTINUOUS SERVICE OF 2.5 BY 6-INCH DRY CELLS

End point in volts	Resistances used in ohms						
	2	4	8	16	24	32	40
1.2	4.3	10	39	142	260	414	549
1.0	9.3	35	94	296	548	889	1148
0.8	16.5	51	143	414	751	1078	1550
0.6	28.2	76	225	954	1240	1600	1763
0.4	55	207	648	1197	1711	2280	2040
0.2	160	450	882	1318	1914	2626	3140

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WATT-HOURS FROM 2.5 BY 6-INCH DRY CELLS DISCHARGED CONTINUOUSLY

End point in volts	Resistances used in ohms						
	2	4	8	16	24	32	40
1.2	3.7	4.3	8.1	15.2	18.8	21.7	23.8
1.0	6.7	13.0	16.5	26.9	33.4	39.8	42.0
0.8	9.7	16.3	21.5	32.8	40.3	44.6	50.6
0.6	12.5	19.4	26.6	48.9	49.5	52.7	53.2
0.4	15.4	27.3	39.1	52.6	54.3	58.2	54.8
0.2	19.8	32.6	41.5	53.3	55.2	59.3	57.1

Capacity on Intermittent Service. — Neither the ampere-hour nor watt-hour capacity of a cell on *continuous* service is a measure of its capacity on intermittent service. What the user wishes to know is the actual number of hours of service that he can obtain from a cell when used to operate a definite piece of apparatus, which as a rule takes current only intermittently, e.g., for telephone or ignition service. From curves given in Ordway's paper for 3 cells connected in series and discharged through the stated resistances the following table has been made up.

HOURS OF INTERMITTENT SERVICE OF 2.5 BY 6-INCH DRY CELLS

(The hours given are the hours the cell is actually supplying current)

End point in volts, 3 cells	Continuous discharge			5 minutes each hour night and day			5 minutes each hour, 8 hours per day, 6 days per week		
	5 ohms	10 ohms	20 ohms	5 ohms	10 ohms	20 ohms	5 ohms	10 ohms	20 ohms
3.6	4	12	30	4	45	80	3	15	45
3.0	9	25	65	29	65	145	12	30	60
2.4	15	40	100	48	90	190	23	45	75
1.8	25	60	150	65	130	225	35	70	100
1.2	42	140	475	80	160	250	52	100	150
0.6	95	...	...	93	200	290	70	115	165

From the above table it is apparent (1) that the terminal voltage falls off more rapidly on continuous discharge than on intermittent discharge, counting hours of *actual discharge* only, but (2) that during the latter stages the terminal voltage falls off more rapidly for the intermittent discharge, this latter effect occurring earlier as the external resistance is increased. The second effect is probably due to the deterioration of the battery while standing on open circuit. It should be kept in mind that the length of time the cells were in service during the intermittent tests were respectively 12 and 40 times the period of actual discharge.

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Proper Arrangement of Cells for Best Results. — The data given in the above tables may be used as a basis for the determination of the number and proper arrangement of cells for a given service. For example, if a certain piece of apparatus has a resistance of 8 ohms and cannot be operated at a voltage under 0.8, then 143 hours of service can be obtained from a single battery. If however 4 cells in parallel are used, the drain on each cell will be one-fourth as great as before, which is equivalent to discharging each cell through 32 ohms. Therefore the 4 cells will give 1078 hours of service, or 270 hours per cell. If the 4 cells were connected in series, then drain on each would be 4 times as great as for a single cell, which is equivalent to discharging each cell through 2 ohms, but each cell could discharge to 0.2 volt instead of 0.8. The 4 cells in series would then give 160 hours, or only 40 hours per cell. The parallel arrangement is therefore the best in this case.

For ignition service 6 cells in series are usually required in order to obtain a sufficiently high voltage. On heavy service of this kind two or more such series groups connected in parallel are usually more economical than a single group. For telephone service 3 cells in series are usually required in order to obtain a sufficiently high voltage. For such light service a single group of cells is more advantageous than two or more groups in parallel; any gain which might at first sight be effected is more than offset by the deterioration caused by local action on standing. This may be seen by a consideration of the data on intermittent service given above.

Tests of Dry Batteries. — The proper testing of dry batteries has been the subject of considerable discussion during the last few years. See *Trans. Am. Electrochem. Soc.*, 1909 to date. A preliminary report was submitted by a committee of this society in April, 1912. The following is a brief summary.

In measuring the terminal voltage of a dry battery a voltmeter having a fairly high resistance, 300 ohms or more, should be used. The ammeter and leads for measuring the short-circuit current should have a combined resistance of 0.01 ohm. The internal resistance test is not recommended.

Service Tests. — Dry batteries to be used in telephone work should be tested by discharging 3 cells, connected in series, through 20 ohms resistance for a period of 2 minutes, each hour, during 24 hours per day and 7 days per week, until the closed-circuit voltage of the battery at the end of a period of contact falls to 2.8 volts (0.93 volt per cell). Report the results as the number of days during which the closed-circuit voltage remains above the limiting value of 2.8 volts. This test has been modified and supplanted by the so-called A.T. and T. test, which is as follows: three cells connected in series are discharged through 20 ohms for 10 periods of 4 minutes each in 10 consecutive hours of 6 days per week. On the seventh day every other period is omitted. The end of the test is taken at 2.8 volts for the battery on closed circuit. The results are expressed as the number of days the test lasted.

For ignition service discharge 6 cells connected in series through 16 ohms resistance for 2 periods of 1 hour each per day, seven days per week, the periods being 11 hours apart. Determine at the end of every 12th period of closure the current which the 6 cells are capable of sending through a 0.5 ohm coil in series with an ammeter, the two being in parallel with the 16-ohm coil. The test is considered completed when the current through the 0.5 ohm coil at the end of a period of closure falls below 4 amperes. Report the results as the number of hours of actual discharge to this limiting value of the current.

For flash-light service discharge the battery through a resistance of 4 ohms for every cell in series, for a period of 5 minutes, once each day, until the closed circuit voltage at the end of a discharge period falls to 0.75 volt per cell in series. Report the result as the number of minutes of actual discharge until the voltage reaches this limiting value. At the present time (1921) the end point is gen-

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nally taken as 0.50 volt per cell instead of 0.75 volt, because the modern lamps re usable to a lower voltage.

Full details for making these tests, together with a description of proper utomatic arrangements for opening and closing the circuit at the designated mes, will be found in the *Trans. Am. Electrochem. Soc.*, 1912, Vol. 21, p. 282. he timing device is an ordinary cheap clock provided with suitable contacts y means of which the hand closes the circuit.

Shelf-life Test. — Keep the cells open-circuited in a dry room at normal mperature. Determine the short-circuit current at the end of every 8 weeks. eport results as the number of months before the short-circuit current falls elow 10 amperes.

SPECIFICATIONS FOR DRY BATTERIES. — See *Circular No. 79, ureau of Standards*, April 25, 1919.

COST OF DRY BATTERIES (Pre-war prices). — Dry batteries of andard size (2.5 by 6 inches) cost at retail from 10 to 25 cents, depending upon e quality of the battery. When bought by the barrel, good dry batteries may e had for 10 cents apiece.

BIBLIOGRAPHY. — Cooper, W. R., *Primary Batteries*, Ayrton & Mather, *ractical Electricity*. For recent data on dry batteries see the *Trans. Am. Electro-hem. Soc.*, particularly Ordway, D. L., *Some Characteristics of the Modern Dry ell*, 1910, Vol. 17, p. 341, *Report of Committee on Dry Cell Tests*, 1912, Vol. 21, . 275 (which contains references to numerous other articles). Helfrecht, A. J., *Deterioration in Small Dry Cells with Age*, Trans. Am. Electrochem. Soc., Sept. 5, 1919; *Electrical Characteristics and Testing of Dry Cells*, Bur. Stand., Circ. o. 79.

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BATTERIES, STORAGE, ALKALINE TYPE. — (*See also Automobiles, Electric; Batteries, Storage, Applications of; Batteries, Storage, Lead Type*) The alkaline type of storage battery consists in its best-known form, i.e., the Edison battery, of an iron-nickel element immersed in dilute caustic-potash solution. The alkaline type of storage battery was first exploited commercially by Edison in 1904. At the present time (1921) it is being used extensively for the propulsion of electric vehicles, the operation of railroad block signals, the electric lighting of trains and in radio work.

THEORY OF ALKALINE STORAGE BATTERY. — Numerous active elements have been used in the alkaline type of storage battery. The elements in the Edison type of alkaline battery consist of nickel hydroxide for the active material of the positive plate, iron for the active material of the negative plate and a solution of potassium hydrate and lithium hydrate for the electrolyte.

The fundamental principle of the Edison storage battery is the oxidation and reduction of metals in an electrolyte which neither combines with nor dissolves either the metals or their oxides. Also, an electrolyte which, notwithstanding its decomposition by the action of the battery, is immediately re-formed in equal quantity, and is, therefore, a practically constant element without change of density or conductivity over long periods of time. Therefore, only a small quantity of such electrolyte is necessary, permitting a very close proximity of the plates. Furthermore, it is unnecessary to take hydrometer readings until about three hundred cycles of charge and discharge have been made; this is simply to determine when it is necessary to empty out the old solution and put in new. The active materials of the electrodes being insoluble in the electrolyte, no chemical deterioration takes place therefrom.

The chemical reactions in charging the Edison storage battery are: (1) the oxidation from a lower to a higher oxide of nickel in the positive plate, and (2) the reduction from ferrous oxide to metallic iron in the negative plate. The oxidation and reduction are performed by the oxygen and hydrogen set free at the respective poles by the electrolytic decomposition of water during the charge. The charging of the positive plate is, therefore, simply a process of increasing the proportion of oxygen to nickel. The proportions of nickel to oxygen in definite oxides of nickel are as follows:

	Atomic Proportions by Weight			
	Ni	O	Ni	O
NiO	1	1	1	.273
Ni_3O_4	1	1.33	1	.364
Ni_2O_3	1	1.5	1	.409
$Ni\,O_2$	1	2	1	.545

The relative amounts of oxygen necessary to oxidize nickelous oxide, or NiO, which is the oxide corresponding to the green nickel hydrate used in making the battery, to the various oxides are given in the three reactions:

$$(1)\quad 6\,NiO + {}_2\,O = {}_2\,Ni_3O_4$$
$$(2)\quad 6\,NiO + {}_3\,O = {}_3\,Ni_2O_3$$
$$(3)\quad 6\,NiO + 6\,O = 6\,NiO_2$$

The NiO_2 is capable of reacting with NiO according to the reaction

$$NiO_2 + NiO = Ni_2O_3.$$

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would be represented by a ratio of 1 : 1.33 (Ni_3O_4) or lower, depending on the discharge.

The discharge of the cell is simply the reversal of the above reactions, the hydrogen reducing the higher oxides of nickel to lower oxides and the oxygen oxidizing the iron to ferrous oxide.

"Gassing." — In the alkaline type of cell, as in the lead type of cell, a certain amount of the water (H_2O) is broken up on charge by the electrolytic action of the charging current. The rate at which gas is evolved during a charge at the normal rate of current remains approximately constant during the first half of the charge, and increases rapidly during the latter portion of the charge. Of the total amount of gas evolved during a 7-hr. charge, about one-half is evolved during the first 5 hr. of the charge. As the oxygen and hydrogen thus liberated form an explosive mixture, provision should be made with a battery of any considerable size to carry the gases away to prevent their becoming a source of danger.

DESIGN. — The only alkaline type of battery in use at present (1921) in the United States is that made by the Edison Storage Battery Co. This battery is made up of a positive plate having as the active material a high nickel oxide, a negative plate having as the active material powdered iron, and an electrolyte consisting of dilute potassium hydrate solution.

Positive Plate. — The positive or nickel plate consists of perforated steel tubes, nickel plated, filled with alternate layers of nickel hydroxide and pure metallic nickel in thin flakes. The nickel is added to give the necessary conductivity to the active material.

The tube is formed from a perforated ribbon of steel, nickel plated, and has a spiral lapped seam. This tube, after being filled with active material, is reinforced with steel bands, which prevent the tube expanding away from and breaking contact with its contents. The tubes are flanged at both ends and held in contact with a steel supporting frame or grid made of cold-rolled steel, nickel plated.

Negative Plate. — The negative or iron plate consists of a grid of cold-rolled steel, nickel plated, holding a number of rectangular pockets filled with powdered iron oxide. These pockets are made up of very finely perforated steel, nickel plated. After the pockets are filled they are inserted in the grid and subjected to pressure between dies which corrugate the surface of the pockets and force them into contact with the grid.

After the plates have been prepared, as outlined above, the positive or nickel plate is further oxidized electrolytically and the nickel hydroxide converted to a high oxide of nickel, probably NiO_2. The negative or iron plate is reduced electrolytically, the powdered iron oxide being converted into metallic iron. See section above on *Theory* for an explanation of the chemical action.

Separation and Insulation. — After the plates are assembled into a complete element, narrow strips of hard rubber are inserted between the plates to insulate them from each other. The side insulator is provided with grooves and a step or projection at the bottom to insulate the complete element from the steel container. The step acts as a support to the element as well as insulating the plates from the bottom of the container. At the ends of the element, that is, between the outside negative plates and the container, are inserted smooth sheets of hard rubber.

Assembly. — The jar is made from cold-rolled sheet steel, nickel plated. The walls of the jar are corrugated to give the greatest amount of strength with minimum weight.

The cover is of sheet steel, nickel plated, provided with three mountings, two

being pockets for containing stuffing boxes about the terminal posts. The thi mounting is an opening for filling the cell with electrolyte, and for the oc sional (every four or five discharges) addition of distilled water to take place of that which is lost during charge. This opening is provided with hinged cap, on the under side of which is loosely hung a spherical segment hard rubber. The latter, when the cap is closed, seats upon the circ opening beneath and is lifted by escaping gas, permitting its free egress. closes the cell however to the admission of foreign gases or other mate from without. The cap is opened only for filling and is held open or cl by a flat steel spring.

The plates are grouped on steel connector rods with steel spacing washe all being attached to a steel terminal post. The terminal posts are insulat from the cover by means of hard and soft rubber washers and bushings.

The cells are assembled in wood trays, the positive and negative termi of adjacent cells being connected together by copper connecting links. Ea individual cell is insulated from the adjacent cell and from the containing w tray.

RATING AND PERFORMANCE. — It is standard practice to rate a Edison battery in terms of the amperes it will give continuously for 5 hours. T rated capacity in ampere-hours is then 5 times this current rate. The norm rate of charge is the same as the normal rate of discharge and the time normal charge is given as 7 hours. In the trade designations employed, e.g. A–6, the letter designates the size of the plate and the numeral the number positive plates per cell, i.e., in the A–6 cell there are 6 positives; see below und *Dimensions, Weight and Cost.* The values of the rated current and output f each size of cell are given in the following table; the average voltage per c during discharge is 1.2 volts. The G type is rated on a 3½ hour basis with normal charging time of 4¾ hours. The normal current rate is 50 per ce higher than the A type of equivalent ampere-hour capacity.

RATED PERFORMANCE OF EDISON CELLS

Size of cell	Normal rate of charge and discharge, amperes	Rated capacity		Watt-hours per pound of cell for rated capacity	Average watts during discharge at normal rate
		Ampere-hours	Watt-hours		
B–2	7.5	37.5	48	12.2	9
B–4	15	75	90	13.0	18
B–6	22.5	112.5	135	13.7	27
A–4	30	150	180	13.3	36
A–5	37.5	187.5	225	13.4	45
A–6	45	225	270	14.1	54
A–8	60	300	360	13.1	72
A–10	75	375	450	13.2	90
A–12	90	450	540	13.2	108

The capacity of new cells increases for at least twenty cycles of charge an discharge. This betterment may be as much as 30 per cent above rating an comes from an improvement of conditions in the nickel electrode which brought about by regular charging and discharging. It is expedited by ov charging. The capacity then decreases slowly with use until the electrol is renewed, which should be done before the capacity has fallen to the rate

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value. The capacity again increases for a few charges and subsequently falls.

Voltage Characteristics. — The charge and discharge voltage characteristics of an Edison battery vary with the conditions, among which are temperature, condition of electrolyte, time since last discharge or charge, etc. Typical charge and discharge voltage curves at the normal rate are given in Fig. 1. It will be noted that the voltage rises rapidly at the beginning of charge, decreases somewhat during the second hour, and then rises gradually during the remainder of the charge. This hump in the voltage curve is characteristic of the Edison battery, and may lead to confusion as to battery's condition of charge. The value and duration of this hump may vary considerably even on successive charges of the same battery. The final charging voltage, with current on, is approximately 1.8 volts per cell, but ranges from 1.7 to 1.95 volts per cell. The rise in voltage near the end of charge is not sufficient to serve as a very satisfactory criterion of complete charge, but the Edison Storage Battery Co. recommends that if the extent of the previous discharge is unknown, the charge at the normal rate should be continued until the voltmeter reading has remained constant for 30 minutes at about 1.8 volts per cell.

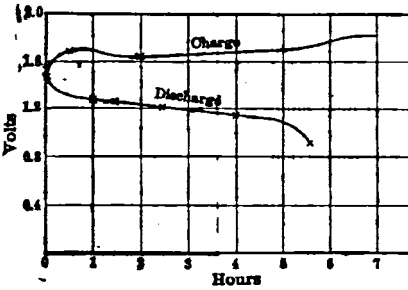


Fig. 1. Voltage Curves at Normal Rate

Effect of Temperature on Charging Voltage. — The normal average temperature of a battery on charge is between 90 and 100° F. The values of average and maximum charging voltage are higher for low temperatures of the electrolyte than for high temperatures. The range is indicated by the results of a series of tests given in the accompanying table.

Temperature, deg. Fahr.	Average voltage	Maximum voltage
35	1.88	1.94
55	1.81	1.92
75	1.76	1.88
95	1.70	1.84
115	1.67	1.77

Discharge Voltage. — On discharge the voltage performance of an Edison battery is more uniform than on charge, although during the early portion of the discharge the voltage is liable to vary considerably from the values indicated in Fig. 1. This depends chiefly on the length of time the cell has stood on open-circuit since the completion of the charge. The average discharge voltage is 1.2 volts per cell when discharged to 1.0 volt per cell (with current on) at the normal (5-hour) rate.

As with lead cells the open-circuit voltage is valueless as an indication of the state of charge. The open-circuit voltage in general will be about 20 per cent higher than the corresponding terminal voltage at normal rate of discharge.

Specific-gravity Characteristics. — The normal specific gravity of the electrolyte is about 1.200, and decreases slowly as the cell is used. (*See section below on Tests of Electrolyte.*) The specific gravity does not change materially on charge or discharge. A slight concentration has been noted during discharge, but the variation is too small to have commercial significance. The specific gravity decreases 0.002 with each 10° F. increase in temperature.

Variation of Capacity with Rate of Discharge. — The ampere-hour capacity of an Edison battery is practically independent of the rate of discharge, provided the discharge is carrried to a sufficiently low voltage. In this connection it may be pointed out that no harm is done an Edison battery by discharging it to zero voltage. The total ampere-hour outputs of a battery, when discharged to zero voltage at various current rates from one-third normal to four times normal, after a normal charge in each case, vary by only 2 per cent. As the low voltage part of a discharge cannot be considered useful, it is customary to consider the discharge completed for any rate of discharge when the voltage has reached a value differing from 0.9 volt per cell by an amount equal to the difference between the resistance drop in the cell corresponding to this rate and that corresponding to the resistance drop at the normal rate. Thus for a cell with an internal resistance (*for values see paragraph below on Internal Resistance*) of 0.003 ohm and a normal rate of 30 amperes, the terminating voltage for a discharge at 60 amperes would be 0.9 − 0.003 (60 − 30) = 0.81 volt. Fig. 2 shows a series of voltage curves for discharges at various rates following normal charges. The discharge has been discontinued in each case in accordance with the above rule. The variations of average voltage, ampere-hour output and time of discharge, with discharge rate are shown in Fig. 3, where values of these factors for the normal (5-hour) rate are each taken as 100 per cent.

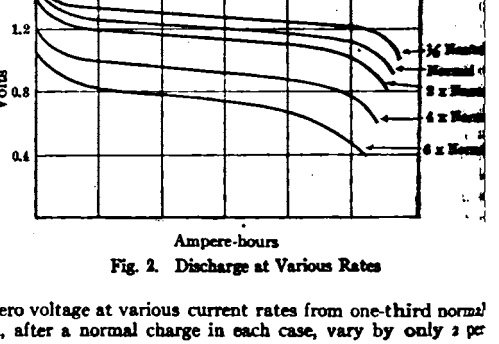


Fig. 2. Discharge at Various Rates

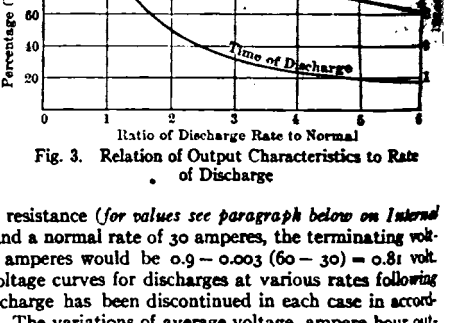


Fig. 3. Relation of Output Characteristics to Rate of Discharge

Variation of Capacity with Rate of Charge. — The energy contained in a newly charged Edison cell depends upon both the rate and length of charge. Fig. 4 gives the variation in the time of discharge at normal rate for various charge rates and periods for a particular battery. In this particular test when the cell was discharged at the normal 5-hour rate to 0.9 volt, after a 7-hour

charge at this same rate it gave this current for 5.9 instead of 5 hours. The curve for the normal rate of charge shows that the capacity for a 10-hour charge is 13.5 per cent and for a 14-hour charge 22.0 per cent greater than for a normal (7-hour) charge. The results of a series of charges of various lengths and subsequent discharges, both at the normal rate, are given in the accompanying table.

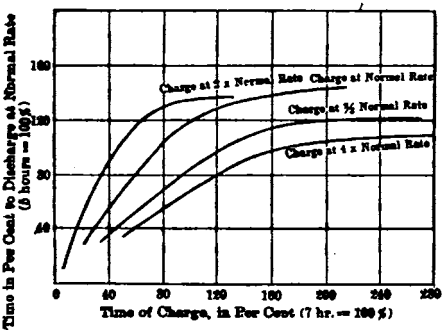


Fig. 4. Capacity at Normal Rate Discharge after Charging at Various Rates and Periods

Length of charge, hours	5.5	7.0	10.0
Length of discharge, hours	5.0	5.8	6.4
Average discharge voltage	1.19	1.202	1.203
Ampere-hour efficiency, per cent	91	83	64
Watt-hour efficiency, per cent	66	59	45

Variation of Efficiency with Length of Charge. — As shown by Fig. 4 the capacity of a cell depends upon the rate as well as upon the length of charge. For charge and discharge at the normal rate, the watt hour efficiency is approximately 72 per cent for a short charge (i.e., one hour or less), it drops to about 58 per cent for a normal or 7-hour charge, and has smaller values for larger charges, being approximately 30 per cent for a 15-hour charge. The normal rate of charge has been chosen by the manufacturers such that for an output of approximately the rated number of ampere-hours at the normal rate the efficiency is higher for the normal rate of charge than for a rate which is considerably higher or lower than the normal.

Variation of Capacity with Temperature. — With the Edison battery, as with all alkaline batteries, there is a critical electrolyte temperature for each rate of discharge below which the capacity falls to a low value The higher the rate of discharge the higher is this critical temperature. If the electrolyte throughout the cell has been chilled below the critical point for a given rate of discharge, the full capacity can be obtained as soon as the cell is warmed above the critical range. A series of tests, reported by W. E. Holland (*Central Station, Nov., 1911*), showed that the temperature should be kept above 55° F. if a large current is to be required. In the operation of Edison batteries in electric automobiles in cold weather it is recommended that the batteries be given a warming charge shortly before the car is taken from the garage. See also next paragraph.

Rate of Cooling of Electrolyte. — The rate of cooling of the electrolyte depends upon the initial temperature of the battery, the circulation of air in

contact with the battery, the temperature of this air, and the rate at which current flows from the battery. Another series of tests reported by Holland (*Central Station, Nov., 1911*) showed that in an open box a battery which had been charged in a room temperature of approximately 65° F. could stand idle in still air at 8° F. for a period of about 4 hours before the electrolyte dropped to 55° F. When placed in a closed box it took about 13 hours for the battery to cool from an initial temperature of 90° F. (which a battery would have at the end of a normal charge) to the critical temperature for high discharge rates. These tests pointed out the efficacy of a closed battery box for keeping cells warm. (*See also Automobiles, Electric.*)

Internal Resistance. — The effective internal resistance of a cell determines the immediate change in voltage at the cell terminals with a sudden change in the discharge rate. For method of measuring see section on *Testing*, below. The value in ohms of the mean effective internal resistance for an A-type cell discharging at normal rate is approximately equal to 0.012 ohm divided by the number of positive plates as given by the designation of the cell size, and for a B-type cell is approximately equal to 0.024 ohm divided by the number of positive plates. For two or more cells in series the total effective internal resistance is the product of this value by the number of cells in series. The internal resistance of Edison cells is such as to cause an immediate drop in terminal voltage of between 7 and 8 per cent with a sudden increase in current equal to the normal rate. The virtual internal resistance increases slightly during the progress of a discharge.

Retention of Charge. — The rate of loss of charge of a battery during idleness varies with the temperature at which it stands. The loss is slight in the cold and becomes greater as the temperature increases. The variation for cells charged under normal conditions and discharged after resting for various periods in one case at normal temperature of 75° F., and in another case at 35° F. is shown in Fig. 5. Accordingly a cell which has not been used for 10 days following a normal charge may be expected to retain at least 85 per cent of its initial capacity. It will be noted that the *rate* of loss of capacity after the second day is practically the same at both temperatures.

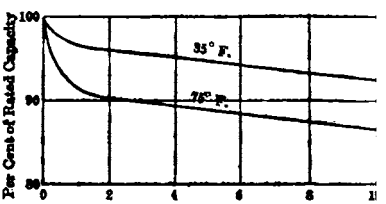


Fig. 5. Retention of Charge when Standing Idle

TESTING. — There are described below only those tests which are of interest in the commercial operation of the batteries. The methods of conducting several of the tests are the same as for the lead type of battery and are described more fully in the article on *Batteries, Storage, Lead Type.*

Tests of Electrolyte. — The normal specific gravity of the electrolyte at 80° F. is 1.200 as measured by hydrometer but may range from 1.160 to 1.230. Specific gravity is not necessarily a true indication of the suitability of the electrolyte, since harmful impurities may get into the electrolyte when watering or in other ways. The manufacturers recommend that the electrolyte be removed when the specific gravity has fallen to 1.160; this will usually be required after from 8 to 10 months of daily service. It is advisable to discharge the battery before renewing the electrolyte, and to give it a 12-hour charge, at the normal rate after renewing.

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Test for Internal Resistance. — The internal resistance of a battery may be ermined by momentarily opening the switch during discharge and noting rise in voltage. This rise represents the *IR* drop in the battery due to its rnal resistance and cell connections. Hence the value of the internal re-ance at the given point of discharge will be the quotient of the volts rise ided by the current rate. This value divided by the number of cells in series l give the internal resistance per cell. Since on interrupting the current the tage may rise for some time, due to change in the e.m.f., a better voltage ding may be obtained by momentarily reducing the current flow instead of ening the circuit. In this case the resistance is found by dividing the differ-ce in voltage at the two rates by the change in current.

Capacity; Efficiency. — In testing for the capacity of an Edison battery at y given rate, the discharged battery should first be charged for 7 hours at e normal (5-hour) discharge rate. The battery is then discharged at the sired constant-current rate until the terminal voltage has reached the value determined by the rule given in the paragraph above on *Variation of Capacity ith Rate of Discharge*. The capacity in ampere-hours is the product of time of scharge in hours by the rate of discharge in amperes. The watt-hour efficiency the battery is the ratio of the energy given out on the discharge to the energy t in on the charge. The term "volt efficiency" is used to express the relation the average voltage of discharge to the average voltage of charge. For harge and discharge at the normal rate the value of the volt efficiency will be lose to 72 per cent for any length of charge not extremely short or long. Thus 2 per cent is the limit of possible efficiency at the normal rate. The watt-hour fficiency on any normal rate test may be calculated accurately enough for all ractical purposes by taking 72 per cent of the ampere-hour efficiency, i.e., by aking 72 per cent of the ratio of ampere-hours output to ampere-hours input.

Test Electrodes. — The best substance for a third electrode in analyzing oltage curves of alkaline batteries is a partially reduced oxide which will ndergo reduction in the electrolyte without polarization, and which is insoluble n the electrolyte. Either cupric oxide or the high nickel oxide of a charged dison positive fills these conditions for alkaline cells. For a discharge at ormal rate the readings of the cell electrodes to a test electrode of cupric oxide re: iron, approximately 0.44 volt, nickel, 0.9 to 0.5 volt; for a test electrode f nickel oxide the readings are: iron, approximately 1.28 volts, nickel — 0.1 to - 0.4 volt.

INSTALLATION. — The A- and B-types of cells are usually assembled by he manufacturer in wooden trays holding from 2 to 12 cells each, according to equirements. There is an air space between cells for ventilation and in-ulation. The standard form of tray is made "bottomless," in order to prevent hort-circuits between cells from the collection of dirt and moisture. If A-type ells are to be used where they will be pulled horizontally for filling, etc., trays vith bottoms are used on account of the greater strength. Data on typical ssemblies in bottomless trays are given in the following table:

Size of cell	B–2	A–4	A–6	A–12
Width of standard tray, in.	6 1/8	6 1/8	6 1/8	9
Over-all height (filler cap closed), in.	9 5/8	14 5/16	14 5/8	15 1/2
Length of trays, in.:				
2-cell tray	5	7 3/4	10	13 1/2
5-cell tray	10 3/4	17 1/8	22 3/4	32 1/4
8-cell tray	16 1/2	27 1/8	36 1/4	....
12-cell tray	24 3/8	40 3/8	....	.....

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For the extra high container which is sometimes furnished (designated by E) the over-all height for B-type is 2 in. greater and for A-type 3 in. greater than the figures given in the above table.

The over-all height with filler cap open is about 1½ in. greater than the height with filler cap closed.

If a battery is to be used for stationary service a clearance of 6 in. above cells should be allowed so as to permit the proper filling of the cells in place. In vehicles from which the battery is removed for filling the clearance need be only ¾ in.

OPERATION. — An Edison battery should never be operated in any manner except in accordance with the instructions received from the Edison Storage Battery Co. Disobeying these instructions may result in forfeiture of the guarantee with regard to the life of the cell. As the detailed instructions differ somewhat for various services, only general directions which apply to all services are noted below.

Charging. — The batteries are now usually shipped in a charged condition. The initial charge should continue for 12 hours at the normal rate. A similar overcharge should be given after 30 days of service, one after 60 days of service, and another after each renewal of electrolyte. The normal charging rates are given above in the section on *Rating and Performance;* the time of a normal charge is 7 hours. The boosting rate may be as high as desired provided the temperature does not exceed 115° F. in any of the cells. The best results are obtained when the temperature is kept between 75 and 95° F. Under average operating conditions the charge in ampere-hours necessary to replace a discharge is from 15 to 25 per cent greater than the discharge. The Edison Storage Battery Co. recommends that if an ampere-hour meter is used, it should be set to operate 20 per cent slow on charge.

Precautions as to Gases. — The battery should be well ventilated while charging, and no open flame or arcing contact should be allowed near the cells while charging or immediately afterward, as the evolved gases may be exploded.

Standing Idle. — An Edison battery may be allowed to stand idle in any state of discharge provided the level of the electrolyte is kept above the plates. After long idleness an overcharge may be required to bring the battery up to rated capacity.

Watering Cells. — The level of the electrolyte must be kept above the plates by adding distilled water from time to time. The frequency of adding water will depend upon the amount and rate of charging. The manufacturers of the battery supply an indicating filler which is of assistance in preventing slopping and over-filling.

Cleaning. — The trays and containers must be kept dry, and dirt or other foreign material must not be allowed to collect between or under cells. Dirt and dampness may cause leakage which may result in corrosion of the containers. The outside of the cans may be cleaned with a steam or air blast. If a container becomes leaky it should be returned to the manufacturer for repair.

DIMENSIONS, WEIGHT AND COST. — The Edison battery is made in two standard types, the plates of the A-type being approximately 4¾ by 9¼ in. and those of the B-type 4¾ by 4⅝ in. Plates of other dimensions can be obtained for special purposes. The sizes of cells are commonly designated by the type letter and a number which indicates the number of positive plates, as for instance, an A-6 cell has 6 positive and 7 negative plates. The several sizes of cells together with data on the dimensions and weight of each are given in the following table:

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DIMENSIONS AND WEIGHTS OF EDISON CELLS

Size of cell	Over-all dimensions of cell, in inches			Weight in pounds	
	Length	Width	Height	Complete cell	Average per cell with trays and connectors
B-2	1.5	5.1	8.8	4.6	5.5
B-4	2.6	5.1	8.8	7.4	8.7
B-6	3.8	5.1	8.8	11.0	12.0
A-4	2.7	5.1	13.4	13.3	14.5
A-5	3.2	5.1	13.4	16.8	18.5
A-6	3.8	5.1	13.4	19.0	21.0
A-8	5.0	5.3	14.0	27.0	30.0
A-10	6.2	5.5	14.0	34.0	37.5
A-12	7.4	5.5	14.6	41.0	45.0

For services, such as the lighting of railroad cars, which require that the tteries work for long periods without the addition of water, the A-type plates e assembled in containers (designated by H) about 3 in. higher in each case han those indicated in the table, in order to obtain additional space above he plates for the electrolyte. The weight per cell is then about 15 per cent reater than the above.

Before the war the cost of Edison cells assembled in trays was approximately .91 per pound, including weight of trays and connectors. This is equivalent a cost of approximately $410 per kilowatt at the normal (5-hour) rate of dis-harge or $105 per kilowatt at the one-hour rate of discharge. The manu-acturers guarantee that these cells will show at least their rated capacity after ing used a specified time, the usual guarantee period for A-type cells being least 4 years and for B-type cells, at least 5 years.

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BATTERIES, STORAGE, APPLICATIONS OF. — (*See also B teries, Storage, Alkaline Type; Batteries, Storage, Lead Type.*) The follow list shows some of the more important applications of storage batteries; th are briefly treated in the following pages.

Central Stations
- Emergency reserve — "Stand-by service."
- Load or voltage regulation.
- Taking peaks.
- Day load on small systems.
- Exciter reserve.
- Remote-control switch operation.

Isolated Plants
- Mine hoists, steel mills and other heavy motor regu tion; see Index.
- Carrying entire load during certain hours of light load
- Load and voltage regulation in office buildings or hot where electric elevators are in service.
- Giving 24-hour service in residences.
- Operation of drawbridges.

Other uses are:

- Regulation of long feeders; see *Trolley Systems, Ov head.*
- Propulsion of pleasure cars, trucks, street cars, s marine boats, launches, industrial trucks and tracti mine, and industrial locomotives, etc.
- Gas-engine ignition.
- Railway passenger-car lighting; see *Lighting of trains Electricity.*
- Railway signaling, see *Signaling, Railway.*
- Telephone and telegraph (q.v.).
- Portable and small stationary lamps.
- Fire and burglar alarm (q.v.).
- Electroplating.
- Dental and other surgical work.
- Automobile starting, lighting and ignition; see *Ignit Electric; Starting and Lighting Systems for Automobi*

Extent of Application in the United States. — The first applicati in America of storage batteries to central-station service was in 1886. In 19 there were in service in the United States, for central-station "stand-by" w 193 storage batteries of the lead-lead acid type, having a combined capacity approximately 177,000 kw-hr. at the one-hour rate of discharge. Most of th are of the Faure or Pasted type, some are of the Planté type, or a combinati of Planté and Faure types.

There were in service in the United States in 1920 approximately 700,0 cells of the lead-lead acid type, operating telephones, lighting railway cars a operating signals.

At the end of 1920 there were in operation lead batteries for other uses appro mately as follows:

For automobile, starting lighting and ignition 15,000,000 cells aggregati approximately 3,000,000 kw-hr.

For farm lighting plants 3,000,000 cells aggregating 1,000,000 kw-hr.

For electric passenger cars, street trucks, mine and industrial locomoti industrial trucks and tractors, 1,166,000 cells aggregating 444,000 kw-hr.

TAND-BY BATTERIES IN CENTRAL LIGHTING STATIONS. — nerly the storage battery in a central lighting station served a dual purpose: as a source of current in an emergency, and second, to take short peaks ad, thus cutting down the generating capacity in service and increasing economy of plant operation. In certain cases the batteries are used in this ner to-day, but owing to the desire always to have the full battery reserve ase of emergency, the peak battery feature is being abandoned and the d-by feature only is being retained.

his method is considered by some authorities to be even more conducive to nomy of station operation than that in which the battery was also used on peak, inasmuch as the presence of a fully charged battery behind the generat- apparatus permits station operation at a much higher load factor than were battery fully or partly discharged. Furthermore, as one of the important ors in the life of the battery is the amount of work it does, this life is greatly eased if the battery be used only for emergency service.

Connections for Battery and Its Auxiliaries, Stand-by Service. — . 1 shows a general standard scheme for the operation of a battery on a ire lighting system, either for peak work or stand-by emergency work. As be noted in this scheme, the neutral of the battery is connected to the tral of the system.

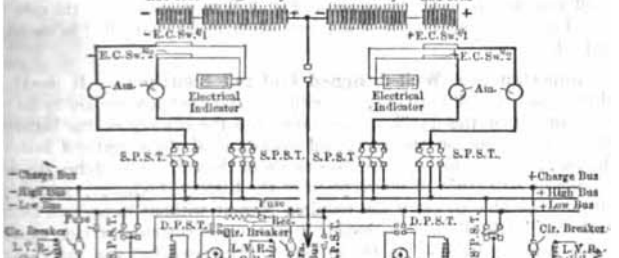


Fig. 1. Connections for Stand-by Service

Charging. — For stand-by emergency work it is standard practice to take battery off the bus for charge and in most cases the battery is floated on y one bus. In this service the battery is kept fully charged and floating on bus-bars continuously, except during charge. Except in case of an emer- cy discharge having been required from the battery, it will only be necessary ive the battery an occasional overcharge about once a week or once in two ks in order to keep the active material in proper condition. Since this over- rge is given at the normal rate for only a few hours, once every week or every weeks, a time for this overcharge can be selected when it will be safe to take battery off the bus. It will also be noted that on charge, sufficient voltage btained for charging the complete battery by adding to the bus voltage the tage of a simple charging booster. It is necessary with the 3-wire system to e two generators, one on each side of the system, in order to be able to charge two halves of the battery at different rates in case the battery has become balanced on discharge. The diagram shows a simple shunt motor driving se two booster generators.

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End-Cells and Switches for Stand-by Service. — The connec between the two sides of the battery and the outside bus-bars of the sy are made through "end-cell switches," by means of which the number of on the system can be varied at will within certain limits. This sch shows two end-cell switches in parallel on each side of the system, this n ber of switches being installed in this case in order to provide sufficient capa for the discharge.

The number of end-cell switches necessary on each side of the system dep upon the current to be carried, upon the number of bus-bar voltages to be m tained from the battery simultaneously, and upon whether or not it is de to keep the battery on the bus during charge. It is frequently required to the battery on more than one bus. In such cases there must be one end switch on each side of the system for each bus. If it is not desired to keep battery on the bus during charge, and if the battery is to float on only one one end-cell switch on each side of the system will be sufficient, provided one end-cell switch has sufficient current-carrying capacity.

If, however, it is deemed advisable to keep the battery on the bus at all ti it will usually be necessary to have at least two end-cell switches on each of the system and the number of end cells required will be greater than number of end cells required where the battery can be taken off the bus charge. This point is referred to again in the next section.

It will be noted from the diagram in Fig. 1 that on discharge the cells connected in series and that the voltage on discharge is controlled by mean the end cells.

Importance of Well-designed End-cell Switches. — It should noted that the end-cell switches used with this standard scheme are by far most important of the auxiliary apparatus and the efficacy of the batter absolutely dependent on the successful operation of these end-cell switc The factors necessary for successful operation of the end-cell switches are, f there must be no chance of interruption of the battery discharge; second, switch must be able to carry the required current without dangerous hea or sparking. End-cell switches having a continuous current-carrying capa of 10,000 amperes are now on the market. These switches can carry 40 amperes for six minutes and the contact brushes can be moved from point point without injurious sparking or heating.

Number and Capacity of Cells for Stand-by Service. — The num and the capacity of the cells depends upon the lowest bus voltage maintai under normal operating conditions, the minimum allowable voltage at the of discharge in case of emergency, and the load required to be carried du emergency.

If the battery can be taken off the bus for charge, the number of cell the main battery will be equal to the lowest bus voltage (between outside bars) divided by 2.1. The number of cells in the entire battery will be e to the lowest allowable voltage in emergency divided by the final voltage cell at the rate of discharge required by the emergency. The difference betw the number of cells in the main battery and the total number of cells will course, be the number of end cells. When the total number of cells in battery is determined it will become necessary to put half the numbe cells, including half the end cells, on each side of the system.

If it is deemed necessary to keep the battery on the bus at all times du charge and discharge, the total number of cells will be determined as indic above, but the number of cells in the main battery will be equal to the voltage divided by 2.7, since this is the average cell voltage at the end of cha In this case, at least two end-cell switches on each side of the system will

ired. On charge one end-cell switch on each side of the system is connected
ie main bus and is set at such a position that the total voltage of the cells
ircuit during charge equals the bus voltage. The other end-cell switch is
o as to include the cells being charged. That is, at the start of charge, the
nit from the charging booster to one end-cell switch will include all of the
, and the circuit from the lighting bus to the other end-cell switch will only
ade sufficient cells to give the lighting-bus voltage. As the charge proceeds,
end-cell switch in the charging circuit will be shifted to cut out end cells as
r charge is completed, and the end-cell switch connecting the battery with
lighting bus will be shifted to cut out cells as the voltage of the battery comes
so that the voltage of the cells in circuit on the lighting bus can be held at
lighting-bus voltage.

t is seen that with this operation the end-cells included between the two end-
switches will have to carry the charging current plus or minus any current
nsferred between the battery and the lighting bus. It is thus apparent that
a this method of operation, unless especial care is taken to float the battery
he true lighting-bus voltage, the end cells will be worked unequally. It is
seen that, if it is desired to keep the battery on the bus at all times, the
ount of end-cell copper is considerably increased and the cost of the battery
allation is proportionately increased, for the number of end-cells required
reater than the number of end cells required when the battery can be taken
the bus for charge. On account of this increase in cost and the possibilities
unequal work on the end cells, it is desirable to install the simpler scheme
wn in *Fig.* 1.

Determination of Size of Stand-by Battery. — As an example of the
thod used in determining the number and capacity of cells required for this
e of work, suppose it were desired to install a battery to take care of an
rgency of 20,000 amperes for 20 minutes at a normal bus voltage of 230
ts with a minimum allowable voltage during emergency of 225 volts. The
minute rate of discharge is 8 times the normal rate, as shown in Figs. 3
6 in the article on *Batteries, Storage, Lead Type*, and it will be noted from
6 that the final voltage per cell at the end of this rate is 1.5 volts. The
l number of cells will be 225 divided by 1.5, or 150 cells. If it is desired
se standard practice, taking the battery off the bus for charge, the number
ells in the main battery will be equal to the normal bus voltage, 230, divided
2.1, or 110 cells.

t will, therefore, be necessary, in this case, to install a battery having 150
, including 40 end cells, each cell having a capacity of 20,000 amperes for
minutes. This battery will be installed with 75 cells, including 20 end cells,
each side of the neutral. In standard stand-by practice the 20 end cells on
h side of the neutral will be connected to the end-cell switches, with two
s per switchpoint for a few of the cells and with 3 or 4 cells per switch-
nt for the remainder of the end cells. A certain number of two-cell con-
tions will be required in order to take care of the variation in the bus voltage,
t may be necessary to cut in and out cells while the battery is floating.
: rest of the equipment necessary should be in accordance with the diagram
wn in Fig. 1.

LARGE REGULATING BATTERIES FOR RAILWAY WORK,
C. — Often the load (particularly a railway load) on the power house is
ject to frequent and violent fluctuations, causing severe strains on the gen-
ing apparatus in service and in many cases requiring the operation of a
ater number of units than would be necessary to furnish a steady average
l. This not only results in a lower load factor and consequent loss of econ-
y, but it reduces the surplus capacity of the generating station by the extra

amount of apparatus required in operation. Another loss in economy is to the rapid changes in the cut-off point of reciprocating engines, due to violent fluctuations of load. Fig. 2 shows a simplified wiring diagram of scheme generally used.

Carbon Regulator. — The carbon regulator shown in Fig. 2 consists piles of carbon disks arranged in two groups on opposite sides of the fulcr of a lever, the lever being subjected at one end to the tension of a spring at the other end to the pull of a coil connected in series with the main bus-bar. Variations in the force applied to opposite ends of this lever will increase the pressure on one group of carbon disks and decrease the pressure on the other, thus varying their relative resistances. These piles are connected in series across the battery terminals, and the field winding of the booster exciter is connected between the middle poi the battery and a point in the circuit between the two groups of carbon di Variation in the resistances of these two piles, produced by variation of pressure of the lever, will cause current to flow in one direction or the ot through the field of the exciter, thus controlling the operation of the boo and compelling the battery to charge and discharge with small variation current in the series coil.

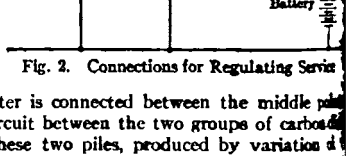


Fig. 2. Connections for Regulating Servic

In this manner the load on the generator can be maintained constant wi a few per cent on either side of the average value for which the apparatus been adjusted. The load on the generator is determined by the tension of spring, which may be adjusted to balance any average current in the series If the average load on the line should exceed for a considerable period of t the generator load for which the spring is adjusted, the battery will be subje to a sustained discharge which may in time exhaust its available capacity. on the other hand, the average load on the line falls off for a considerable pe of time, the battery will be subjected to a sustained charge which may prod excessive and unnecessary overcharge. To follow these variations in aver load, it is necessary to adjust the spring from time to time.

Automatic "Average" Adjustor. — In order to eliminate the neces for such frequent adjustment by hand in cases where the average load is c tinually changing and where the generator is capable of handling these compa tively slow changes, the automatic average adjustor has been designed. T piece of apparatus consists of a small motor connected by a reducing gear to drum which controls the tension of the carbon regulator spring. The armat of this motor is connected across the main bus-bars through a fixed resista which maintains a practically constant current through the armature. T field of the motor is connected across the terminals of the booster.

Whenever the booster voltage is in the direction to discharge the batte the motor field is energized and the motor revolves in the direction to incre the tension of the spring, thus gradually increasing the load on the gener and relieving the battery of its discharge until the booster voltage comes b to zero. If, on the other hand, the booster voltage is in the direction to cha the battery, the motor of the average adjustor will operate in the oppo direction, gradually relieving the tension on the spring and reducing the aver load on the generator until the booster voltage is again brought back to

he battery is again restored to its floating condition. This transfer of load en the battery and generator is brought about slowly so that the battery l free to relieve the generator of all quick fluctuations of load. The battery, ver, is relieved from a considerable amount of sustained peak charge and arge.

Load-limiting Device. — To prevent the average adjustor from throw- ad on the generator beyond its capacity, a load-limiting device has been ed. This consists of an electrolytic valve in series with the field e motor. Ordinarily this valve is short circuited by a switch. When the which regulates the tension of the spring has traveled to a certain point sponding to the maximum permissible load on the generator, a projection nted on the shaft of this drum engages with the switch and opens it, where- the valve prevents current from passing through the motor field in a tion to cause a further increase in the spring tension. The valve will, ever, permit the current to flow in the opposite direction so that as soon as load has decreased sufficiently to cause the battery to charge, the motor will rate so as to relieve the tension on the spring and at the same time permit the ch to close, thus restoring the original adjustment.

utomatic Current Stop. — While the capacity of a storage battery to stand an excessive momentary overload without injury is practically un- ited, the booster must be protected by an automatic circuit breaker. When- e the setting of this circuit breaker is exceeded on heavy overload and the aker opens, the entire maximum load is thrown on the generator. This ally results in opening the generator circuit breaker also and interrupting supply of current to the line. To avoid this and permit the battery to nish the maximum current which the booster can handle without danger of rloading the latter or opening the circuit, there has been designed an auto- tic current stop. This stop is arranged to automatically prevent the battery n discharging above a certain predetermined value, for which this stop has n adjusted. All load demand above this predetermined value is thrown upon generator. The generator is thus subjected only to the excess of load above maximum capacity of the battery booster, instead of having the entire load he line suddenly thrown on it when the battery circuit breaker opens. The ustment of this automatic current stop can be changed within certain limits meet the requirements.

Batteries for Controlling Alternating-current Loads. — For controlling tuations of an alternating-current load a solenoid which is responsive to the rgy component of the alternating current is substituted for the series coil wn in Fig. 2. The general operation of this scheme is the same as described ve, except that it is, of course, necessary to discharge the battery on to the rnating-current bus through suitable alternating-current-direct-current trans- ming apparatus. There are in service at present several battery installations ich regulate fluctuating alternating-current loads. Most of these installa- ns are based on the carbon regulator principle, as outlined above.

Number of Cells and Capacity of Cells and Booster. — The number and acity of cells required for regulating work depends upon the bus voltage and on the nature of the fluctuating load. It is also frequently desirable to ize a regulating battery for emergency and peak work, and the extent of the ergency and peak requirements will also be a factor in fixing the capacity of battery. The number of cells installed will be equal to the bus voltage ided by 2.1, since this is the floating voltage per cell. A reference to Fig. 2 ws that during the regulation of load fluctuations all of the battery discharge ws through the armature of the booster generator. It is thus seen that it ecessary for the booster to generate sufficient voltage to make up for the drop

in battery voltage on discharge. This drop in battery voltage depends upon capacity of the battery, and the amount and duration of the discharge. fore the booster can be properly designed it will be necessary to have comp data on these points.

Emergency Work. — For emergency work, where the battery is carr the entire load without the assistance of any generating apparatus, it ma may not be necessary to keep the booster in circuit, depending upon whe or not it is desired to maintain a constant bus voltage. If it is not desire maintain a constant bus voltage, a saving can be effected by cutting the boo out of circuit and allowing the battery to discharge directly on to the syste

Peak Work.— For peak work, where the battery must work in par with the generators, it will either be necessary to keep the booster in ci in order to maintain the same voltage as the generator or else to give the ge ators a drooping characteristic so that the battery can discharge in par with the generators without the aid of the booster.

Current Capacity. — If it is desired to float the battery on the sys at all times in order to regulate load fluctuations, it will be possible to float battery about 75 per cent fully charged. If this battery must have a defi capacity always available for peak or emergency work, it is seen that the bat must be of sufficient capacity, when 75 per cent fully charged, to deliver the l called for by the emergency or peak conditions.

Determination of Size of Regulating Battery. — In all cases whe battery is to be considered for any one of the above conditions or any combi tion of them, it is recommended that the complete data summarized belo sent to the battery manufacturer with a request for a complete report cove the battery and accessories recommended to suit the conditions. The d necessary are as follows:

Number, type and capacity of boilers, if the plant is a steam plant.
Schedule of boiler operation, if the plant is a steam plant.
Number, type and rating of generators.
Schedule of generator operation.
Bus voltage maintained.
If the generators are of the alternating-current type, give frequency, num of phases, and the number and rating of any static transformers used
If the station in question is a substation, describe the complete substa equipment along these same lines.
Give complete 24-hour load curve showing half-hour readings of the t load on the station bus bars. A graphic recording meter chart wil sufficient, if such an instrument is available.
If possible, obtain five-second readings on the total indicating ammete wattmeter, over a period of one-half hour during the time of maxim fluctuations.
If the battery is required to assist the generators on the peak, give the amo of load in kilowatts required from the battery and the length of time load is required. It would be well to have an exact load curve show the shape of this peak, if it is possible to obtain such a record.
If the battery is to be used for emergency, give the amount of the load the time over which this emergency extends. In all cases state the ex nature of the load required, that is, whether it is a motor load, a ligh load, etc.

BATTERIES FOR REMOTE-CONTROL SWITCH OPERATION

It is standard practice in central stations of any magnitude to install a sto battery of sufficient capacity to give ample insurance against interruptio

switch-control circuit. It is the usual practice to utilize this battery, not for the operation of the remote-control switches, but for the operation of signal lamps and a sufficient number of emergency lamps throughout the on. In some stations the remote-control switches are operated from the ter bus bars, but it is better practice to operate these switches together with r signal lamps and the emergency lamps from a separate source of power.

ontrol Battery Connections. — Fig. 3 shows a scheme which is more or standard with the larger central-station companies. This figure shows a or-generator set consisting of an in- ion motor driving a direct-current rator whose voltage can be varied 1 110 volts up to 168 volts, the r voltage being required to com- dy charge the 62 cells in series. nder normal operation the battery ated on the 130-volt bus with the or-generator set, the battery switches g thrown into positions 1 and 2. It be noted that with this arrange- t all 62 of the cells are floating the bus. When it becomes necessary to charge the battery, the battery tches are thrown into positions 1 and 4, and the generator voltage is raised iently to start the charge of the entire 62 cells. With this arrangement voltage at the load bus bars will be the voltage of 55 cells. At the finish of rge the battery switches are thrown into positions 3 and 4. It will be noted in these positions the group of 7 end cells is out of circuit, as they have re- ed their complete charge, and the motor-generator set will be furnishing er to charge the 55 cells and to carry the load.

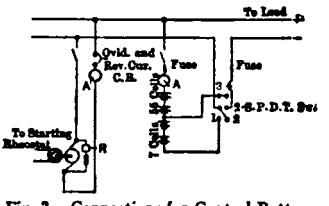


Fig. 3. Connections for Control Battery

ize of Battery. — With this arrangement the voltage at the bus bars may y from 145 volts to the minimum voltage of the battery on discharge. The nber of cells for this scheme can be varied to suit the voltage conditions. e capacity of the battery is fixed by the maximum current demand, the total pere-hour current demand over the period of estimated possible shutdown, l the minimum allowable voltage on the load bus bars. With these condi- s known, it will be possible with the aid of trade catalogues showing the ge and discharge curves of the battery and the battery capacity at various s, to select a battery to suit the conditions.

Control Battery on Exciter Bus. — If the oil-switch load is furnished from exciter bus it will be necessary to float the emergency battery on the exciter s, or to supply automatic means for throwing the battery on the exciter bus en the voltage of the exciter bus drops below a certain predetermined value. this method is used, unless the battery is of sufficient capacity to carry the ire exciter load, it will be necessary to place a reverse-current circuit breaker ween the battery and the exciter load, so that when the exciter bus "goes d" the battery will be automatically cut off from the exciter bus and left the remote-control switch bus.

EXCITER BATTERIES. — It is standard practice with the larger central- tion companies to install a battery of sufficient capacity to carry the total ximum exciter load for from one hour to two hours continuously. The nber of cells will depend upon the voltage of the exciter bus, which is usually) but is sometimes as high as 250 volts.

If it is desired to maintain constant the voltage on discharge, it will be neces- y to utilize end cells by means of an end-cell switch. In this case the number cells in the main battery will be equal to the bus voltage divided by 2.1, and

the total number of cells in the battery will be equal to the bus voltage divi by the voltage per cell at the end of discharge for the discharge rate used. T difference between the number of cells in the main battery and the number cells in the whole battery will be the number of end cells. These end c can be connected to the points on the end-cell switch singly or in pairs, d pending upon the voltage regulation desired. If it is not desired to maint a constant voltage on an exciter bus, the end cells will not be required. T total number of cells will be kept on the bus bars and as the voltage of th battery falls the field excitation of the generators can be maintained constant changing the generator field rheostats.

The ampere capacity of the cells will be determined by the amount and dur tion of the load to be carried. Knowing the ampere capacity, the length time and the minimum allowable voltage during the period, the number of ce and the type of battery can be determined by the use of the charge and di charge curve and battery rating given in trade catalogues.

LINE BATTERIES FOR RAILWAY WORK. — (*See also Trolley Sy tems.*) The functions of a storage battery floating on an electric railway li at a distance from the power house are as follows:

1. To improve the line voltage and displace a certain amount of feed wire.
2. To relieve the power house of fluctuations of load.
3. To keep the cars moving when the power supply is temporarily interrupted.
4. To supply power for the operation of a few cars or lights at night when t power house is shut down.

Location. — Before any calculations can be made, the location of the batte must be decided. Where there are no other determining factors, the batte would ordinarily be located about three-quarters of the distance from the pow house to the end of the line, or, if the line is fed from both ends, midway betwe the feeding points. In some cases the location of the maximum momentar load, due, for example, to a severe grade or to the passing of two cars at a sidi will influence the location of the battery. In other cases the location of a su able piece of property owned by the company, or the location of a car ba where attendance would be available, may be the determining factor.

Line Battery without Boosted Feeder. — In this class of line-batte installation the number of cells is determined by the average line voltage the proposed battery site on the basis of approximately 2.1 volts per cell. Th if the average voltage at the battery site, as determined by voltage readi taken at frequent intervals, such as five or ten seconds, over a considerab length of time, should be found to be 500 volts, the number of cells suitable f this average voltage would be 238. If it is found that, owing to changes in loa conditions at different hours of the day or on different days of the week, th average voltage varies considerably for prolonged periods of time, it may b necessary to provide means for changing the number of cells connected to th line. This may be accomplished by separating a group of cells at one end o the battery, and arranging suitable switches so that these cells may be connect either in series with the main battery when the average voltage is high or i parallel with an equal number of cells of the main battery when the averag voltage is low It is found preferable to connect these end cells in parallel wi a portion of the main battery, and thus keep them active rather than disconne them from the system entirely.

Calculation of Size of Battery Required. — See article on *Trolley Syste Overhead*, and *Bulletin No. 134* of The Electric Storage Battery Co.; also Ch 44 of Lyndon's *Storage Battery Engineering.*

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BATTERIES FOR SMALL CENTRAL STATIONS AND ISOLATED PLANTS. — The objects of a battery installation in small electric lighting and power plants may be any one or all of the following:

1. Twenty-four-hour service with but a few hours daily operation of engine.
2. Reduction in size of engine and dynamo otherwise required.
3. Improved voltage regulation.
4. A source of current during breakdown of machinery, or while repairs are being made.

Twenty-four-hour Service. — In this service the battery supplies the current during the hours when the engine is not running. As the capacity of a battery of normal size in many instances in this class of work, especially in residential service, is not generally exhausted in daily operation, it may usually be charged by running the engine and dynamo only two or three hours each day at the most convenient time. In summer, when the lighting hours are shorter, it may be sufficient to charge only once in two or three days.

Reduction in Size of Generator. — If the plant is so designed that the combined capacities of the dynamo and the battery are equal to the maximum load requirements, a smaller engine and dynamo may be installed than would be required if the dynamo alone had to carry the total maximum load. The battery will then be discharged in parallel with the dynamo, to assist it by taking a part of the total load on special occasions, as when the maximum number of lights is in use.

Improved Regulation. — Objectionable fluctuations of voltage and consequent flickering of lights, due, for example, to the operation of an electric elevator or other motor work, may be eliminated by floating the battery across the lighting bus.

Emergency. — In case of temporary derangement of the engine or dynamo, which may occur when the lighting service is most important, or in case repairs to the machinery are required, a battery will serve to tide over the break and avoid any interruption in the current supply.

Small Regulating Battery with Counter Cells. — Fig. 4 shows an ideal arrangement for small battery lighting plants where the capacity of the battery does not greatly exceed 300 ampere-hours at the normal rate. This figure shows 62 cells in the main battery with 8 counter cells, the whole being designed to operate on a 110-volt bus-bar. It will be noted that the battery is charged with two halves in parallel. During charge each half is placed across the bus-bars in series with a fixed resistance. At the beginning of charge the counter cells are all in circuit and assist the fixed resistances in reducing the bus voltage to the proper charging voltage. The counter cells are cut out of circuit as the battery voltage rises. On discharge, all of the cells in the main battery and the full number of counter cells are connected in series. As the voltage falls on discharge the counter cells are cut out of circuit, thus maintaining a steady voltage at the bus-bars. The number of cells and counter

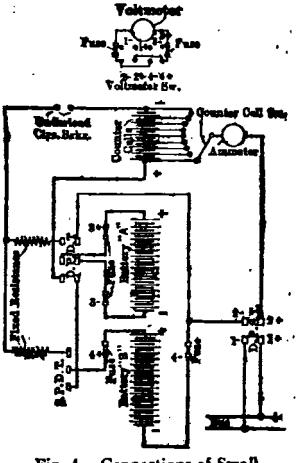


Fig. 4. Connections of Small Regulating Battery

cells shown in the figure are selected to maintain a steady voltage of 110 volts at the normal rate of discharge. The counter cells are composed of unformed battery plates or grids, and since they have very little active material they have practically no capacity. Each counter cell will, however, furnish an opposing voltage of approximately 2.3 volts; this counter voltage is practically constant over the range in current demand for an ordinary small station.

Small Regulating Battery with Charging Booster. — For larger-sized plants this method of operation is not economical owing to the loss in the charging rheostats and the loss in the counter cells. For a straight lighting plant where a battery of more than 400 ampere-hours capacity is required, it is usual to use the scheme shown in Fig. 5. It will be noted in this scheme that the cells in series are connected to the bus for discharge, the voltage being controlled by cutting in and out the end cells at one end of the series. On charge the required voltage to complete the charge is obtained by adding to the bus-bar voltage the voltage of a small booster generator.

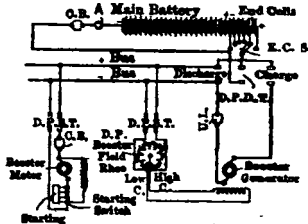


Fig. 5. Connections of Small Battery with Booster

Size of Battery. — For ordinary small plants which operate at a bus voltage of 110 the standard equipment consists of 64 cells, including 12 end cells. The capacity and type of the cells are fixed by the ampere-hour requirements and the minimum-voltage requirements on discharge. For any bus voltage other than 110 volts the complete number of cells, including the end cells, can be determined by dividing the minimum allowable bus voltage by the minimum voltage per cell at the end of discharge at the rate which will be used. The number of cells in the main battery will be equal to the bus voltage divided by 2.1. The difference between the number of cells in the main battery and the total number of cells will give the number of end cells. An end-cell switch having one point more than the number of end-cells required will be necessary.

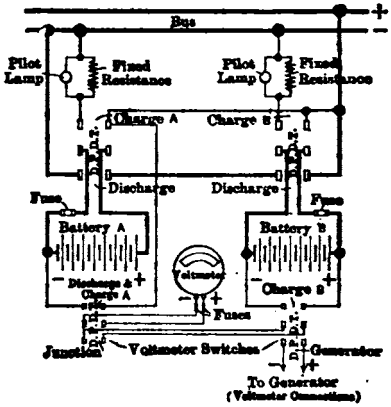


Fig. 6. Connections of Small Battery without Booster Cells

Small Battery without Voltage Regulation. — If voltage regulation on discharge is not required, the scheme shown in Fig. 6 can be used. It will be noted that this scheme is practically the same as shown in Fig. 4 except that the counter cells have been omitted and only 56 cells are used.

Small Battery on 3-Wire System. — In small central stations or isolated plants which utilize the 3-wire 110 to 220-volt system, the battery is arranged in two halves, one on each side of the neutral. A group of end cells on each side of the system and two booster generators direct con-

nected to one motor are used. This scheme of operation is shown in general in Fig. 1 which is described in detail above in the section on *Stand-by Batteries*.

Small Battery for Low-voltage Lighting — So-called Farm Lighting Plants. — Since the advent of the tungsten lamp 32-volt plants are growing very popular.

Numerous manufacturing concerns have gone extensively into this business and there are several concerns to-day marketing these plants by the thousands. One concern in America during 1920 marketed considerably more than 50,000 complete farm lighting plants.

All of these plants consist of a gas engine driving a 32–42-volt generator, a switchboard and a storage battery. The capacity of the low-voltage farm lighting plant varies from ½ kw. to 5 kw. Usually where the capacity required exceeds 5 kw., especially when the distance of transmission exceeds a few hundred feet, it is better to go to 110 volts, as the low-voltage plant is designed primarily for small loads and short distances of transmission.

There are various schemes of operation which are now successfully used, but they all include a storage battery. These schemes vary all the way from the one extreme, where only sufficient storage battery is installed to automatically start up the engine-generator unit when the load is switched on, to the other extreme where a storage battery of quite large capacity is used and all the load is usually taken from the storage battery, the engine generator set being run only at intervals (about once a week) to charge the battery.

Because of the multiplicity of schemes it will not be attempted here to describe any of them in detail and it is suggested that those interested obtain literature from numerous manufacturing concerns putting out these plants.

As an evidence of the growth in the use of storage batteries for this application there were in service at the end of 1920 in low-voltage farm lighting plants approximately three million storage battery cells aggregating a capacity of one million kilowatt-hours.

SMALL REGULATING BATTERIES FOR ELEVATORS, ETC. — Fig. 7 shows a scheme of load regulation which has been adopted as standard for situations where it is desirable to operate a lighting load and a fluctuating motor load from the same generator. This scheme is known as the "constant-current" scheme.

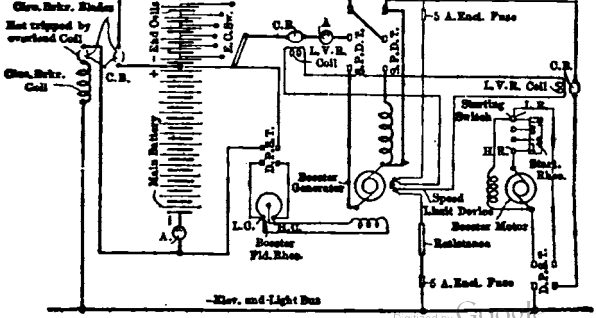


Fig. 7. Connections for "Constant-current" Regulation

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Elevator Load Regulation. — This scheme finds its greatest use in office buildings, hotels, etc., where electric elevators are in service. The load on such a plant is a very fluctuating one on account of the heavy current required for starting the elevators. This starting current is generally about twice the elevator running current. Moreover, as the elevators are not in service continuously, the average current per elevator is usually much less than the running current per elevator. There is generally, therefore, a considerable difference between the average load on the station and the maximum momentary load. This difference varies with the number and type of elevators, the character of elevator service and the magnitude of the lighting load. If the fluctuations above and below the true average are a comparatively large percentage of the true average load, they are liable to cause fluctuations in the generator voltage with consequent flickering of lights. In addition to this objection, the generating capacity necessary without a battery must be increased and it is necessary to operate the whole plant at a poor load factor.

Constant-current Scheme. — Reference to Fig. 7 shows that the battery and the elevator circuit are in multiple, and that the booster is in series between the lighting bus and the elevator bus. The booster in the constant-current scheme, as the name would imply, is wound in such a manner that the current going through it is rendered constant. Therefore, the parallel system of battery and elevator circuit can only draw a constant current from the generator, and it follows that all of the fluctuations due to the elevator load must be taken by the battery. When the elevator current is greater or less than the average, the difference is given or absorbed by the battery. It is important to note that the battery voltage applied to the elevator motors is that of the battery alone and is therefore variable. Ordinarily this is not a disadvantage as the heavy load is caused by the starting of motors, in which case high voltage is not an object.

It will be noted that the scheme given in Fig. 7 shows end cells. These are used for regulating the voltage on the lights when the generator is shut down and the booster is out of circuit, the battery carrying the entire lighting and elevator load.

Other Uses of Small Regulating Batteries. — Electric-elevator service has been taken as an example, as this is the class of work usually encountered. This scheme may be used, however, for other fluctuating loads, such as are due to electric cranes, shop tramways, mine hoists, etc., and in general for any fluctuating load where the maximum load is greatly in excess of the average load and constant potential on the motor bus is not required.

For fluctuating loads where constant potential on the power bus is required, the scheme described above under *Large Regulating Batteries* and shown in **Fig. 2** should be used.

Number and Capacity of Cells. — The number of cells in the main battery is usually determined by dividing the bus voltage by 2.1. The number of end cells necessary will be determined by the minimum allowable voltage and the final cell voltage at the end of discharge when the battery is carrying the entire load. The capacity of the battery will be determined by the amount of the fluctuations to be taken care of by the battery and the amount of load to be taken out of the battery when the generating apparatus is shut down.

Booster. — It will be noted in Fig. 7 that the diagram shows a differentially-wound booster. The desired regulation is obtained by means of the series field which carries the constant current between the lighting bus and the elevator bus, and which is designed to produce a booster voltage in the direction to oppose this current. The relation between the series field and the shunt field is adjusted for any given average load.

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A straight shunt booster with the field controlled by the carbon regulator as shown in Fig. 2 can be utilized with this constant-current scheme, if the solenoid is connected between the lighting bus and the elevator bus and if the carbon regulator actuated by this solenoid is utilized to control the field of the exciter as shown in Fig. 2. In all other respects this carbon regulator constant-current scheme operates according to the same general principle as the scheme for the differentially-wound booster.

It will be noted also that with the scheme shown in Fig. 2 the booster is in series with the battery and carries only the battery current, whereas in the constant-current scheme shown in Fig. 7 the booster carries the average current of the fluctuating load. The relative magnitude of the fluctuations as compared with the average will determine which booster will be least expensive and may, therefore, be a factor in deciding between the two schemes.

Two- and Three-wire Systems. — The scheme shown in Fig. 7 is for a two-wire system. This same general scheme is utilized for a three-wire system where the motor load is connected across the outside wires and the lights are balanced on each side of the neutral. Where the three-wire system is used, the general principles of the scheme are exactly the same as shown in Fig. 7, except that it will be necessary to have one booster generator and one set of end cells on each side of the system.

ELECTRIC-VEHICLE BATTERIES. — The growth in the use of storage batteries for electric vehicle propulsion has been enormous during the past few years. This is especially true in case of street trucks, industrial trucks and tractors and mining and industrial locomotives. The voltage and capacity of the battery necessary to operate any given vehicle is usually specified by the manufacturer of the vehicle, as the design of the vehicle determines the number of watt hours per car mile under certain definite conditions. Unless the vehicle user is a battery expert and a vehicle expert, it is not advisable that he specify either the number or capacity of cells to be used.

Desirable Characteristics of Vehicle Batteries. — The following are the chief characteristics of a good vehicle battery.

1. Low internal resistance, because of high current demand required for acceleration or for ascending grades.

2. Small capacity temperature coefficient, in order that the capacity of the battery shall not be unduly affected by chilling of the cells.

3. Voltage characteristic as nearly flat as possible under average conditions of discharge.

4. Construction of sufficient ruggedness to prevent breakage of parts in ordinary service.

5. Assembly such as to minimize possible labor and attention for flushing, cleaning, removing short-circuits, etc.

6. Ability to stand some abuse, as the average vehicle operator is not a battery expert.

The use of batteries for vehicle work is treated in greater detail in the article on *Automobiles, Electric.*

DRAWBRIDGE BATTERIES. — It is becoming standard practice to install storage batteries in connection with electrically-operated drawbridges, chiefly as an insurance against the interruption of power from the generating station. The voltage of drawbridge motors is usually 220 or 500. The number of cells and the capacity of the cells to meet the requirements will depend upon the maximum and minimum allowable voltages, and the total energy required from the battery before recharging.

Size of Drawbridge Battery. — Assume a 2000-ton bascule lift bridge with a 185-foot span. This bridge is to be operated with 220-volt motors. The time

required to open or close is 1¼ minutes, or a total of 3 minutes for a complete opening and closing. Assume the following conditions: The battery will be required to open and close the bridge 40 times on one charge, the maximum allowable voltage during bridge operation will be 250 and the minimum allowable voltage 200; the average current demand over a complete cycle will be 100 amperes with a maximum momentary current demand of 320 amperes lasting a few seconds.

It is seen that the total energy in ampere hours required for the 40 complete openings and closings of the bridge would be equal to $\frac{3 \times 100 \times 40}{60} = 200$ ampere hours during a total period of $3 \times 40 = 120$ minutes or 2 hours. The battery, therefore, must have a capacity not less than 200 ampere hours at the 2-hour rate of discharge. Bearing in mind the voltage limits specified above, an inspection of Figs. 3 and 6 in the article on *Batteries, Storage, Lead Type*, will show that the battery capacity will be fixed by the voltage limits in this case and not by the ampere-hour requirements. In any case that may arise, if there is any doubt as to which requirement will fix the capacity of the battery, select a battery having the ampere-hour capacity required and then examine Fig. 6 to see if a battery having this ampere-hour capacity will meet the voltage requirements.

For a maximum allowable voltage of 250 and a floating voltage of 2.1 volts per cell, there would be required 120 cells. Referring to Fig. 6 and using the upper curves, for plates 10¾ inches square, we will assume that the battery must not discharge at a higher rate than 4 times the normal rate. At 4 times the normal rate the voltage drops almost immediately to 1.9 volts per cell. With 120 cells the voltage would drop to 228 volts. It is noted that the normal rate of this battery will be 80 amperes, and the average discharge of 100 amperes will be 1¼ times the normal rate. By interpolating a curve between the normal curve and four times the normal curve, it is seen that with an average discharge at this rate for 2 hours, the voltage per cell at the end of the two hours, with 100 amperes flowing, will be approximately 1.9 volts, or the voltage of the 120-cell battery will be 228 volts. If, now, the current were increased to 320 amperes (4 times the normal rate), and this current flow continued for an appreciable period of time, the voltage would drop further, by about 20 volts, leaving a voltage of 208 at the battery terminals. It is, therefore, evident that the voltage requirements will be met by a 120-cell battery having a capacity of 80 amperes at the normal rate.

A battery having a normal rate of 80 amperes could be discharged at 1¼ times the normal rate for something over 4 hours. It is, therefore, seen that the battery which we selected has more than ample ampere-hour capacity to meet the requirements, its capacity being fixed by the momentary current demand.

It usually will be found that the capacity of cells required for drawbridge operation is fixed by the maximum discharge rate and not by the ampere-hour capacity at the average rate.

Size of Charging Generator.— If a separate power plant is installed for the operation of the drawbridge, it will be well to install an engine-generator set having an available voltage range of from 220 to 325 volts. There may be required 2.7 volts per cell for charge, which with 120 cells would call for 324 volts. If the battery installed is of sufficient capacity to carry the bridge a complete day or more on one discharge, it is good practice to install a generator of only sufficient capacity to charge the battery at the normal rate and to

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emergencies, the generator must have sufficient capacity to carry the maximum current required by the bridge motors.

IGNITION BATTERIES FOR PORTABLE AND STATIONARY GAS ENGINES. — Probably the largest single application of storage batteries to-day is for the starting, lighting and ignition of gasoline automobiles. There are now in service in this use storage batteries of the lead-acid type numbering approximately 15,000,000 cells with an aggregate capacity of approximately 3,000,000 kw-hr. Batteries of from three to twelve cells (6 to 24 volts) are used for this purpose, but the common standard to-day is a 6-volt (3-cell) battery with a capacity of from 80 ampere hours to 150 ampere hours. For this purpose the essential requirement is a battery of as low internal resistance as can be designed compatible with a reasonable life.

For further details in regard to automobile starting and lighting batteries the reader is referred to the various manufacturers of automobiles and starting and lighting equipment and also to the bulletins and catalogs of the various storage battery manufacturers. See also *Ignition, Electric* and *Starting and Lighting Systems for Automobiles.*

For stationary engines of large capacity it is customary to use a voltage ranging from 90 to 110 volts. Glass-jar batteries of sufficient ampere-hour capacity to meet the requirements are installed in a cabinet in the main engine room. The number of cells in the main battery necessary to float on the system will be equal to the bus voltage divided by 2.1. The capacity of the battery will depend upon the number of ampere-hours required on one charge and the minimum allowable voltage during a discharge. These requirements being known, the correct number and type of cells can be determined from the characteristics of the batteries (*see Batteries, Storage, Lead Type and Alkaline Type*), in connection with trade catalogues.

Occasionally, there is installed in addition to the cells in the main battery a group of end cells which can be cut in on discharge by means of a single switch and thus hold up the voltage of the battery. The number of cells in this end-cell group usually varies from 3 to 8, depending upon the voltage requirements.

Usually a large ignition battery is charged by placing the two halves in parallel, each half being connected to the bus through a fixed resistance somewhat after the fashion explained above and indicated in Fig. 6.

BATTERIES FOR STEADY-VOLTAGE REQUIREMENTS. — It is frequently required to obtain a source of direct current with a steady voltage, as, for instance, in electroplating, instrument calibration, telephone work, laboratory work, etc. In such cases there should be chosen a battery that has more capacity at the normal rate than the ampere hours actually required before recharging, in order that the battery may be worked on the flat portion of the discharge curve.

For instance, to furnish 10 amperes continuously for 8 hours at about 20 volts, with a variation of 1 per cent between the beginning and the end of the discharge, the time of discharge must be limited to about 50 per cent of the total time. A cell having a capacity of 10 amperes for 16 hours should, therefore, be chosen.

BIBLIOGRAPHY. — See Bibliography in article on *Batteries, Storage, Lead Type.*

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BATTERIES, STORAGE, LEAD TYPE. — (*See also Batteries, Storage, Applications of; Batteries, Storage, Alkaline Type; Electrochemistry, Principles of.*) The following is a brief outline of the contents of this article:

Types of Lead Cells ..... p. 108
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Design 109
Methods of Testing 115
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Dimensions and Weights 120
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TYPES OF LEAD CELLS. — A secondary or storage cell is any voltaic couple which can be regenerated, after exhaustion, by passing a current through it in a direction opposite to the direction of current flow when the couple delivers energy to the external circuit. Three types of storage batteries are now in use in this country, the Planté type, the Faure type, and the alkaline or Edison type. The special features of the alkaline type are treated in a separate article, viz., *Batteries, Storage, Alkaline Type.*

Planté Type. — The principle of the storage battery was discovered in 1801 by Gautherot, a Frenchman. However, practically nothing further was done until 1860 when Gaston Planté constructed a storage cell consisting of two lead strips immersed in dilute sulphuric acid. Planté found that, by giving this cell a long charge by passing the current through in one direction, and then giving the cell a long charge in the opposite direction, and repeating this cycle many times, the capacity of the cell was considerably increased. Little improvement was made in the Planté cell until a number of years after Planté's discovery.

At present the Planté type of storage battery is made by preparing a pure lead plate with a large superficial area exposed and then oxidizing the surface electrolytically so that it is covered with lead peroxide. A plate formed this is a positive plate. To form a negative plate the peroxide, after electrolytic formation, is reduced to metallic sponge lead by reversal of current. In this manner a thin layer of active material which is porous and which adheres firmly to the supporting lead plate is produced.

Use of Planté Type. — The Planté type is used chiefly where weight and space are of no great importance.

Faure or Pasted Plate. — In 1880 Camille A. Faure, in France, and Charles F. Brush, in America, simultaneously developed the "pasted" type of storage battery. In this type of storage battery the active material, on both the positive and negative plates, instead of being formed electrolytically, as was done by Planté, was applied, in the form of a paste, to a stiff lead-antimony alloy supporting grid. This type of plate is now commonly called the Faure type of plate, and it was the discovery of this type that gave the storage battery its first commercial impetus.

Use of the Faure or Pasted Plate Type. — The Faure type is used chiefly where it is desired to obtain the greatest possible capacity with a minimum of weight and space occupied. This type is used chiefly for vehicle propulsion and for central-station "stand-by service."

THEORY. — The electrochemical theories of the storage battery are quite complicated and the various authorities on these subjects do not agree on all details. In this outline no attempt will be made to cover the various theories in detail; only the simplest fundamental chemical actions will be described.

Positive and Negative Plates. — The terms positive and negative are employed throughout this article in accordance with engineering usage; that is, the positive plate is the one from which the current flows on discharge and the negative plate is the one into which current flows on discharge. In a lead battery the positive plate, on which the lead peroxide is formed, has a comparatively hard surface of a reddish-brown or chocolate color, while the negative plate, which carries the sponge lead, has a much softer surface of a grayish color.

Chemical Reactions. — The active elements of the lead-lead acid type battery consist of lead peroxide (PbO_2) on the positive plate, sponge lead (Pb) on the negative plate and dilute sulphuric acid (H_2SO_4) for the electrolyte. Whatever the secondary reactions may be, it is agreed that the final result of discharge is the formation of lead sulphate ($PbSO_4$) on both the positive and negative plates, the SO_4 radical of the sulphuric acid combining with the lead of both plates to form this compound, resulting in the formation of some water (H_2O), with a consequent decrease in the specific gravity of the electrolyte. On charge the electric current splits up the lead sulphate ($PbSO_4$), returning the SO_4 radical to the electrolyte, oxidizes the positive plate to its original condition of lead peroxide (PbO_2) and reduces the negative plate to its original condition of sponge lead (Pb). This action may be represented as follows:

$$\underset{+\text{Plate}}{PbO_2} + 2H_2SO_4 + \underset{-\text{Plate}}{Pb} = \underset{+\text{Plate}}{PbSO_4} + 2H_2O + \underset{-\text{Plate}}{PbSO_4}$$

If this equation read from left to right is the equation of discharge; if read from right to left, it is the equation of charge. In practice, on charge, towards the end of charge some of the water (H_2O) is split up by the current into its component parts, hydrogen (H) and oxygen (O), the hydrogen being liberated at the negative plate and the oxygen at the positive plate. This occurs whenever the intensity of charging current is greater than can be utilized in decomposing the lead sulphate remaining in the plates.

DESIGN. — The capacity of a storage-battery plate depends not only upon the amount of active material but also upon the active surface exposed to the electrolyte. Plates should therefore be designed to expose a maximum amount of surface consistent with the strength of the supporting grid or lead base. In order that the active material of the plates can be acted upon by the electrolyte, it should be as porous as is consistent with its proper support by, and proper contact with, the grid or supporting lead base.

Sponge lead and lead peroxide possess little mechanical strength. Lead peroxide is a poor conductor. Since mechanical conditions require a certain amount of rigidity in the plates and since the current generated by the active materials must be carried away, a battery plate must necessarily consist of two parts, viz., the grid or supporting base and the active material which in the lead battery is finely-divided porous sponge lead or porous lead peroxide.

Lead Plates. — There are certain ideal requirements to be met by a lead storage-battery plate, among which may be mentioned:

1. The grid and active material should be so proportioned as to obtain, as near as possible, uniform current distribution over the entire surface.
2. The active material should be applied to, or formed on, the grid in such a manner that good electrical contact exists when the plate is new and this contact should be maintained during the life of the plate.
3. In pasted plates and pellet plates the grid should be of material that is not injuriously affected by the electrolyte.

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4. The material of the grid should be such as to insure a minimum of loc action between itself and the active material.

5. The surface of the active material exposed to the action of the electroly should be as great as is compatible with proper mechanical strength and suitable provision for the natural expansion of the active material in use.

6. The plates should be so made and assembled as to allow the maximum pos sible diffusion of the electrolyte through and around the plates and through th containing vessel.

7. The grid or lead base should be of ample cross section to carry the curre generated under working conditions without undue loss.

8. The lugs which collect the current from the grids should be of ample cro section, and when designed for heavy currents they should be so arranged as t distribute the current uniformly through the grid.

9. The negative, sponge-lead plate should be constructed so that the spong lead retains its porous character and does not grow hard and dense in servic and thus lose its capacity.

10. The lead and the electrolyte should be pure; otherwise secondary reaction will be set up, with a consequent decrease in efficiency.

Of the many lead plates on the market to-day, the most commonly used are the "pasted," Planté and composite or "pellet" plates. Cuts showing the construction of the various types of plates may be found in manufacturers' catalogues; the essential features of design are briefly discussed below.

Pasted Plates. — The pasted plate is usually made by applying to a hard lead-antimony grid a paste made of some oxide of lead, usually litharge (PbO) or red lead (Pb_3O_4), and some liquid and other substances. In the so-called "Iron-clad" battery made by the Electric Storage Battery Co., the active material is held in perforated hard rubber tubes. Various substances are used to mix with the lead oxide, the idea being to increase the hardness, porosity, toughness and conductivity. Some of the substances used by different manufacturers include anthrocine, glycerine, graphite, potassium silicate, asbestos, ammonium-sulphate, etc.

"Forming" of Pasted Plates. — After the grid is filled with the paste the plate is dried. After being completely dried a number of plates are assembled in a forming bath of dilute sulphuric acid with dummy lead plates for the opposite electrode and the forming charge is given by passing the proper current through the voltaic couple thus formed. Positive plates are formed by connecting the plates to be formed as the anode; the current oxidizes the lead oxide further to lead peroxide (PbO_2). Negative plates are formed by passing the current in the opposite direction, reducing the lead oxide to sponge lead. After the forming charge the plates are dried and are ready for the market.

Planté Plates. — Of the various types of Planté plates, among those most commonly in use may be mentioned the central-web type; the cast-lead having no central web; and the composite or "pellet" type. The main idea in any of these methods of manufacture is to produce a large surface on which to form the active material.

Central-web Type. — In the central-web type there is a solid sheet or "web" of pure lead on which the ribs are formed. This web prevents the circulation of the electrolyte through the plate. The ribs are formed from the original lead plate, either by rolling, spinning or cutting. In the rolling and spinning processes the plate is formed from a lead blank by means of a number of steel disks placed side by side and separated by small spacers on a shaft. The lead blank is passed between two sets of disks by forward and backward movements. The disks gradually work deeper into the plate and squeeze it

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lead into the spaces between the adjacent steel disks. In the cut type of plate the ribs are formed from the lead sheet by a tool, which at each stroke turns up one complete rib. The cutting edge works at an angle so that the finished ribs stand out from the surface. The ribs may incline upward from the central web and thus form pockets to hold the active material and prevent its falling away.

The disadvantage of the *web* type is the web itself. There is invariably a tendency towards unequal work on the two sides of the positive plate, this tendency being caused by difference in the plate spacing, unequal capacity of the negative plate on either side, inequality in the shape of the ribs, etc. Where the active material and the active surface of a plate are disposed in planes perpendicular to the face of the plate and extend *through* the plate, excessive action on one side simply works the plate a little further through from that side, the effect on the active material, however, being uniform throughout. With a plate provided with a central web, preventing such action, any inequality of work will charge or discharge one side more than the other, producing a tendency to buckle.

Cast-lead Type. — The type of plate which has no central web is made by casting pure soft lead in a mold, casting having the advantage of allowing for distributing metal in the plate without limitations in manufacturing process. The plate as it comes from the mold consists of a great number of short vertical ribs running entirely through the plate and bound together by transverse ribs to give strength to the plate. In this manner a large surface may be obtained and in a plate having no central web the electrolyte can circulate through the plate, and the active material will be uniformly worked throughout even though the amount of work on the two sides of the plate be unequal. The best-known form of this plate is the "Tudor" positive.

Composite or "Pellet" Type. — The composite or pellet-type plate is made by rolling up into pellets pure soft-lead corrugated ribbons. These pellets or buttons are then forced by pressure into circular openings in a grid composed of a hard-lead-antimony alloy. The openings in the grid are beveled towards the center so that when the pellets are formed the swelling action causes them to rivet tightly into place. The corrugations on the lead ribbon allow the electrolyte to circulate through the plate and thus expose the full surface of the closed lead spiral to the action of the electrolyte. It will be noted that in this type of plate additional mechanical strength is obtained from the supporting grid. The best-known form of this plate is the "Manchester" positive.

"Forming" of Planté Plates. — In all Planté positives, after the ribs or corrugations have been formed on the lead blank or the pellets have been placed in the hard grid, the plates are assembled in a sulphuric-acid bath containing some corrosive chemical, called a "forming agent," together with dummy lead plates. The forming agents used by various manufacturers are usually kept as trade secrets; the nature and method of using such agents determines largely the quality of the battery. To form the positive plates the dummies are connected as the cathodes, and a current is passed through the couple thus formed. The electrolytic action of this current causes lead peroxide (PbO_2) to be formed from the lead of the ribs. The strength and duration of the current produce the desired thickness of lead peroxide on the ribs or pellets.

Negative Planté plates are made from positive plates by electrolytically reducing the lead peroxide to sponge lead. In most types of Planté negatives, however, it is necessary to form them with an initial capacity considerably in excess of the capacity of the positive plate. This is due to the fact that in actual service the sponge lead shrinks and loses its spongy nature, thereby reducing its capacity, since insufficient surface is exposed to the action of the electrolyte.

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"Permanizing" Process. — One of the large manufacturers of storage batteries has recently developed a process for making the Planté negative plate permanent. This method consists of injecting into the sponge lead a material which prevents the shrinking of the sponge lead and thus enables it to maintain its spongy character and its initial capacity. This permanizing process can be applied to the pasted negative plate as well as to the Planté negative plate. The most widely used form of the permanized negative plate is one in which the sponge lead, formed by reducing lead oxide electrolytically, is retained in boxes made by casting a soft-lead perforated sheet on a hard lead-antimony grid. This negative is known as the "Box negative."

Applications of the Various Types of Plates. — In stationary work requiring frequent discharges, where expert attention is available at all times and where the conditions of operation are properly suited to its use, the Planté lead Planté type of plate with through-and-through circulation is the plate that should be used. Where the battery is to receive little attention and where the conditions of service are variable and uncertain, the composite or "pellet" type of plate is the safest plate to use, on account of its rugged structure and its ability to stand great abuse. As stated above, for stand-by service and for vehicle service and other service where high capacity with a minimum weight and space is desired, the pasted type of plate is more desirable.

Electrolyte. — The electrolyte used with the lead type of battery is always a dilute solution of sulphuric acid. The specific gravity of the electrolyte, when the battery is fully charged, varies from about 1.210 for stationary batteries to 1.300 for automobile ignition batteries. These values have been adopted as standard by all the leading manufacturers.

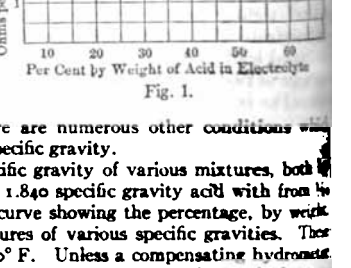


Fig. 1.

The proper specific gravity to use varies with the conditions. Fig. 1, showing the variation with specific gravity of the resistance of one cubic centimeter of electrolyte, shows that the resistance of dilute sulphuric acid is least at a specific gravity of from 1.224 to 1.240, this resistance increasing if the specific gravity be either increased or decreased. There are numerous other conditions which influence the selection of the proper specific gravity.

The curves in Fig. 2 show the specific gravity of various mixtures, both by weight and by volume, of one part of 1.840 specific gravity acid with from ½ to 7 parts of water. There is also a curve showing the percentage, by weight, of 1.840 specific gravity acid in mixtures of various specific gravities. These curves are approximately correct at 60° F. Unless a compensating hydrometer is used in determining the specific gravity, allowance must be made for temperature variation, on the basis of an increase of one point (i.e., one one-thousandth) in gravity for each 3 degrees Fahrenheit *decrease* in temperature, and vice versa; for instance, electrolyte that has a specific gravity of 1.210 at 70° F. will have a specific gravity of 1.213 at 61° F., and 1.207 at 79° F.

Impurities in Electrolyte. — The electrolyte should be free from organic substances, iron, chlorine, copper, arsenic, mercury, nitrates, acetates and the slightest possible trace of platinum. The various battery manufacturers issue exact specifications to the acid manufacturers, specifying the maximum amount of these injurious ingredients which the acid may contain. Electrolyte that is not approved by the company furnishing the battery should never be used.

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Preparation of Electrolyte. — In preparing the electrolyte, sulphuric acid, approved by the battery manufacturer, should be diluted with sufficient pure distilled water to bring the mixture to the required specific gravity. The acid should be poured into the water; *never pour the water into the acid.* If the water is poured into the acid, the heat formed by the mixture is sufficient to cause sputtering and damage may ensue.

The sulphuric-acid manufacturing companies furnish electrolyte for battery work in such large quantities that they carry a stock of various standard mixtures. It will usually be found cheaper and more convenient to purchase the electrolyte ready-mixed than to purchase the concentrated sulphuric acid and prepare the mixture on the ground. The latter course, however, is sometimes adopted where the amount of acid used is considerable and where the item of freight saving is appreciable.

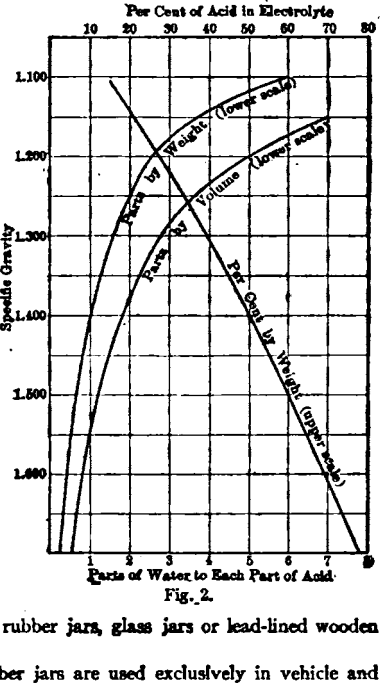


Fig. 2.

Containers for Lead Batteries. — The containing receptacles for holding the battery plates and electrolyte are usually rubber jars, glass jars or lead-lined wooden tanks.

Rubber Jars. — Hard-rubber jars are used exclusively in vehicle and portable batteries. In these batteries the plates are supported on ribs at the bottom of the jars. To reduce cleaning to a minimum, these ribs should be of sufficient height to leave ample space in the bottom of the jar for the reception of the active material which falls away from the plate. If the sediment in the bottom of the jars is allowed to reach the plates and short-circuit them, serious damage will result. The jars themselves should be made of the very best hard rubber which is not affected by sulphuric acid.

Glass Jars are ideal containers for small batteries when they are properly installed. The glass jar has the advantage that the plates and electrolyte can always be seen. The use of the glass jars is limited to the smaller sizes on account of their liability to break, due to strains left in the glass after annealing, temporary strains set up by unequal temperatures between the inside and outside of the jars, and to strains due to weight of the plates and electrolyte. Glass-jar manufacturers have, up to the present time, been unable to produce a thoroughly reliable jar larger than 21 by 13 by 18 inches.

Lead-lined Tanks. — In the larger sizes of batteries lead-lined tanks are standard. Tanks are generally made from specially selected yellow pine, dovetailed together without the use of nails or other metallic fastenings. The upper edges should be slightly beveled inward so that the moisture will drain into the tank. The bottoms under the linings should be drained and venti-

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lated; these bottoms are usually constructed of slats across the tanks, separated by a small spacing to provide drainage. To further facilitate drainage under the lining, the upper surface of these slats should be grooved crosswise. Before the tanks are lined they should be coated inside and outside with two coats of acid-resisting paint, and a third coat should be added outside during installation. The tanks should be lined with lead of 3 to 4 pounds per square foot, depending on their size. The lining should extend over the upper edge of the tank and a short distance down the sides. The outer edge of the lining should be provided with drip points projecting clear of the tank, so that any drip from the lining will clear the wood of the tank and the tank supports. Especial attention should be paid to the seaming of the linings. All seams should be burned with the hydrogen flame with pure lead, without the use of any flux. The lower corners of the lining should be reënforced by puddling with lead. The upper corner should be reënforced by burning on an additional thickness of sheet lead. Each tank should be so built that it is self-supporting without the use of any braces or reënforcements. If this is done, any tank in the battery can be removed and replaced without affecting the remaining tanks in any way. A poorly constructed wood tank is bound to cause trouble. Special attention should be paid to this detail in preparing specifications.

Covers. — While covers are not absolutely necessary for stationary batteries, it is considered good practice to cover all cells. Covers should preferably be made of glass of sufficient weight to prevent excessive breakage in handling. Covers will more than pay for themselves in reducing evaporation and keeping out dirt. They are absolutely necessary in situations, such as steel mills, where the air is liable to contain particles of foreign matter injurious to the battery.

Support of Plates in Container. — As stated above, in the portable and vehicle types of batteries, the plates are supported on ribs at the bottom of the jar.

In stationary types, using glass jars or lead-lined tanks, it is preferable to support the elements from the top. In glass jars, plates are supported on the top edges of the jars by means of lugs cast or burned on to the plates. In lead-lined tanks it is, of course, necessary to insulate the plates from the lead lining. The plates are, therefore, supported in the tanks by vertical sheets of glass resting on the bottoms of the tanks. The bottom of the tank lining, under the glass sheets, should be heavily reënforced. These glass sheets should be ground top and bottom and the lower corners should be cut off at an angle of about 45°, to avoid injury to the lead lining during installation by sharp corners.

Separation and Separators. — Since the positive and negative groups, forming the complete element in a cell, are assembled with positive and negative plates alternating, it is necessary that some means be provided to prevent contact between adjacent positive and negative plates. Such contact would mean a short-circuit and might result in injury to the element. Various forms of separators have been used for keeping the plates apart. The most common practice to-day, and the one considered the best for stationary work, is to use wooden diaphragms. Each wooden diaphragm should consist of a thin sheet of porous wood mounted in slotted dowels which will allow free passage of the electrolyte between the plates. The wood should be specially treated to insure the absence of elements which in conjunction with the electrolyte might form acids injurious to the plates.

In vehicle batteries rubber separators are generally used in addition to the wood separator. That is, a rubber separator is placed on each side of each positive plate and one wood separator between each positive plate and the adjacent negative plate. In the so-called "iron-clad" battery, made by the

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Electric Storage Battery Co., the active material of the positive plate is contained in rubber tubes, and therefore additional rubber separators are not necessary. Ignition batteries use wood separators only. Portable batteries use rubber only. Car-lighting batteries use wood only or rubber only. Yacht-lighting batteries use rubber only.

Sediment Space. — In all types of batteries, no matter what container is used, there should be a certain amount of free space between the bottoms of plates and the bottoms of jars. This space is designed to receive the sediment or active material which falls away from the plates. The amount of sediment space required will depend upon the service, and no fixed rule can be given to cover this point. If not prohibitive from space or expense limitations it would be well to have this sediment space great enough to take all of the active material which will be shed from the plates during their useful life.

Assembly of Parts. — All portable, automobile, car-lighting and other batteries that will be subject to jar or vibration should be assembled in the containing vessel in such a manner that the plates cannot move. They should be packed in as tightly as is possible with due consideration to the amount of electrolyte necessary and the avoidance of injury to the plates when being put into or taken out of the jars. Hard-rubber covers should be used and these covers should be so sealed as to avoid any splashing of the electrolyte. The crates containing the jars should be constructed, as far as possible, without the use of metallic fasteners and they should be thoroughly painted with acid-resisting paint. In portable batteries that will receive rough handling, if several jars are assembled in a single crate, they should be imbedded thoroughly in an acid-proof elastic compound.

Cells assembled in crates should be connected by burning together the adjacent positive and negative terminals. Cell connections should never be soldered. The main terminals of the series in one crate should be brought out and fastened in such a manner that these terminals will not be attacked by the acid.

The methods of assembling and connecting stationary types of cells are described below in the section on *Installation*.

METHODS OF TESTING. — The tests described below are intended to cover only those tests that are of interest in the commercial operation of batteries.

Test of Specific Gravity. — The specific gravity of the electrolyte is the most accurate guide as to the state of charge of a lead-type storage battery. Specific instructions furnished by the manufacturer of the battery are given, showing the range in specific gravity over a given amount of charge and discharge and the operator should be guided by the instructions of the manufacturer. The test of the specific gravity is made by means of a hydrometer having a suitable scale for the type of cell to be tested. In stationary types of batteries the hydrometer has a scale reading of 1150 to 1250 and is left floating in one cell. In all portable types of batteries, and ordinarily in vehicle- and car-lighting batteries, it is usually necessary to draw some of the electrolyte from the cell in order to test its specific gravity with the hydrometer, which should have a scale reading of 1150 to 1300. Hydrometer syringes, with hydrometer contained in a glass barrel, can be obtained on the market for this purpose. There is also on the market a regular acid-testing set consisting of a syringe for withdrawing the acid and a test tube into which the acid is poured from the syringe, in order that the hydrometer may be floated for reading.

Test for Impurities in Electrolyte. — The proper testing of electrolyte for impurities requires not only some knowledge of chemistry, but also experience in such work, in order to correctly interpret results; it is therefore inadvisable

for the ordinary user to attempt it. Furthermore, it is usually entirely unnecessary that he should, since the leading battery manufacturers make analyses for their customers free of charge. The harmful impurities most likely to be present are iron, hydrochloric acid, oxides of nitrogen, sulphurous acid, arsenic, organic matter and platinum. In order to insure freedom from the latter, it is advisable to specify acid which has not been concentrated in platinum.

Test of Internal Resistance. — The most accurate method of determining the internal resistance of a cell is to subject it to a discharge current of a certain amount, and after the voltage has become sufficiently constant to permit accurate reading with the discharge current flowing, the current is instantly interrupted and the rise of voltage noted. This rise of voltage divided by the current will give the internal resistance. If this test is made on a battery of more than one cell in series the result shows the internal resistance of the entire battery, including the cell connections.

Test of Capacity. — The capacity of a storage cell depends on various conditions, such as the temperature, the rate of discharge, the strength of the electrolyte, the character of service to which it has previously been subjected, and the attention it has received. The "normal capacity" of a storage cell is usually expressed in ampere hours at the 8-hour rate at 70° F., down to a certain definite voltage per cell. For instance, when it is said that a cell has a capacity of 100 ampere hours, it is *usually* meant that this cell can be discharged at a rate of 12½ amperes continuously for 8 hours at 70° F., down to the limiting voltage specified by the battery manufacturer. In lead cells this limiting voltage is usually taken at 1.75 volts per cell. The "watt-hour" capacity of a battery is equal to the ampere-hour capacity multiplied by the average voltage during discharge.

The "available" ampere-hour and watt-hour capacity of a battery varies with the rate of discharge, the available capacity decreasing with increase of rate. The higher the rate of discharge the lower the limiting voltage at end of discharge. Therefore, to test the capacity at any given rate of discharge, the limiting voltage at that rate as specified by the manufacturer should be known.

Bearing in mind the above facts, to test the capacity of a storage battery at any given rate, the battery should be first charged at the normal rate, as specified by the manufacturer, until the voltage and gravity in all of the cells will rise no further and until all cells gas freely at both the positive and negative plates. The capacity of the battery, as a whole, will be limited by the capacity of the lowest cell and all cells should be as nearly as possible in a condition of full charge before the discharge is started to test the capacity of the battery. Individual cell readings should be taken of the voltage and gravity while the charging current is flowing.

When it is certain that the battery is fully charged, discharge the battery at a constant current at the desired rate, down to the limiting voltage at this rate. The ampere-hour capacity will be equal to the constant current in amperes, multiplied by the time of the discharge in hours; and the watt-hour capacity of the battery will be the ampere-hour capacity multiplied by the average voltage during discharge.

In order to be sure that the battery is in good condition it is well to take several complete discharges before making the final charge, preceding the final test discharge.

On each charge and discharge observations should be taken of the voltage, the current, the temperature and the specific gravity. The temperature of the room should be held as nearly constant as possible throughout the test. In order to facilitate the plotting of curves, the readings should be taken at intervals of time which are even factors of an hour.

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dmium Test. — When a strip of cadmium is placed across the top of the s in a cell, and properly insulated from them, there will be a difference in ıtial, as measured by a voltmeter, between the cadmium and the positive s and between the cadmium and the negative plates; the sum or difference ending on the relative directions of the two potential differences) between two readings being equal to the internal voltage of the cell.

ch a test, when properly interpreted, is a valuable guide to the capacity condition of the positive and negative plates separately. The results are, ver, very apt to be misleading to one who has not had a wide experience orage-battery work. See *Tech. Paper* No. 146, Bureau of Standards.

ıst of Efficiency. — The ampere-hour efficiency of a battery is the ratio ıe output on discharge in ampere-hours to the input on charge in ampere-s; the watt-hour efficiency of a battery is the ratio of the output on dis-ge in watt-hours to the input on charge in watt-hours.

ıe efficiency of a battery depends upon numerous conditions, chief among h are the charge and discharge rates and the temperature.

has been noted above that the *available* capacity of a battery depends upon lischarge rate. For instance, if a battery is discharged at the one-hour rate ıe allowable final voltage limit, the energy taken out at this rate is approxi-ly only fifty per cent of the energy that could be taken out at the normal . However, if, at the end of one hour's discharge at the one-hour rate, the of discharge be reduced to the normal rate, much of the available *normal* acity of the battery can be obtained.

t is thus seen that any statement of the true efficiency of a battery should ude the charge and discharge rates. It is also seen that in order to make a efficiency test an average of several charges and discharges should be taken, the battery should be given several discharges and charges before the actual is begun. Failure to observe these conditions may result in figures that misleading. The writer has seen test figures showing an efficiency of more ı one hundred per cent; he has also seen figures showing efficiencies far below actual efficiency.

o determine the efficiency of the battery, get all the cells in satisfactory dition by preliminary charge and discharge, as outlined above under the acity test, and then take a preliminary discharge down to the final voltage ified by the manufacturer for this rate of discharge. The first test charge uld then be made at the normal rate until the cells are fully charged. The test discharge should then be taken at the specified rate down to the same l voltage used in the preliminary discharge. The watt-hour efficiency of battery will then be the ratio of the total watt-hours discharged to the l watt-hours charged. If greater accuracy is desired, this cycle should be eated several times (say, from four to six times) and the watt-hour efficiency l then be the ratio of the total watt-hours of all the discharges to the total t-hours of all the charges.

RATING AND PERFORMANCE. — The capacity of a storage-battery te of a given size varies somewhat with the conditions, chief among which the specific gravity of electrolyte, the temperature of electrolyte, the ount of electrolyte, the original formation of the plate, the design of the d, the age of the plate, the length of time between charge and discharge l the final voltage limit specified.

Rating of Stationary Batteries. — The rate of discharge of a storage battery he number of amperes that it will supply continuously for 8 hours, for 3 hours for 1 hour. The 8-hour rate is the so-called "normal" rating, the 3-hour rate approximately twice the normal rating and the 1-hour rate is approximately times the normal rating. The *capacity* of a storage battery is usually

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stated in ampere hours. Since the capacity varies with the rate of discharg it is necessary to specify the rate of discharge in stating the capacity ampere-hours. If the rate is not specified, the normal rate is assumed.

Certain plates especially designed for high rates of discharge are rated terms of the amperes they will supply for 6 hours, this rating being designat as "normal." The corresponding 1-hour rate is 4 times this 6-hour rate.

While the above is standard for ordinary batteries, plates for certain class of service are designed to give the normal rate for from 7 to 7½ hours.

The capacity of a storage battery is sometimes expressed in kilowatts, b this is ambiguous unless the rate of discharge is specified.

Rating of Vehicle and Ignition Batteries. — It is standard practice rate a vehicle battery in terms of the amperes it will give continuously for 4½ or 5 hours, specifying the battery to have a capacity of so many amper hours at one of these rates. In most portable types of ignition batteries t batteries are rated at so many ampere-hours at the "service rate," i.e., the ra of discharge (amperes) corresponding to the service for which they are designe

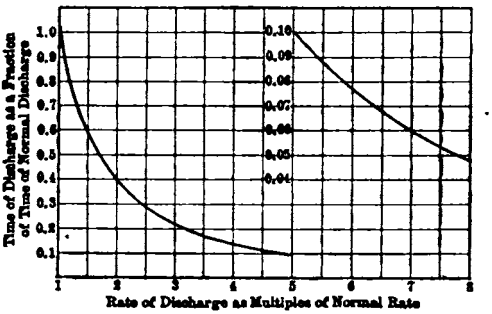


Fig. 3.

Variation of Rate of Discharge with Time of Discharge. — Fig. 3 show an average capacity curve for a Planté plate, the time for a complete di charge at any rate being shown as a fractional part of the normal time and t rate of discharge for any given time being shown as a multiple of the normal rat

From these curves it will be noted that a cell which will give its normal ra for 8 hours will give 4 times that rate for about 1⅛ hours; and a cell whic will give 4 times the normal rate for 1 hour will give the normal rate for onl 7 hours. These are approximately correct relations for the average Plant cell. Trade catalogues usually specify the normal rate for 8 hours and times the normal rate for 1 hour. This is due to the fact that a cell which regularly worked at the normal rate will tend to hold its 8-hour capacit while a cell which is regularly worked at 4 times the normal rate will tend t lose some of its 8-hour capacity and finally give only 1 hour at 4 times th normal rate.

Variation of Capacity with Rate of Discharge. — It will be note from the capacity curves that the available capacity in ampere-hours decreas with increase of rate of discharge. This is largely due to the time required f fresh electrolyte to penetrate into the pores of the active material of the plat At the higher rates of discharge the diffusion of electrolyte is not sufficient

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he battery, the battery be allowed to rest or the rate of discharge be de-ed, additional capacity can be obtained from the battery.

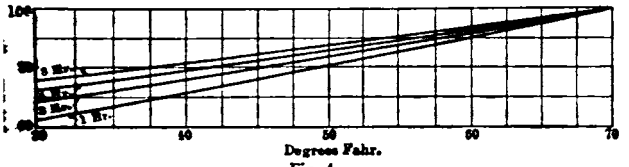


Fig. 4.

Variation of Capacity with Temperature. — Fig. 4 shows the varia-n of capacity with temperature at various rates of discharge. This change apacity is temporary and the capacity will be restored to its original value en the temperature is restored to its original value.

Voltage and Specific-gravity Characteristics. — The charge and discharge tage characteristics of a battery vary with the conditions. Fig. 5 shows sical average voltage and spe-c-gravity charging characteris-s of a Planté type of cell de-gned for stationary service. It ill be noted that the specific grav-r increases gradually until all of e lead sulphate in the plates has en reduced, the (SO_4) radical ing returned to the electrolyte form sulphuric acid, which ac-unts for the steady increase in cific gravity and for the fact at the specific gravity will rise further after the battery is mpletely charged.

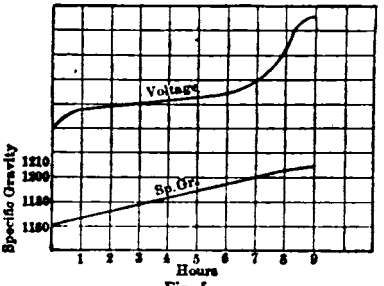


Fig. 5.

Final Charging Voltage (Fig. 5). — The scale of volts on the upper rve has been purposely omitted, t this curve shows the general ape of charging curve for any pe of lead battery. The final arging voltage of any lead type battery varies over a consider-le range, according to the type cell, age of plates, temperature electrolyte, strength of electro-te, etc. The final charging vol-ge may vary anywhere from 4 to 2.8 volts per cell. It will e noted that the voltage rises pidly at the beginning and at e end of charge.

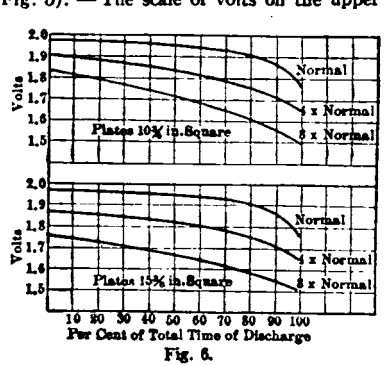


Fig. 6.

Discharge Voltage. — Fig. shows discharge curves at the rmal, four times the normal and eight times the normal rates, respectively, for wo different sizes of Planté plates The upper set of curves are for plates 10¾ nches square and the lower set of curves are for plates 15¾ inches square.

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These curves, used in conjunction with the capacity curves shown in Fig. 3, will enable anyone to determine the approximate performance of any lead battery when the capacity at any given rate is known.

The voltage readings at the very beginning of the discharge are liable to vary more or less from those shown on the curves depending upon the length of time the cell has been allowed to stand on open circuit after the completion of the charge.

Open-circuit Voltage. — The open-circuit voltage of a lead cell is of no value as an indication of its state of charge. A healthy cell will regain its full voltage on open circuit, even though fully discharged, if sufficient time is allowed for depolarization.

Internal Resistance. — The true internal resistance of a cell may be determined by the method explained above in the paragraph on *Test of Internal Resistance*. This internal resistance determines the *immediate* change of voltage at the cell terminals with any sudden change of discharge rate. In the ordinary commercial types of lead cells at 70° F. the internal resistance is such as to cause an immediate drop in terminal voltage of between 5 per cent and 7 per cent, with a sudden increase of current equal to four times the normal rate of discharge, the drop being proportional to the change in current. If this change in current is not strictly momentary, the change in terminal voltage will be greater, due to the effect of polarization. The internal resistance of a cell increases with reduction of temperature; at 0 °F. the internal resistance is twice as great as at 70° F.

DIMENSIONS AND WEIGHTS. — In determining the dimensions and weights of a storage battery to meet the requirements, it is suggested that the proper type of battery be determined in accordance with the curves and examples given above and a battery be selected from trade catalogues to meet the specifications. When the battery has been thus chosen, the dimensions and weights of individual cells can be obtained from the trade catalogues. In order to determine the total installed dimensions and weights, it will be necessary to make a layout according to standard practice. The distances between adjacent cells and the dimensions of aisles are given below in the section on *Installation*.

SPECIFICATIONS, CONTRACTS AND PROPOSALS. — (*See also article on Specifications.*) In preparing specifications for a storage-battery plant and accessories, special care should be taken to avoid drawing up specifications in such a manner as needlessly to embarrass the manufacturers who are requested to bid.

Preliminary Specifications. — It is recommended that preliminary specifications of a very general nature be prepared. These specifications should contain complete detailed data of the conditions to be met, so that the manufacturers who are requested to bid can readily determine the number and capacity of cells, the proper scheme of operation, the correct design of booster, switchboard and other accessories recommended by them to meet the requirements in hand. That is, the preliminary specifications should state plainly just what the battery is intended to accomplish. These preliminary specifications should be sent to the manufacturer with a request for a complete proposal.

Manufacturer's Proposal. — This proposal should give detail specifications covering the apparatus recommended by the manufacturer. In order to obtain the best results, it is recommended that after these proposals are received, the prospective purchaser confer with the bidders that are to be considered, and that complete final specifications be prepared, covering all details of the necessary equipment. These final specifications can then be sent to the manufacturers for their final bids.

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nal Specifications. — As a guide in preparing the final specifications the ts enumerated below should be thoroughly covered:

aber of cells;
aber of plates in elements initially installed;
of plates;
acity of the elements initially installed;
rging rate of the elements initially installed;
: of the containing vessels expressed in the number of plates which the vessel can contain;
arators and supports;
ctrolyte;
ulation;
embling and lead burning;
bars, both plain and reënforced;
d-cell switches;
copper work and cables;
itchboard in detail;
Detailed specifications for booster and exciter apparatus according to the A.I.E.E. Standardization Rules.
Foundation for booster and switchboard;
Testing instruments;
Battery room;
Erection;
Skilled and unskilled labor;
First charge;
Operation;
Test;
Freight, cartage;
Delivery;
General scheme of operation;
Temporary work;
Cutting of walls, etc.;
Access, storage and hoisting;
Acceptance.

If specifications are drawn, covering all of these points clearly and if the ecifications are attached to, and form part of, the contract, no trouble should se in the future from misunderstandings.

Contract. — The contract should cover the price, time of payments, guarantee, tection from patent litigation and insurance of the material during conuction.

INSTALLATION AND ERECTION. — *Never install any battery without lowing explicitly the detailed instructions furnished by the manufacturer who de the battery.*

If the battery is of considerable capacity, detail drawings showing the method installation should be obtained from the battery manufacturer. The leading nufacturers issue printed instructions and detail drawings describing the thod of installation. Much time and money can be saved by obtaining these ta from the battery manufacturers.

Spacing of Glass Jars. — The spacing between cells along rows varies from ½ inches with the smaller types of multiple plate-glass cell batteries to 3½ ches for the largest size multiple plate-glass cell batteries. This space is the ace from jar to jar. It is standard practice to place the jars on wood or glass nd trays filled with sand; the distance between the sand trays along the rows ries from ½ inch to 2⅛ inches, depending upon the size of the glass jars. As e outside dimensions of the sand trays are not usually given in trade catames, it would be well in figuring the length of the rows to use the spacing tween glass jars as given above, for the outside dimensions of the glass jars e usually stated.

With glass-jar batteries the aisle space between the rows should never be s than 24 inches, and aisles of 36 inches are recommended. In the case of uble rows or where a row is installed near a wall or partition, the distance tween rows, or the distance between a row and the wall, should not be less an 6 inches.

All batteries should be installed in one tier, if space is available, though glass-r batteries (and occasionally lead-lined wood-tank batteries) can be installed

in two or three tiers, if more space is not available. In installing batteries i more than one tier, sufficient headroom should be allowed in each tier to perm the removal of the elements from the jars without displacing the jars. Th minimum headroom for a single-tier glass-jar battery varies from 4½ feet t 5 feet; for two tiers from 5 feet to 7½ feet and for three tiers from 7 feet to 1 feet, depending upon the size of the battery. In all cases the ceiling of th battery room should be of sufficient height to allow for the passage of a ma without stooping.

Spacing of Lead-lined Tanks. — Lead-lined tank batteries should alway be installed in one tier, if space is available. More than one tier should not b installed without consulting with the battery manufacturer. With lead-lin tanks the distance between tanks along rows is from 2 to 2¼ inches. Th aisle space between rows should never be less than 30 inches and should alway be sufficient to allow the tank to be pulled out into the aisle for repairs. Whe space will not allow the tank to be pulled out its full length the aisle shou have at least sufficient width to allow the tank to be stood on end in the aisl In double rows or in rows next to the wall, at least 18 inches should be allow between rows or between the tanks and the walls so that a man can get in t examination. The battery room should have sufficient headroom for a ma to walk upright. With large-sized batteries where the amount of gases libe ated on overcharge is considerable, sufficient headroom should be allowed f proper ventilation.

Dimensions of Containers. — For any given type of plate, either in gl jars or lead-lined wood tanks, there is one dimension for all jars or tanks whi is practically constant, independent of the number of plates in the cell. This the dimension parallel to the horizontal edge of the plates. This dimensi is usually specified in trade catalogues as the "width." The other dimensi is the dimension across the row and is usually specified in trade catalogues the "length."

Dimensions of Battery Room. — Keeping in mind these definitions o can determine from trade catalogues the approximate inside dimensions of battery room necessary to house the battery in question. Note, however, th any manufacturer will gladly furnish a sketch showing an ideal layout for given battery and such a layout should always be obtained from the manufa turer, if there is sufficient time. If there is available space in a buildi already built, the battery manufacturer will gladly prepare a sketch showi the layout of any given battery in the available space.

Insulation of Cells. — Cells in stationary batteries, whether in glass j or in wood tanks, must be insulated from the ground and from each other.

Glass jars are usually mounted in glass or wooden sand trays which rest glass insulators. The glass insulators, in turn, rest on wooden racks or stringer these racks or stringers being mounted on vitrified brick set on the batte room floor.

For lead-lined wood-tank cells the standard practice at present is to mou each tank on a sufficient number of oil insulators. These insulators consi of a glass insulator provided with a circular trough partly filled with oil. th oil surrounding a central section which supports the tank. Over the insulat is placed a lead-alloy cap, designed to exclude spray or other foreign matt from the oil. This cap rests on the central section of the glass insulator, the being no connection between the tank and the glass except at this section. Th oil around this central section of glass is for the purpose of preventing a fil of acid from collecting thereon; if, by any chance, acid or water should g into the trough, it would sink to the bottom, the oil would float on top, a perfect insulation would be maintained.

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The glass insulator rests upon a heavy earthenware truncated cone, having ee feet. Between this cone and the glass is a Y-shaped lead washer. Thus ee-point support is obtained between the floor and the earthenware, and ween the earthenware and the glass. This form of support is not necessary ween the glass and the tank, because the wood and lead cap take up any face inequalities.

Connections between Cells. — In glass-jar batteries of small size, elements adjacent cells are usually bolted together. In the larger-sized glass-jar tteries and in all lead-lined wood-tank batteries the positive plates in one cell burned to the negative plates in the adjacent cell through the medium of ead bus bar. The bus bars at the ends of rows, and wherever current taps made, are reënforced by a bar of copper embedded in the lead.

Battery-room Design. — Though no battery should be installed without ecific instructions from the manufacturer, the following points should receive cial attention.

Floor. — The floor of the battery room should be made acidproof and uld be graded to drain. A wood floor should never be used, as it is bound become acid soaked and eventually be destroyed. For small batteries a ent floor can be used, but, unless it is kept thoroughly washed, acid will t holes in it. A glazed tile floor is preferable.

Ventilation. — All battery rooms should be well ventilated. With small tteries natural ventilation is usually sufficient; with large-capacity batteries, here the gassing during overcharge is considerable, artificial ventilation should provided. Exhaust ventilation is preferable to compression ventilation.

Temperature. — The temperature of the battery room should be kept near 70° F. as possible.

Exposed Metal. — The amount of exposed iron or metal work in the ttery room should be reduced to a minimum on account of the action of acid mes upon it. Any iron or metal work that must be in the battery room should protected with an acid-resisting paint.

OPERATION. — *Never operate any battery in any manner except in accordce with the instructions of the battery manufacturer furnishing the battery.*

With all large battery plants there should be supplied by the manufacturer e proper testing instruments and detail instructions for the operation of the ttery under the conditions obtaining. The blank forms furnished by the nufacturer should be filled in at regular intervals and mailed to the manucturer for analysis and recommendations.

No general instructions for the proper operation of a battery are given in is article, since the different manufacturers differ in their opinions on certain ints of operation.

Printed instructions for operating any type of battery can be obtained free charge from the manufacturer.

Attention from Operator. — The successful operation of a battery plant es not require much time from the operator, but attention given the battery hould be systematic and absolutely in accordance with the instructions furished by the manufacturer. If the manufacturer's instructions are followed xplicitly and systematically, it will be found that the battery can be kept in ood condition with a small amount of labor and time. If the operator neglects follow the regular instructions and does not appeal to the manufacturer until t gets into trouble, the usual result will be considerable loss in time and money.

Addition of Water. — Pure distilled water, or natural water that has been nalyzed and approved by the battery manufacturer, should be added to the lls from time to time to replace evaporation. If there is not available a source

of pure, natural water, and if distilled water cannot be purchased cheaply, a distilling outfit will usually be found necessary with large sizes of batteries. Standard water stills, for this purpose, can be purchased on the market.

Addition of Acid. — *Acid should never be added to a battery except upon the recommendation of the battery manufacturer.* The manufacturer should specify the specific gravity and the proper amount of acid.

REPAIRS. — Very few repairs, other than battery plates, should be required. For replacing the plates in the larger sizes of batteries, a lead-burning outfit and the necessary lead-burning material will usually be required. No one but a skilled lead burner should attempt to burn in plates.

Smaller sizes of batteries, with bolted connections between adjacent cells, can be purchased from the manufacturer with each element assembled.

Leaky Tanks. — A leaky tank should be repaired immediately. No one but an expert sheet-lead burner should be allowed to repair a leaky lead-lined tank. To repair the leaky lead-lined tank it will be necessary to cut loose from the bus bars all of the plates in the leaky tank and remove the tank into the air. If it is necessary to keep the rest of the battery in commission while the repairs are being made, the cell or cells cut out should be jumped by a jumper of sufficient current-carrying capacity.

FIRST COST. — It is impossible to give exact figures for the total cost of installation of a complete battery plant of any size. An analysis of the first costs of a great many plants now in operation shows that the first cost per kilowatt for the entire battery installation, exclusive of building, varies from $80.20 per kilowatt to $250.00 per kilowatt. The kilowatt rating as used here and elsewhere in this article is an arbitrary rating determined by multiplying the one-hour discharge rate in amperes (four times the normal rate) by double the number of cells.

ANNUAL COST. — The total annual cost includes operation, maintenance, depreciation and interest.

Operating Cost. — The operating cost will consist largely of labor. Any material except necessary water should be included under maintenance.

Maintenance and Depreciation. — The cost of maintenance of a battery varies with the conditions. Other things being equal, the life of a battery is dependent upon the work done. The maintenance cost of a battery varies from 4 per cent to 10 per cent per annum. When the battery is used only for strictly emergency service the maintenance cost may be less than 4 per cent.

These figures cover not only maintenance, but also what is commonly included under the term depreciation. The plate being the essential component of the battery, plate renewals, which are made from time to time, involve such improvements that have been made in design and construction and serve to bring the battery up to date. An increase of voltage or capacity to meet changed conditions may be effected by the addition of cells or by increasing the number of plates in each cell, without sacrifice of the original investment. In the opinion of the writer there is, therefore, little, if any, true depreciation in a battery installation which is properly maintained.

BIBLIOGRAPHY. — Lyndon, L., *Storage Battery Engineering;* Wade, E. J., *Secondary Batteries.*

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BEARINGS. — *(See also Friction; Lubricants and Lubrication; Shafting.)* The common types of shaft bearings may be classified as follows:

Plain Cylindrical Bearings. — The usual form of bearing is a metal cylinder of cast iron, brass, bronze or gun-metal, mounted in a pedestal, bracket or frame, which serves as a support for the shaft. The portion of the shaft within the bearing is called the journal. Plain bearings are usually lined with some soft metal, such as babbitt metal or other white metal. In a self-aligning bearing the seating of the bearing in the pedestal is made a portion of a sphere, so that the bush may automatically align itself with the shaft. Cylindrical bearings are sometimes provided with an oil bath within the pedestal just below the bearing proper; rings or chains running loosely over the journal through slots in the bearing and dipping into this bath supply a steady stream of oil to the rubbing surfaces.

T. D. Lynch (Amer. Soc. Test. Mat., June, 1913) gives the following data in regard to plain Babbitt bearings: (1) The constituent metals of the alloy (*see Alloys*) must be of superior grade. (2) A temperature of 500° C. or less has been found sufficient for satisfactory alloying (3) A pouring temperature of 460° C. has been found to give excellent results. (4) The shell should be heated to 100–150° C. before the bearing metal is poured in. (5) Babbitted bearings must not be jarred during the solidification of the metal. (6) A Brinell hardness of 23.5 for lead-base and 30 for tin-base babbitts have been found to give excellent results.

Roller Bearings. — In this type of bearing the journal is supported on rollers which are in turn supported by smaller shafts in smaller bearings. The rollers support the journal of the main shaft.

Step Bearing. — A step bearing is essentially a large pivot bearing used at the end of vertical shafts carrying a heavy load. The end of the shaft is provided with a steel plate or "step," which rests on a second plate or bearing. The bearing proper may be either of the ball or roller type, or may be a plane surface with one or more grooves into which oil can be forced under pressure. The stationary plate is sometimes supported on short helical springs and is held against rotation by dowel pins (*H. G. Reist, A.S.M.E. Journ. 40, p. 393, May, 1918*).

Thrust Bearings. — Thrust bearings are used on horizontal shafts when the shaft is subjected to a horizontal thrust. They are similar to step bearings for vertical shafts, except that a collar fitting around the shaft is used instead of a plate at the end of the shaft. Steamship shaft bearings have numerous collars on the shaft, with thrust blocks between them. Roller or ball bearings may be used instead of collars.

Ball Bearings. — A ball bearing consists essentially of a track of curved cross-section which is filled with a set of balls. For a discussion of the use of ball bearings in electric machinery see H. N. Turnbull (*Elec. Rev. and West Ltn. 70, p. 1054, 1917*).

Pivot Bearings. — Various types of pivot bearings are used. The pivot may be either a flat surface, a pointed cone, a truncated cone, a hemisphere or a surface of special form, such as Shiele's "tractrix."

ALLOWABLE LOADS AND SPEEDS. — If the pressure on a bearing is too great the oil film between journal and bearing surface will be destroyed and the bearing will overheat and "seize." Various formulas have been developed for the allowable pressure in terms of the speed and type of bearing.

Safe Loads, Line Shaft and Mill Bearings. — F. W. Taylor (*Trans. A.S.M.E., 1905*), as the result of an investigation of line shaft and mill bearings

that were running near the limit of durability and heating, yet not dangerously heating, gives the formula

$$p = \frac{400}{v},$$

where p = pressure in pounds per square inch of projected area (i.e., product of diameter of the journal by its length) and v = peripheral velocity of journal in feet per second.

The formula is applicable to bearings in ordinary shop or mill use on shafting which is intended to run with the care and attention which such bearings usually receive, and gives the maximum or most severe duty to which it is safe to subject ordinary *chain* or *oiled* ball- and socket-bearings which are *babbitted*. It is not safe for ordinary shafting to use *cast-iron boxes*, with either sight feed, wick feed or grease-cup oiling, under as severe conditions as $p \times v = 200$.

Safe Loads, Miscellaneous Bearings. — Alford in *Bearings and their Lubrication*, gives the following allowable bearing pressures in pounds per square inch of projected area.

Kind of bearing and condition of operation	Allowable bearing pressure in lb. per sq. in. of projected area	
United States Naval Practice		
Main engine bearings	275– 400	For weight alone.
Main engine crank pin bearings	400– 500	For weight alone.
Steam turbine bearings	85	For weight alone.
Thrust bearings for torpedo boats	50	For weight alone.
Merchant Marine Practice		
Main engine bearings	400– 500	
Main engine crank pin bearings	400– 500	
High-speed Stationary Engine Practice		
Main bearings	60– 120	For dead load.
Main bearings	150– 250	For steam load.
Crank pin bearings, overhung crank	900–1500	
Crank pin bearings, center crank	400– 600	
Cross-head pin bearings	1000–1800	
Slow Speed Stationary Engine Practice		
Main bearings	80– 140	For dead load.
Main bearings	200– 400	For steam load.
Crank pin bearings	800–1300	
Cross-head pin bearings	1000–1500	
Gas Engine Practice		
Main bearings	500– 700	
Crank pin bearings	1500–1800	
Cross-bead pin bearings	1500–2000	
Electrical Machinery Practice		
Generator and motor bearings	30– 80	
Main engine bearings, driving generators	40– 80	
Horizontal steam turbine bearings	60– 400	
Vertical steam turbine steps	200–1000	

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Kind of bearing and condition of operation	Allowable bearing pressure in lb. per sq. in. of projected area
MISCELLANEOUS PRACTICE	
Bearings for slow speed and intermittent load as in punch presses, shears and the like	3000–4000
Main bearings of slow speed pumping engines	600
Heavy line-shaft bearings, bronze or babbitt lined	100– 150
Light line-shaft bearings, cast-iron	15– 25
Heavy slow-speed step bearings	2000
Drill-press thrust collars	325
Angular-thrust bearing for boring mill tables	75

Safe Loads, Roller Bearings. — The following table gives the safe load in pounds for Mossberg roller bearings (*Trans. A.S.M.E., 1905*). D = diameter of journal, in inches; d = diameter of roll, in inches; N = number of rolls; P = safe load on journals, in pounds. The rolls are enclosed in a bronze supporting cage.

D	d	N	P	D	d	N	P	D	d	N	P
2	¼	20	3,500	6	1 1/16	24	50,000	15	1⅝	28	255,000
2½	5/16	22	7,000	7	1 5/16	22	70,000	18	1⅝	32	325,000
3	⅜	22	13,000	8	⅞	22	90,000	20	1½	34	400,000
4	7/16	24	24,000	9	1	24	115,000	24	1½	38	576,000
5	5/16	24	37,000	12	1¼	26	175,000	..	....	..	.....

Surface speed of journal from 0 to 50 feet per minute. Length of journal 1½ diameters. The rolls are made of tool steel not too high in carbon, and of spring temper. The journal or shaft should be made not above a medium spring temper. The box should be made of high-carbon steel and tempered as hard as possible.

Marks in his "Mechanical Engineers' Handbook" gives the following formulas for load capacities of roller bearings.

"For rollers such as are used on bridge turn tables and in similar places where the speeds of rotation are slow, the safe load in pounds is $P = cnld$, in which n = number of rollers in the bearing, l and d the length and diameter of each roller, in., $c = 360$ for hard cast-iron rollers running on hard cast-iron tracks, and $c = 850$ for hard steel rollers on hard steel tracks. Where $l > 5d$, smaller values of c should be used. In case conical rollers are used, d is the mean diameter.

"The Standard Roller Bearing Company determines load capacities of roller bearings by the formula $P = 130{,}000d^2\,nl/3s$, in which P = load on bearing, lb.; d = diam. of roller, in.; n = number of rollers; l = length of each roller, in.; and s = circumferential speed of each roller, ft. per min. In bearings with conical rollers d is the diameter of the roller at its mid-length. The safe load per inch of length of a solid roller is taken at 2000 lb., with the assumption that one-third the number of rollers take the whole load on the journal.

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"Another formula for the safe load on a roller bearing is $P = kld^2/(ND + 2000d)$ in which N = r.p.m. of the shaft; D = diam. of the sleeve or roller path, in.; and k = 1,200,000 to 2,000,000 for first class workmanship, hardened steel rollers with $l = d$, running on hardened ground surfaces; k = 400,000 for ordinary workmanship and soft steel rollers running on a soft steel shaft."

Safe Loads, Ball Bearings. — The following formula is given by Mr. Henry Hess, 1910. See also paper by Mr. Hess in *Trans. A.S.M.E., 1907*.

Let

W = total safe load on bearing in pounds,
n = number of balls,
d = diameter of balls in *eighths of an inch*.

Then for *radial* (cylindrical) bearings

$$W = Knd^2,$$

where K ranges from 0.9 to 9 depending upon the condition and type of bearing and the hardness of the balls, but for ordinary speeds is practically independent of the speed. (*See Kent's Mechanical Engineers' Pocket-Book.*)

For *thrust* bearings

$$W = \frac{K_1 nd^2}{\sqrt[3]{N}},$$

where N is the number of revolutions per minute, which may range from 3000 down to 1 revolution per minute, as for crane hooks and similar elements. For high quality ball K_1 ranges from 25 to 40 for a race having a cross section of radius 1.66 × (radius of balls). For unhardened steel, occasionally used for very large races, $K_1 = 0.5$.

In both types of bearings the balls must be carefully selected to make sure that all that are used in the same bearing do not vary among one another by more than 0.0001 inch. A ball that is more than that larger than its fellows will sustain more than its proportion of the load, and may therefore be overloaded and will in turn overload the races.

FRICTION OF BEARINGS. — The coefficient of friction of a well-lubricated plain cylindrical bearing is practically independent of the projected area of the journal, the pressure per unit area remaining constant, and in the case of plain bearings is also practically independent of the nature of the rubbing surfaces, provided these are smooth.

Friction of Plain Bearings. — The coefficient of friction of plain bearings however, does depend to a very great extent upon the following factors:

1. The method of lubrication.
2. The nature of the lubricant.
3. The temperature of the lubricant.
4. The peripheral velocity of the journal.
5. The pressure of the journal on the bearing surface.

1. The more perfectly the bearing is bathed in oil the less will be the coefficient of friction. The friction coefficient of a scantily lubricated bearing may be from 6 to 10 times the coefficient when an oil bath is used.

2. As a rule the lower the viscosity of an oil the less will be the coefficient of friction. There are other factors, however, which must be taken into account in selecting the proper lubricant for any service (*see article on Lubricants and Lubrication*).

3, 4 and 5. The variation of the friction coefficient with temperature, speed and pressure is shown by the curves in Fig. 1. The pressures are nominal

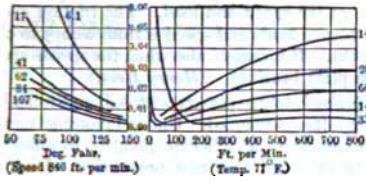


Fig. 1. Numbers at end of curves are pressures in lb. per sq. in.

pressures, i.e., pounds per square inch of projected area of journal. These curves are taken from a paper by Stribeck (*Zeit. Ver. Deutsch. Ing., 1902, Vol. 46*, p. 1341), and are test results on a Sellers bearing with oil rings; journal 13 inches long, 2.75 inches in diameter, lubricated with "gas motor oil." These curves are typical of ordinary bearings.

POWER LOST IN BEARINGS. — Let

f = coefficient of friction,
W = weight on journal or pivot in pounds,
r = radius in inches,
d = diameter in inches,
S = space in feet through which sliding takes place per minute,
r_1 = inner radius in inches,
r_2 = outer radius in inches,
n = number of revolutions per minute,
α = the half-angle of the cone, i.e., the angle of the slope with the axis.

Type of bearing	Friction torque in in.-lb.	Power loss ft.-lb. per min.
Flat surfaces		fWS
Shafts and journals	$\frac{1}{2}\ fWd$	$0.2618\,fW\,dn$
Flat pivots	$\frac{2}{3}\,fWr$	$0.349\,fWrn$
Collar-bearing	$\frac{2}{3}fW\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2}$	$0.349\,fWn\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2}$
Conical pivot	$\frac{2}{3}\,fWr \operatorname{cosec}\alpha$	$0.349\,fWrn \operatorname{cosec}\alpha$
Conical journal	$\frac{2}{3}\,fWr \sec\alpha$	$0.349\,fWrn \sec\alpha$
Truncated-cone pivot	$\frac{2}{3}fW\frac{r_2^3 - r_1^3}{r_2 \sin\alpha}$	$0.349\,fWn\frac{r_2^3 - r_1^3}{r_2 \sin\alpha}$
Hemispherical pivot	fWr	$0.5236\,fWrn$
Tractrix, or Schiele's "anti-friction" pivot	fWr	$0.5236\,fWrn$

It should be noted that for peripheral speeds of 100 feet and over the coefficient of friction is approximately proportional to the square root of the peripheral velocity of the journal. These particular curves also indicate that the coefficient of friction is approximately inversely proportional to the square root of the pressure. Other experimenters, however, have found that this variation is inversely as the first power of the pressure.

Friction of Roller and Ball Bearings. — The friction coefficient of a well-made annular ball bearing is 0.001 and 0.002 of the total load on the journal

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and is independent of the speed and load. The friction coefficient of a good roller bearing under normal loads and speed is from 0.0035 to 0.014; it rises very much if the load is light. It increases also when the speeds are very low, though not so much as with plain bearings. (*Henry Hess.*)

Lubrication is absolutely necessary with ball-and-roller bearings, although the contrary claim is often advanced. Under favorable conditions an almost imperceptible film is sufficient; a sufficient quantity to immerse half the lowest ball should always be provided as a rust preventive. Rust and grit must be kept out of ball-and-roller bearings. Acid or rancid lubricants are as destructive as rust. (*Henry Hess.*)

Comparison of Plain, Roller and Ball Bearings. — Thomas, Maurer and Kelso (*A.S.M.E. Journ. 36, p. 89, March, 1914*), give the following relative power consumption, based on tests of 20 bearings of each type:

Bearings	100 ft. per min.		300 ft. per min.	
	77° F.	100° F.	77° F.	100 F°.
Ball	1.0	1.0	1.0	1.0
Roller	2.2	2.5	2.7	3.0
Plain Babbitt	3.0	3.6	4.5	4.0

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BELTS AND BELTING. — (*See also Ropes and Rope Drive.*) Belts are usually made of tanned leather, though rubber belts are frequently employed, as well as various woven fabrics. Rubber belts are made of two or more layers of canvas connected together with a rubber composition, and then heated until the rubber vulcanizes. The "ply" of a rubber belt is the number of layers of canvas. Leather belts are referred to as single, light-double, medium-double, standard-double and 3-ply. Wire belts with paper driving surface have recently been developed in Germany (*Zeits. Vereines Deutsch. Ing. 63, p. 1057, Oct. 1919*).

Thickness of Belts. — The following figures are from a paper by Samuel Webber (*Am. Mach., May 11, 1909*). The thickness of leather belts, however, is variable, depending on the hide and process of manufacture.

BELT THICKNESS, INCHES

Leather		Rubber	
		30-oz. duck, new rubber vulcanized	
Single thickness	1/8	3-ply	0.18
Light-double	1/4	4-ply	0.24
Medium-double	5/16	5-ply	0.30
Standard-double	1/3	6-ply	0.35
3-ply	9/16	7-ply	0.40
		8-ply	0.45

Weight. — The average weight of leather per cubic inch is 1/30 pound (*Barth*). The average weight of rubber belting made of 30-ounce duck is about 0.045 pound per cubic inch.

Strength. — The strength of the solid leather in belts is from 2000 to 5000 pounds per square inch; at the lacings, even if well put together, only from 1000 to 1500. If riveted, the joint should have half the strength of the solid belt. Rubber belts have approximately the same tensile strength as leather belts. The working tension on the driving side is generally taken at not over one-third of the strength of the lacing, or from one-eighth to one-sixteenth of the strength of the solid belt.

Belt Tension. — Let

T_1 = actual, or "total," tension in pounds per square inch on driving side of belt,

T_2 = actual tension in pounds per square inch on slack side of belt,

T_0 = "initial" tension in belt, i.e., the tension in each side when the belt is at rest,

$T = T_1 - T_2$ = effective tension in pounds per square inch, i.e., T corresponds to the force actually driving the driven pulley,

T_c = the tension produced in the belt due to centrifugal action as it goes around the pulleys,

m = weight of belt per cubic inch in pounds,

f = coefficient of friction between belt and pulley,

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n = ratio of arc of contact between belt and pulley to an arc of 180°, i.e., if the arc of contact is 180°, $n = 1$,

$C = 1 - \epsilon^{-nf\pi}$. The value of $\epsilon^{-nf\pi}$ may be found directly from the table in the article on *Exponential Functions*, putting $nf\pi = x$,

V = velocity of belt in feet per minute.

Then

$$T_c = \frac{mV^2}{9660}, \tag{1}$$

$$T = C(T_1 - T_c), \tag{2}$$

$$T_2 = T_1 - C(T_1 - T_c), \tag{3}$$

$$T_0 = \left(\frac{\sqrt{T_1} + \sqrt{T_2}}{2}\right)^2 \text{ approximately.*} \tag{4}$$

Barth recommends that for belts running at various speeds the initial tension T_0 should not be the same in all belts, but that the belts should be tightened initially to such a tension that under load the sum

$$A = T_1 + \tfrac{1}{2} T_2 \tag{5}$$

is a constant. Barth also states, basing his conclusion in part on the studies of the economics of belting made by F. W. Taylor (*Trans. A.S.M.E., Vol. 15, p. 204*), that the best values of A for greatest economy are the following:

	Machine belts	Counter-shaft belts
Maximum value of A, belt first put on	320	240
Minimum value of A, belt to be retightened	240	160

These values of A are for full-load conditions. The corresponding values of the various tensions are given below.

Belt Friction and Belt Slip. — The value of the factor C depends upon the coefficient of belt friction, which is subject to considerable variation, depending upon the condition of the belt and pulleys. Barth gives the following formula for f for leather belts on cast-iron pulleys

$$f = 0.54 - \frac{140}{500 + V}.$$

Barth also gives a formula for the belt slip which may be written

$$s = \frac{V_1 - V_2}{V} = \frac{320}{V}\left(\frac{1 + 0.0055\,V}{85 + 0.03\,V}\right),$$

where V_1 and V_2 are the peripheral velocities of the driving and driven pulley respectively.

* See paper by C. G. Barth, *Trans. A.S.M.E.*, 1909, Vol. 31, p. 29. In this paper Barth also gives a more exact formula, and takes into consideration the difference in the relation between T_1, T_2 and T_0 for vertical and horizontal belts.

Power Loss Due to Belt Slip is proportional to the slip, i.e., if the slip is 0.03 the power lost is 3 per cent of the power transmitted by the belt. Under normal conditions the power loss due to belt slip is from 2 to 4 per cent. The power loss in mill shafting due to the friction of the shaft bearings ranges from 10 to 60 per cent, depending upon the type of bearing, belt tension, etc., See article on *Bearings*.

Power Transmitted by Belt. — Let

V = velocity of belt in feet per minute,
w = width of belt, in inches,
t = thickness of belt, in inches,
m = weight, in pounds, of 1 cubic inch of belt,
T_1 = actual tension in driving side of belt in pounds per square inch of belt cross-section,
s = slip of belt as a fraction of belt speed.

Then the horse-power transmitted by the belt is

$$P = \frac{wtCVT_1}{33{,}000}\left(1 - \frac{mV^2}{9660\,T_1}\right),$$

where C, defined above, depends on the belt friction and arc of contact between belt and pulley.

As a rough approximation C may be taken equal to 0.6, and the second term in the bracket zero, at least for low speeds, and the formula then becomes

$$P = \frac{wtVT_1}{55{,}000},$$

or the horse-power transmitted per square inch of belt cross-section is

$$p = \frac{VT_1}{55{,}000}.$$

The power lost in the transmission from one pulley to the other, excluding the loss due to shaft friction, is sP, the driving pulley absorbing approximately $(P + 0.5\,sP)$ horse-power and the driven pulley receiving $(P - 0.5\,sP)$ horse-power.

The following tables are derived from curves in the paper by Barth above referred to.

HORSE-POWER TRANSMITTED BY BELTS DRIVING MACHINES
(For $A = T_1 + 0.5\,T_2 = 240$)

Velocity, ft. per min.	500	1000	2000	3000	4000	5000	6000
Initial tension, T_0	124	120	121	128	136	144	152
Centrifugal tension T_c	o+	3	13	31	56	86	124
Difference, $T_0 - T_c$.....	123	117	108	97	80	58	28
Tension on tight side, T_1...	210	212	211	207	198	187	173
Tension on slack side, T_2...	60	54	57	68	84	107	134
Effective pull, $T_1 - T_2$	150	158	154	139	114	80	39
Sum of tensions $T_1 + T_2$	270	266	269	274	282	294	307
H.p. per sq. in. of section..	2.27	4.79	9.33	12.64	13.82	12.12	7.09

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HORSE-POWER TRANSMITTED BY BELTS DRIVING COUNTER-SHAFTS

(For $A = T_1 + 0.5\ T_2 = 160$.)

Velocity of belt, ft. per min.	500	1000	2000	3000	4000	5000
Initial tension, T_0.....	82	81	83	89	96	102
Tension on tight side, T_1...	140	141	140	134	125	114
Tension on slack side, T_2...	40	38	41	53	69	92
Effective pull, $T_1 - T_2$.....	100	103	99	81	56	22
Sum of tensions	180	179	181	187	194	206
H.p. per sq. in. of section...	1.51	3.12	6.04	7.36	6.79	3.33

Proper Size of Belt to Transmit a Given Amount of Power. — Using the same notation as in the preceding paragraph, the proper cross-section of the belt in square inches is approximately

$$wt = \frac{55{,}000\,P}{VT_1},$$

or exactly

$$wt = \frac{33{,}000\,P}{CVT_1\left(1 - \frac{mV^2}{9660\,T_1}\right)}.$$

The various "handy formulas" for determining the proper cross-section of belt are all of the form of the approximate formula, and differ only in regard to the proper value to assign to the tension T_1. A working tension, that is the difference between the tensions on the tight and slack sides of the belt, of 45 pounds for a single (thickness) belt 1 inch wide is commonly used, giving a nominal tension of $6 \times 45 = 270$ pounds per square inch. Taking the coefficient C at 0.6, the actual tension in a belt designed in accordance with this rule is 450 pounds per square inch. The value of C varies through a wide range, say from 0.25 to 0.90, chiefly due to the variability of the coefficient of friction.

The following table, deduced from Barth's curves, may be considered as representative of modern practice.

CROSS-SECTION OF LEATHER BELT PER HORSE-POWER TRANSMITTED, IN SQUARE INCHES

Speed, ft. per min.	500	1000	2000	3000	4000	5000	6000
Machine belts.....	0.44	0.209	0.107	0.079	0.072	0.082	0.111
Countershaft belts.....	0.662	0.320	0.166	0.136	0.147	0.300	....

All belts should have a contact area with the smaller pulley of at least 165 degrees. If this is not possible to obtain under normal conditions an idler should be provided to increase the belt contact.

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Pulley Face and Belt Speed. — The following table may be used fo etermining the pulley face and best belt speed for moderate-speed machines or slow-speed machines the pulley sizes are the same as those used with moder te machines of the same frame dimensions.

PULLEY FACE AND BELT SPEED

Horse-power	Kilowatts	Belt width in inches	Pulley face in inches	Belt speed in feet per minute for moderate-speed machines
1 to under 5	1 to under 4	2	2½	2000
5 " 10	4 " 8	3	3½	2500
10 " 15	8 " 11	4	4½	2500
15 " 20	11 " 15	5	6	2500
20 " 25	15 " 19	6	7	3000
25 " 30	19 " 23	7	8	3000
30 " 40	23 " 30	8	9	3000
40 " 50	30 " 37	10	11	3000
50 " 60	37 " 45	12	13	3000
60 " 75	45 " 56	14	15	3000
75 " 100	56 " 75	16	17	3500
100 " 125	75 " 93	16	17	4000
125 " 150	93 " 112	18	19	4000
150 " 200	112 " 159	20	21	4500
200 " 250	159 " 186	22	23	5000
250 " 300	186 " 224	26	27	5000
300 " 350	224 " 261	30	31	5000
350 " 400	261 " 298	32	33	5000
400 " 450	298 " 336	36	37	5000
450 " 550	336 " 410	40	42	5000
550 " 650	410 " 485	44	46	5000
650 " 750	485 " 560	48	50	5000
750 " 850	560 " 634	52	54	5000
850 " 950	634 " 709	56	58	5000
950 " 1050	709 " 783	60	62	5000

Relations of Driving and Driven Pulleys. — The maximum ratio betwee the diameters of the driving and driven pulleys should not exceed 6 : 1. Th ratio will determine the distance between the pulley centers, and good propor tions are given in the accompanying table.

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CARE AND OPERATION OF BELTS. — The following is taken from an article by F. W. Taylor (*Trans. A.S.M.E., Vol. 15, p. 203*). See also an excellent article by C. J. Morreson (*Eng. Mag. 51, p. 567, July, 1916*).

The best distance from center to center of shafts is from 20 to 25 feet.

Idler pulleys work most satisfactorily when located on the slack side of the belt about one-quarter way from the driving pulley.

Belts are more durable and work more satisfactorily made narrow and thick, rather than wide and thin.

It is safe and advisable to use a double belt on a pulley 12 inches diameter or larger; a triple belt on a pulley 20 inches diameter or larger; a quadruple belt on a pulley 30 inches diameter or larger. As belts increase in width they should also be made thicker.

Approximate Ratio	Minimum Distance Between Centers in Feet
2 : 1	8
3 : 1	10
4 : 1	12
5 : 1	15
6 : 1	20

The ends of the belt should be fastened together by splicing and cementing instead of lacing, wiring or using hooks or clamps of any kind.

Belts should be cleaned and greased every five to six months.

Belt-clamps having spring-balances between the two pairs of clamps should be used for weighing the tension of the belt accurately each time it is tightened.

Double leather belts, when treated with great care and run night and day at moderate speed, should last for 18 years (the tension being adjusted in accordance with Barth's rules).

In figuring the total expense of belting, and the manufacturing cost chargeable to this account, by far the largest item is the time lost on the machines while belts are being relaced and repaired.

The total stretch of leather belting exceeds 6 per cent of the original length.

The stretch during the first six months of the life of belts is 15 per cent of their entire stretch (the tension being adjusted in accordance with Barth's rules).

A double belt will stretch 0.81 per cent of its length before requiring to be tightened (the tension being adjusted in accordance with Barth's rules).

The most important consideration in making up tables and rules for the use and care of belting is how to secure the minimum of interruptions to manufacture from this source.

The average double belt when running night and day in a machine shop will cause an interruption to manufacture not oftener than once in sixteen months (the tension being adjusted in accordance with Barth's rules).

The oak-tanned and fulled belts showed themselves to be superior in all respects except the coefficient of friction to either the oak-tanned not fulled, the semi-rawhide, or rawhide with tanned face.

Belts of any width can be successfully shifted backward and forward on tight and loose pulleys. Belts running between 5000 and 6000 feet per minute and driving 300 h.p. are now being daily shifted on tight and loose pulleys to throw lines of shafting in and out of use.

The best form of belt-shifter for wide belts is a pair of rollers twice the width of belt, either of which can be pressed onto the flat surface of the belt on its slack side close to the driven pulley, the axis of the roller making an angle of 75° with the center line of the belt.

Dressings for Leather Belts. — We advise that no belt dressing should be used except when the belt becomes dry and husky, and in such instances we recommend the use of a dressing. Where this is not used beef tallow at blood

warm temperature should be applied and then dried either by artificial heat or the sun. The addition of beeswax to the tallow will be of some service if the belts are used in wet or damp places. Our experience convinces us that resin should never be used on leather belting. (*Fayerweather and Ladew.*)

Some forms of belt dressing, the compositions of which have not been published, appear to have the property of increasing the coefficient of friction between the belt and the pulley, enabling a given power to be transmitted with a lower belt tension than with undressed belts. C. W. Evans (*Power, Dec., 1905*) gives a diagram, plotted from tests, which shows that three of these compositions gave increased transmission for a given tension, ranging from about 10 per cent for 50 pounds tension per inch of width to 100 per cent increase with 20 pounds tension.

Dressings for Rubber Belts. — Rubber belts will be improved, and their durability increased, by putting on with a painter's brush, and letting it dry, a composition made of equal parts of red lead, black lead, French yellow and litharge, mixed with boiled linseed oil and japan enough to make it dry quickly. The effect of this will be to produce a finely polished surface. If, from dust or other cause, the belt should slip, it should be lightly moistened on the side next the pulley with boiled linseed oil. (*From circulars of manufacturers.*)

Lacing of Belts. — In punching a belt for lacing, use an oval punch, the longer diameter of the punch being parallel with the sides of the belt. Punch two rows of holes in each end, placed zigzag. In a 3-inch belt there should be four holes in each end — two in each row. In a 6-inch belt, seven holes — four in the row nearest the end. A 10-inch belt should have nine holes. The edge of the holes should not come nearer than ⅝ inch from the sides, nor ⅞ inch from the ends of the belt. The second row should be at least 1¾ inches from the end. On wide belts these distances should be even a little greater.

Begin to lace in the center of the belt and take care to keep the ends exactly in line, and to lace both sides with equal tightness. The lacing should not be crossed on the side of the belt that runs next the pulley. In taking up belts observe the same rules as in putting on new ones.

Setting a Belt on Quarter-twist. — A belt must run squarely on to the pulley. To connect with a belt two horizontal shafts at right angles with each other, say an engine-shaft near the floor with a line attached to the ceiling, will require a quarter-turn. First, ascertain the central point on the face of each pulley at the extremity of the horizontal diameter where the belt will leave the pulley, and then set that point on the driven pulley plumb over the corresponding point on the driver. This will cause the belt to run squarely on to each pulley, and it will leave at an angle greater or less, according to the size of the pulleys and their distance from each other.

In quarter-twist belts, in order that the belt may remain on the pulleys, the central plane on each pulley must pass through the point of delivery of the other pulley. This arrangement does not admit of reversed motion.

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BLOCKS AND TACKLE. — (*See also Ropes and Rope Drive; Chains and Chain Drive.*) A simple block used with rope tackle consists of one or more pulleys mounted in a casing or shell. They may be single, double, triple, etc., depending upon the number of sheaves or pulleys. In chain blocks, instead of simple pulleys, spur or worm and wheel gearing (*see Gears and Gearing*) or differential pulleys are used. In the triplex block, made by the Yale and Towne Co., the power is transmitted to the hoisting-chain wheel by means of a train of spur gearing operated by the hand chain. In the duplex block the power is transmitted through a worm wheel and screw.

Fig. 1 shows schematically a differential pulley. The two upper pulleys are rigidly fastened together and rotate as one piece. The rims of these pulleys are shaped to mesh with the links of the chain and prevent the latter from slipping. Let D_1 and D_2 be the respective diameters of the larger and smaller upper pulleys. Then if the diameter of the lower pulley is $(D_1 + D_2)/2$, the pull P' required to raise a load W, neglecting friction, is

$$P' = \frac{D_1 - D_2}{2D_1} \cdot W.$$

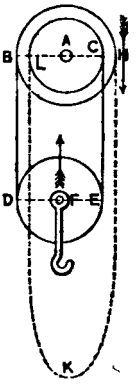


Fig. 1.

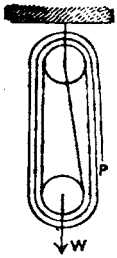


Fig. 2.

ACTUAL PULL REQUIRED; EFFICIENCY OF BLOCK AND TACKLE. — In the case of a simple block and tackle the pull P' required to raise a load W is, neglecting friction,

$$P' = \frac{W}{N},$$

where N is the number of lengths of rope shortened when the lower block rises (in Fig. 2 $N = 6$). The actual pull required is this theoretical pull P' divided by the efficiency expressed as a fraction, or

$$P = \frac{100\,W}{Ne},$$

where e = the per cent efficiency. The distance in feet through which the pulling rope must be pulled to raise the load 1 foot is equal to the number (N) of lengths of rope shortened.

In the case of a differential pulley the actual pull is

$$P = \frac{100\,(D_1 - D_2)\,W}{2D_1 e},$$

where e is the per cent efficiency and the other symbols as above. The distance through which the hand chain must be pulled to raise the load 1 foot is

$$\frac{2D_1}{D_1 - D_2}.$$

In any case, if the rope or chain pulls on the lower block at an angle, the block will be pulled out of the line drawn between the load and the upper block, and the effective pull will be less than the actual pull on the rope in the ratio of the cosine of the angle the pulling rope makes with the vertical, or line of action of the resistance, to unity.

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Efficiency of Rope Blocks. — S. L. Wonson, *Eng. News*, June 11, 1903, es the following:

Number of rope lengths shortened, N	Manila rope, 1¼ to 2 in.		¾-inch wire rope	
	Ratio of load to pull	Efficiency, per cent, e	Ratio of load to pull	Efficiency, per cent, e
2	1.91	96	....	..
3	2.64	88	2.73	91
4	3.30	83	3.47	87
5	3.84	77	4.11	82
6	4.33	72	4.70	78
7	4.72	67	5.20	74
8	5.08	64	5.68	71
9	5.37	60	6.08	68
10	....	..	6.46	65
12	....	..	7.08	59

Pull Required with Chain Blocks. — The following table is taken from a catalogue of the Yale and Towne Co.

Capacity in tons, (2000 lb.)	Pull in pounds required on hand-chain to lift full loads			Feet of hand-chain to be pulled by operator to lift load one foot high		
	Triplex	Duplex	Differential	Triplex	Duplex	Differential
¼	...	...	72	...	...	18
½	62	68	122	21	40	24
1	82	87	216	31	59	30
1½	110	94	246	35	80	36
2	120	115	308	42	93	42
3	114	182	557	69	126	38
4	124	142	...	84	155	..
5	110	145	...	126	195	..
6	130	145	...	126	252	..
8	135	160	...	168	310	..
10	140	160	...	210	390	..

For loads from 10 to 20 tons two hand-chains are provided.

SAFE LOAD. — Blocks are usually designed to carry a load as great as that of the rope or chain which fits the grooves in the sheaves (*see Ropes and Rope Drive; Chains and Chain Drive*).

BIBLIOGRAPHY. — See the works on *Machine Design* given in the Bibliography in article on *Bearings;* also circulars of Yale & Towne Mfg. Co., N. Y., and Boston & Lockport Block Co.

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BLOWERS AND COMPRESSORS. — (*See also Draft, Mechanical; Fans.*) A blower is any kind of apparatus that is used for blowing or forcing air or other gas into or out of a room or other receptacle. When it is used to draw air from a room or vessel and discharge it into another vessel or into the external atmosphere it is commonly called an "exhauster." A fan is a blower in which motion is given to the air by means of thin blades or vanes (*see Fans*). A blowing engine is a large machine in which air is compressed in and discharged from a cylinder which is fitted with a reciprocating piston. When a blowing engine delivers air at high pressures, say 30 pounds per square inch and upwards, it is called an air compressor. Following is a brief description of the several kinds of blowers.

Displacement Blowers. — Into a closed tank containing air a stream of water is caused to flow, displacing the air and blowing it out through an opening provided for it. By using two tanks with suitable valves, the action may be made continuous.

Hydraulic Blowers. — A large tank is surmounted by a vertical pipe into the top of which water enters in such a way as to "entrain" or drag air along with it, which is separated from the water when it reaches the tank and is blown out through an air pipe while the water escapes through another opening. Tests of a compressor of this kind at Magog, P. Q., Canada, showed a capacity of from 967 to 1165 cubic feet of air per minute at a pressure of 53 pounds per square inch, and an efficiency of from 60 to 70 per cent. See paper by W. O. Webber, *Trans. A.S.M.E.*, Vol. 22, p. 599.

Jet Blowers. — A jet of water, compressed air, or steam flowing into a short pipe of a diameter greater than that of the jet will induce a current of air to flow through the pipe, which may thus be used as a blower or exhauster. The steam jet is in common use for blowing air into furnaces and gas producers, and is used as an exhaustor to increase the draft of chimneys. It is usually very wasteful of steam, and should be used only in emergencies, when blowing machines are not available, or when the steam used to drive the jet is also used for other purposes, as for combining with the carbon of the fuel in gas producers.

Positive Rotary Blowers. — These are built like rotary pumps, with two rotating shafts, geared together so as to turn in opposite directions, each carrying an "impeller," a casting approximating a figure 8 in section; the curve of the two impellers is so shaped that they touch or nearly touch on lines parallel to the shafts during the whole period of rotation, and also nearly touch the casing which surrounds them. A blower thus built delivers a constant quantity of air at each revolution, differing in this respect from centrifugal fans which deliver a varying quantity according to the resistance the air meets at the outlet. The economical range of these blowers is between 8 ounces and 1 pounds pressure per square inch. For higher pressures then 8 pounds the blowing engine is more economical.

Blowing Engines. — A cylinder with a reciprocating piston when used for blowing air is called a blowing engine, whether it is driven by a steam engine a water wheel or an electric motor. Blowing engines are commonly used to furnish air to blast furnaces and Bessemer converters, at pressures of from 4 to 30 pounds per square inch. They are simple in construction, but are usually large, heavy and costly relative to the quantity and pressure of air furnished by them, on account of their moderate speeds, and there is a tendency to supplant them by

High-speed Centrifugal Compressors. — These are built on the principle of steam turbines or high-pressure centrifugal pumps and are driven at very high

speeds, 1800 to 3500 r.p.m. The General Electric Co. makes a line of these compressors for pressures ranging from 1 to 3.25 pounds per square inch, and for delivering 800 to 28,000 cubic feet of free air per minute. By using several such compressors in series, one delivering into another, pressures of 100 pounds per square inch may be obtained.

POWER AND EFFICIENCY. — The useful work done by a blower is that equivalent to the isothermal compression of the air to the pressure in the receiver (or to the static plus the velocity pressure in the delivery main if the air were cooled to the atmospheric temperature) plus the work of delivering it against that pressure. If P_1 = absolute pressure at inlet in pounds per square foot; P_2 = pressure in the receiver; V_1 = volume of entering air at the pressure P_1, in cubic feet per minute, then useful work in foot-pounds per minute = $P_1 V_1 \log_e \frac{P_2}{P_1}$. The useful or "air horse-power" is this quantity divided by 33,000.

When P_2 is but slightly in excess of P_1 the work per minute is $(P_2 - P_1)V_1$ nearly, the error being less than 5 per cent when $P_2 = 1.1\ P_1$, and less than 1 per cent when $P_2 = 1.01\ P_1$.

When the air is compressed adiabatically, that is, without cooling during compression, the *useful* work is the same as in isothermal compression, but the actual work done in the cylinder (not including work lost by friction and leaking) is greater, or

$$3.463\ P_1 V_1 \left\{ \left(\frac{P_2}{P_1} \right)^{0.29} - 1 \right\}.$$

The efficiency of blowing machines (i.e., the ratio of the air horse-power to the horse-power required to drive the machine) ranges from 95 per cent in the case of a slow-moving engine with large inlet and outlet valves, down to almost zero in poorly designed rotating machines. Centrifugal compressors have an efficiency under normal load of from 40 to 60 per cent (*see Fans*). A 39 by 84-inch positive blower, made by the Connersville Blower Co., is reported to have given an efficiency ranging from 68.5 per cent at an air pressure of 0.5 pound per square inch to 86 per cent at a pressure of 3.5 pounds per square inch, the displacement of air in each case being approximately 18,000 cubic feet per minute. The efficiency of steam-jet blowers is very low.

SPECIFICATION FOR BLOWER. — The following memoranda are intended to assist in writing specifications. See also under *Fans* and article on *Specifications*.

Principal Characteristics and Conditions of Service.—Purpose of blowers.

Style and Description; Details of Construction. — Shall have horizontal, upward or downward discharge. Location of air outlet with reference to rotating parts. Hand or automatic closing of dampers when blower stops. How coupled to motor or engine, i.e., direct or belted. If direct driven, give details of coupler to disconnect blower from motor. Lubrication. Tools. Enclosure of moving parts to reduce danger.

Performance and Tests. — Cubic feet of air per minute. Air pressure, ounces or inches of water column at stated temperature.

ELECTRIC DRIVE OF COMPRESSORS. —(*See also Motors, Industrial Applications of.*) As compressors of the reciprocating type must be driven at a low speed, the synchronous motor is well adapted for driving them, chiefly because this motor operates normally at unity power factor and can be efficiently operated at leading power factors to counteract the lagging power factor

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due to induction motors driving other apparatus on the system. Slow-speed induction motors must be built with a large number of poles and will then operate at very low power factors with a comparatively low efficiency. Other reasons favoring the synchronous motor drive for this service are the steady load and the new torque required in starting, as a by-pass is generally provided so that the compressor works only against atmospheric pressure when starting. The motor should be able to be started from the alternating-current side and should for this reason be provided with the usual "squirrel-cage" winding. There is usually sufficient flywheel effect in the machine itself to keep within a reasonable angle of displacement, so that no trouble is experienced from "hunting."

The centrifugal type of compressor operates at a comparatively high speed. For driving the smaller size compressors the squirrel cage induction motor is used, but for larger units where a low starting current is desirable the phase wound type of motor should preferably be selected. When design difficulties prevent the use of the induction motor for driving the larger size centrifugal compressors it has been the recent practice to use two-pole, 60-cycle synchronous motors built along the line of the turbo-alternator.

For direct-current installations compound-wound motors are generally used for driving reciprocating compressors and shunt-wound motors for the centrifugal type.

DIMENSIONS, WEIGHTS AND COSTS. — There is so great a variety of blowers and compressors that it is impossible in the space available to give a representative table of dimensions, weights and costs. The reader is referred to the manufacturers' catalogues and price lists. Representative manufacturers are the Ingersoll-Rand Co., the American Blower Co., the Sturtevant Co., and the Connersville Blower Co. (*See also Kent's Mechanical Engineers' Pocket-book.*)

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BOILERS, STEAM. — (*See also Chimneys; Condensers, Steam; Conveyors; Lift, Mechanical; Feed-water Heaters; Fuels; Pipes and Piping; Power Stations; Pumps; Separators, Steam; Steam.*) The simplest form of boiler is a closed metal cylinder partly filled with water, with a pipe for the introduction of feed water, another pipe for the escape of steam and means for maintaining a fire under the boiler. Modifications of this elementary form are made: (1) for the purpose of insuring that as large a fraction as possible of the heat energy generated by the burning fuel shall be absorbed by the water and as small a fraction as possible shall be lost in the escaping hot gases and by radiation; and (2) for the purpose of increasing the heating surface and therefore the evaporative capacity of the boiler, with as great an economy of space occupied and of cost in the metallic structure as possible, without at the same time endangering the safety of the boiler, or decreasing its durability, facility for cleaning or other desirable qualities.

DEFINITIONS. — Certain special terms used in reference to boilers are defined below.

Boiler Horse-power. — This term was originally introduced to indicate the size of boiler required for an average reciprocating engine, the boiler being said to have the same horse-power as that of the engine. Due to improvements in the design of steam engines a boiler of a given horse-power rating may be made to supply an engine (e.g., a compound condensing engine) of 3 times the rating of the boiler. The American Society of Mechanical Engineers has adopted the following definition:

"A boiler horse-power is equivalent to the evaporation of 34.5 pounds of water per hour from feed water at 212° F. to saturated steam at the same temperature."

Adopting Marks and Davis's figures for the properties of steam (*see Steam*) 34.5 pounds of steam from and at 212° F. is equivalent to 33,479 B.t.u. per hour, or to an evaporation of 30.018 pounds from 100° F. feed-water temperature into steam at 70 pounds gage pressure.

It is customary in the trade to consider 10 square feet of heating surface as equivalent to a boiler horse-power, for stationary boilers. The term boiler horse-power is not used in connection with locomotive or marine boilers, and there is a tendency to discontinue its use for stationary boilers, expressing their size in square feet of heating surface, and their evaporative capacity in pounds of water evaporated from and at 212° F. per hour.

Equivalent Evaporation. — Factor of Evaporation. — For the purpose of reducing the results of a boiler test made under certain conditions of feed-water temperature and steam pressure and quality to a common standard, it is customary to use the equivalent evaporation from and at 212° F. as that standard. The pounds evaporated under actual conditions are multiplied by a "factor of evaporation," F, which is determined by the formula

$$F = \frac{H - h}{970.4},$$

in which H = total B.t.u. above 32° F. in 1 pound of steam at the actual pressure and degree of superheat, and h = total B.t.u. above 32° F. of 1 pound of the feed water. The values of H and h are given in steam tables (*see Steam*). If the steam contains x per cent of moisture, use for H in the above formula

$$H = H'\left(1 - \frac{x}{100}\right) + \frac{h'x}{100},$$

where H' is the total heat of saturated steam at the given pressure and h' is the heat of the liquid at the given pressure, as given in steam tables.

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Boiler Efficiency. — The efficiency of the boiler alone is usually defined as the ratio of the number of B.t.u. absorbed by the water per pound of combustible *actually* burnt, to the number of B.t.u. in one pound of the combustible. The over-all efficiency of the boiler and grate is the ratio of the B.t.u. absorbed by the water per pound of *coal as fired* to the number of B.t.u. in one pound of this coal. This over-all efficiency differs from the efficiency of the boiler alone according to the amount of coal lost through the grates.

"Economy" or Water Rate. — Boiler efficiency is also frequently expressed in terms of the number of pounds of water evaporated from and at 212° F. per pound of combustible in the coal actually burnt (this corresponds to the efficiency of the boiler alone), or per pound of coal as fired (this corresponds to the efficiency of boiler and grate). The number of pounds of water evaporated from and at 212° F. per pound of coal is frequently referred to as the "economy" of the boiler, or its "water rate."

The relation between efficiency and economy may be expressed as follows:

Let e = boiler efficiency, in per cent,
B = B.t.u. per pound of coal,
w = economy, i.e., the equivalent number of pounds water evaporated per pound of coal.

Then

$$w = \frac{Be}{97{,}040}.$$

For example, if the coal contains 10,000 B.t.u. per pound and the boiler efficiency is 70 per cent, then the economy is $10{,}000 \times 70/97{,}040 = 7.2$ pounds water per pound coal.

CLASSIFICATION OF BOILERS. — Boilers may be classified as *externally* and *internally fired*, *water tube* and *fire tube*, *through tube* and *return tube*, *horizontal* and *vertical*. An *internally fired* boiler is one in which the furnace is built inside of the boiler, and its roof and sides form a part of the heating surface of the boiler; the locomotive and Scotch marine, the Lancashire and the vertical-tubular boiler are of this type. An *externally fired* boiler is one in which the furnace is separate from the boiler itself and is usually placed underneath it, but sometimes at the side of it in a structure lined with fire-brick. A *fire tube* boiler is one in which the hot gases pass through the tubes, whereas the water is contained in an external shell through which the tubes pass. A *water tube* boiler is one in which the water is contained in the tubes and the hot gases pass around them. A *through tube* boiler is one in which the hot gases pass directly through the tubes from the fire to the smoke flue, whereas in a *return tube* boiler the gases are caused to pass under the shell containing the tubes to the farther end, thence upward through the "back connection," or rear of the setting and return through the tubes to the "breeching" or flue connection to the chimney. The term "return tubular" is applied only to fire tube boilers.

APPLICATIONS OF VARIOUS TYPES. — Externally fired *return tube* boilers in sizes up to 200 horse-power and for pressures up to 150 pounds per square inch are very commonly used. Boilers of this type are comparatively cheap and do not require expensive setting. In large power stations externally-fired *water tube* boilers are almost invariably used in this country. These boilers are built in sizes up to 2300 horse-power and for all practicable pressures. Babcock and Wilcox, Heine, Sterling and Wickes boilers are of the water tube type. In the first two makes the tubes are slightly inclined, in the third they are quite steeply inclined, and in the last they are vertical.

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Selection of Type of Boiler. — In selecting the type of boiler to be used in any particular case the following points should be taken into consideration: (1) steam pressure desired; (2) space available; (3) danger of explosion; (4) liability to minor troubles which cause temporary stoppage; (5) durability; (6) ease of making repairs; (7) facilities for cleaning and removing scale and for inspection; (8) water-storage capacity; (9) rapidity at which steam can be raised; (10) steadiness of water level; (11) dryness of steam; (12) cost, including setting.

The question of economy of fuel is not generally dependent on the type of boiler as the same economy may be obtained with all types provided each is so designed that (1) there is sufficient heating surface; (2) the fuel can be thoroughly burned in the furnace, so that no unburned gases are allowed to reach the heating surface, and (3) the path of the gases through the boiler is properly baffled so that they are not "short-circuited," leaving part of the heating surface out of the current.

DESIGN AND CONSTRUCTION. — The essential parts of the boiler in the case of a water tube boiler are the tubes, steam drums and mud drums, grates and setting. The tubes are usually 4 inches in diameter in large stationary boilers, and are usually more or less inclined. The steam drums are large cylindrical vessels which serve as a reservoir for the water and steam. The mud drums are arranged to collect a considerable part of the sediment formed by evaporation of the water. Suitable blowpipes are provided for draining off the water and for discharging the sediment and scale-forming material. The water level in the boiler is usually indicated by a gauge glass or try cocks, or both, connected either directly to the boiler shell or to a water column. Suitable manholes and handholes are provided to give access to the various parts of the boiler.

Heating Surface. — For maximum fuel economy with any kind of boiler it should be proportioned so that at least one square foot of heating surface should be given for every 3 pounds of water to be evaporated from and at 212° F. per hour. Still more liberal proportions are required if a portion of the heating surface has its efficiency reduced by: (1) tendency of the heated gases to short-circuit, that is, to select passages of least resistance and flow through them with high velocity, to the neglect of other passages; (2) deposition of soot from smoky fuel; (3) incrustation. If the heating surface is clean, and the heated gases pass over it uniformly, little if any increase in economy can be obtained by increasing the heating surface beyond the proportion of 1 square foot to every 3 pounds of water to be evaporated, and with all conditions favorable but little decrease of economy will take place if the proportion is 1 square foot to every 4 pounds evaporated; but in order to provide for driving of the boiler beyond its rated capacity, and for possible decrease of efficiency due to the causes above named, it is better to adopt 1 square foot to 3 pounds evaporation per hour as the minimum standard proportion.

For maximum commercial economy, taking into consideration not only the cost of fuel but also the interest, depreciation and taxes on the cost of the plant, a higher rate of driving may be required, even as high as 6 or 8 pounds per square foot of heating surface per hour at the time of maximum or peak load, if the high loads last only a few hours each day.

Measurement of Heating Surface. — The usual rule is to consider as heating surface all the surfaces that are surrounded by water on one side and by flame or heated gases on the other, using the external diameter for water tube boilers and the internal diameter for fire tube boilers.

Grates. — Three kinds of grates are employed, the stationary, the rocking or shaking, and the traveling grate. The grate bars are made of cast iron. Rock-

ing grates have the advantage of permitting clearing the fire-bed of ash and clinker without opening the fire door and require less manual labor than the stationary grate. A traveling grate is one form of a mechanical stoker (*see Stokers, Mechanical*).

Grate Surface. — The amount of grate surface required per horse-power and the proper ratio of heating surface to grate surface are extremely variable, depending chiefly upon the character of the coal and upon the rate of draft. With good coal, low in ash, approximately equal results may be obtained with large grate surface and light draft, and with small grate surface and strong draft, the total amount of coal burned per hour being the same in both cases. With good bituminous coal, like Pittsburgh, low in ash, the best results apparently are obtained with strong draft and high rates of combustion, provided the grate surfaces are cut down so that the total coal burned per hour is not too great for the capacity of the heating surface to absorb the heat produced.

With coals high in ash, especially if the ash is easily fusible, tending to choke the grates, large grate surface and a slow rate of combustion are required, unless means, such as shaking grates, are provided to get rid of the ash as fast as it is made.

The following table is adapted from a more extensive one given in Gebhardt's *Steam Power Plant Engineering*.

Nature of plant	Number of plants	Character of fuel	Average ratio of heating surface to grate surface
Central stations	10	Illinois screenings, 15 to 20% ash	65
Central stations	14	Bituminous	60
Central stations	1	Bituminous	31
Central stations	9	Anthracite	40
Mfg. plants	20	Anthracite	35
Office building	6	Bituminous	48

Calculation of Required Heating Surface and Grate Area. — From the data given above the proper grate area and heating surface may be calculated as follows:

Example 1. — Steam required per hour at the "peak of the load," 6000 pounds; 3000 pounds ordinarily. Steam per pound of the poorest coal under the given conditions of feed-water temperature and steam pressure at maximum rate of driving, 6 pounds. This corresponds to 6000/6 = 1000 pounds of coal per hour. Maximum rate of combustion under worst conditions 25 pounds of coal per square foot of grate per hour. The required grate surface is then 1000/25 = 40 square feet. Heating surface for maximum economy at ordinary driving will be 3000/3 = 1000 square feet, requiring 6000 × 3/3000 = 6 pounds of steam per square foot of heating surface per hour at highest rate. Ratio of heating to grate surface, 1000/40 = 25 to 1.

Example 2. Let 3000 pounds of steam be required per hour uniformly. The coal is of good quality so that 9 pounds of water will be evaporated per pound

f coal when the rate of driving does not exceed 3 pounds of evaporation per quare foot of heating surface per hour. The rate of combustion of this coal ay be as high as 30 pounds per square foot of grate per hour, but to have ore easy firing, 20 pounds is chosen. Then,

Heating surface = 3000/3 = 1000 square feet;
Coal per hour = 3000/9 = 333 pounds;
Grate surface = 333/20 = 16.7 square feet;
Ratio of heating to grate surface = 1000/16.7 = 60 to 1.

Air Passages through Grates. — The usual practice is to make the ir opening 30 to 50 per cent of the total grate area. With coal free from finker much smaller openings may be used.

Flues and Other Gas Passages. — Rules are usually given making the rea of gas passages bear a certain ratio to the area of the grate surface; thus a ommon rule for horizontal tubular boilers is to make the area over the bridge all 1/7 of the grate surface, the flue area 1/8, and the chimney area 1/8.

For average conditions with anthracite coal and moderate draft, say a rate f combustion of 12 pounds of coal per square foot of grate per hour, and a atio of heating to grate surface of 30 to 1, this rule is as good as any, but it is vident that if the draft were increased so as to cause a rate of combustion f 24 pounds, requiring the grate surface to be cut down to a ratio of 60 to 1, the reas of gas passages should not be reduced in proportion. The amount of oal burned per hour being the same under the changed conditions, and there being no reason why the gases should travel at a higher velocity, the actual reas of the passages should remain as before, but the ratio of the area to the grate surface would in that case be doubled.

Mr. Barrus states that the highest efficiency with anthracite coal is obtained when the tube area is 1/6 to 1/10 of the grate surface, and with bituminous coal when it is 1/6 to 1/7, for the conditions of medium rates of combustion, such as 10 to 12 pounds per square foot of grate per hour, and 12 square feet of heating surface allowed to the horse-power.

Boiler Settings. — The boiler proper is usually mounted in a brick setting with suitable iron buckstays. The setting also forms the walls of the furnace. Common red brick is usually employed for the setting except for those parts which are exposed to a sufficiently high temperature to require the use of fire brick. Sometimes a separate furnace, or "Dutch oven," directly in front of the boiler, is used.

OIL BURNERS AND FURNACES. — In burning liquid fuel in steam-boiler or other furnaces it is of the utmost importance that the fuel be completely atomized and that each minute particle be surrounded by sufficient air for its complete combustion. Failure in this results in the formation of smoke and soot. The following methods of injecting the oil and air into the furnace are used in connection with steam boilers:

(1) *Steam injection.* A fine jet of steam at high pressure is employed to inject both oil and air into the furnace. Furnaces fired by this method are very successful in burning oil without smoke, if the oil is not fed to the furnace at a rate faster than that for which the burner is designed. (2) *Air injection.* Air at about 40 pounds pressure per square inch is used to inject and atomize the oil. Burners of this type are very successful, and they give higher temperatures than steam injectors. The objection to them is the cost of the air-compressing machinery. (3) *Mechanical injectors.* The oil under pressure operates a revolving device in the nozzle of the burner which causes the oil to be delivered in a very fine spray. Some burners of this type have given excellent results. With these burners it is necessary to supply the oil under a high pres-

sure, say from 50 to 80 pounds per square inch and to heat it before reaching the burner to a temperature of from 120° to 180° F. in order to reduce its viscosity.

More important than the burner is the furnace. It must be of sufficient size to give ample room for complete combustion of the gases formed by decomposition of the oil before these gases are allowed to be chilled by contact with the heating surfaces of the boiler. For economy of oil the air supply should be regulated so that the excess of air is not more than 50 per cent above that theoretically required for complete combustion.

POWDERED FUEL BURNERS AND FURNACES. — In burning powdered fuel, it is necessary that the coal be dried to a moisture of 1 per cent or less. The coal must be ground to such fineness that 95 per cent will pass through a 100-mesh screen and 80 to 85 per cent through a 200-mesh screen. Reliable regulation of the coal and air supply seems to be the principal requirement of a good burner. John V. Cullney specifies the essentials as: (*a*) uniform feed; (*b*) proper mixture of coal and air; (*c*) proper control and ability to vary coal supply; (*d*) simplicity; (*e*) compactness. The life of furnaces using pulverized coal varies with the type of furnace. Information available at the present time indicates that the life of such furnaces is about the same as for furnaces using oil. The working temperatures of powdered fuel furnaces seem to range from 1800 to 3000° F.

Cost of Grinding and Handling, including Upkeep (Pre-war figures). — These items vary considerably with plants of different size and under different operating conditions. The cost of grinding, drying, handling, etc., per ton of fuel, as reported by four companies is as follows:

For Plant (*a*) about 45 cts. per ton, subdivided as follows:

Labor	15 cts.
Power	10
Repairs	14.5
Coal for drying	5.5
	45 cts.

For Plant (*b*), based on 200 tons in 24 hours, excluding overhead charges, interest, and depreciation.

Price of coal	Cost of grinding, handling, etc.
$1	17.6 cts.
2	21.8
3	23.9

For Plant (*c*), 140 tons per 24 hours in plant built 16 years ago.

	Cost per ton.	
Labor, operating	15.64 cts.	
Labor, repairs	1.70	
Supplies, fuel, power, etc.	14.71	
Oil and waste	1.25	
Repairs	4.54	
		37.84 cts.
Interest, depreciation and obsolescence		1.35
		39.19 cts.

For Plant (*d*), from 11.4 cts. per ton to 49.2 cts., depending upon the degree of pulverization, amount of coal consumed, etc.

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SUPERHEATERS. — To obtain the advantages of superheated steam (*see* ...am), various forms of superheaters are employed. A superheater consists ...entially of a number of small tubes, through which the steam is passed, ...anged to be heated by the hot gases in the boiler or from some external ...rce. In this country the superheater is nearly always placed within the ...iler setting. Frequent cleaning of the exterior walls of the superheater tubes ...th steam is necessary to prevent the accumulation of soot. It is customary ...provide for the flooding of the superheaters when the boiler is banked and ...en steam is being raised; this procedure may be undesirable when the feed ...ter contains much scale-forming impurity, as superheater tubes are not ...dily cleaned internally.

PERFORMANCE OF BOILERS. — The number of boiler horse-power ...., the number of pounds of steam from and at 212° F. divided by 34.5) which ...n be obtained from a boiler depends upon the heating surface of the boiler, ...e grate area of the furnace, the quality of coal used, the method of firing, etc. ...nsequently the horse-power rating of a boiler is at best but an exceedingly ...gh indication of its capacity, and therefore the modern tendency is to rate ...oiler in terms of the number of square feet of heating surface. If the horse-...wer rating is also given, this is usually taken arbitrarily for water tube boilers ...the number of square feet of heating surface divided by 10; that is, 1 boiler ...se-power is taken as equivalent to 10 square feet of heating surface. Some ...ge modern boilers, however, are operated normally under conditions such ...t the boiler horse-power actually developed is twice the rating on this basis. ...ilders of fire tube boilers usually rate them on the basis of 11 to 12 square ...et per boiler horse-power.

Boiler Capacity. — The capacity of a boiler may be expressed in terms ...the boiler horse-power which may be obtained from it, or, more definitely, ...terms of the number of pounds of water which can be evaporated in it. The ...pacity of a boiler, by which is meant the quantity of steam it will make in a ...ven time, depends (1) upon the quantity of heat that can be generated in ...e furnace, and (2) upon the percentage of this heat that is absorbed by the ...iler and not wasted in the chimney gases or by radiation.

The first essential of boiler capacity for a given heating surface is furnace ...pacity, and this depends chiefly upon three things, area of grate surface, ...uality of fuel and force of draft. It may also depend upon the kind of grate, ...plain or shaking grate, or mechanical stoker; upon the roof of the furnace, ...hether formed of the heating surface of the boiler, or of fire brick; and upon ...e introduction of air above the fire in addition to that which passes through ...e grate. The second essential of boiler capacity is boiler efficiency. Other ...hings being equal, anything that increases the efficiency of a boiler increases ...s capacity in the same ratio.

Factors Affecting the Efficiency of a Boiler. — Boiler efficiency de...ends: (1) on the quality of the coal (or other fuel) as regards its content of ...oisture and volatile matter (*see article on Fuels*); (2) on the completeness ...ith which the coal is burned in the furnace, before the gases of combustion ...ach the heating surface; (3) on the combustion being effected with the least ...ossible excess of air, above 20 per cent excess being necessary to avoid imperfect ...mbustion; (4) on the cleanness of the heating surface, inside and out; (5) on ...e proper baffling of the gases, so as to avoid short-circuiting; (6) on the heat ...st by radiation; and (7) on the extent of the heating surface relative to the ...uantity of heat generated, or to the rate of driving of the boiler, as measured ...y the heat absorbed in a given time per square foot of heating surface (*see ...ction on Heating Surface, below*). In general the efficiency of a boiler may be ...epresented approximately by the equation

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$$e = \frac{T_1 - T_2}{T_1},$$

in which T_1 is the temperature of the fire and T_2 the temperature of the chim gases. The temperature T_1 is proportional to the heat generated in the furn assuming the specific heat of the gases to be constant, and T_2 to the heat in the chimney. The loss by radiation is not considered in the formula. this is generally not over 2 to 3 per cent when a boiler is driven at a normal r

Values of Boiler Efficiency. — The *highest* efficiency that is obtai with ordinary boilers and furnaces, fired by hand, is about 79 per cent v anthracite and 76 per cent with bituminous coal. As high as 81 per cent s possibly be obtained with bituminous coal with very large boilers, provi with mechanical stokers, and 82 per cent with oil fuel. With economiz heating the feed water by the waste heat of the gases from the boiler, the c bined efficiency of boiler and economizer may be as high as 90 per cent.

The necessary conditions for obtaining these high figures of efficiency (1) that the coal is of good quality, low in moisture; (2) that the coal is bur uniformly and with uniform conditions of air supply, so that the grate is obstructed by clinker or imperfectly covered by coal; (3) that the rate of dri does not exceed 3 pounds evaporation per square foot of heating surface hour; (4) that the air supply does not exceed 20 pounds per pound of coa burned; (5) that the combustion of the gases is completed in the furnace that no unburned gases touch the heating surface of the boiler and bec chilled below the point of ignition; (6) that the path of the gases through boiler is so baffled as to cause them to traverse uniformly all parts of the hea surface; (7) that the heating surface is free from soot and dust on the out and from scale or grease on the inside.

The conditions of high efficiency above described are obtained only in best-managed plants, where the chimney gases are constantly analyzed a check on the air supply (*see below under Tests of Boilers*). In the average p in everyday practice the efficiency may be anywhere from 10 to 30 per c below the best possible.

Boiler efficiencies are usually graded as follows: 50 to 60 per cent, poor; 6 70 per cent, fair; 70 to 75 per cent, good; over 75 per cent, excellent.

Effect of Rate of Evaporation on Efficiency. — On the basis o square feet of heating surface per boiler horse-power (34.5 pounds of steam f and at 212° F.) approximately 3 pounds of steam are evaporated per square of heating surface when the boiler is developing its rating at normal steam pres and temperature. If there is sufficient grate surface and draft the evapora may be increased to 6 or in emergency to 15 pounds of steam per square of heating surface. The efficiency, however, falls off with increased rat driving. The following figures are taken from a test by D. S. Jacobus (*Tr A.S.M.E., 1911*) on a large Stirling boiler (23,650 square feet of heating surfa

Equivalent evaporation per square foot =	3.24	3.40	3.72	4.18	5.22	5.62	6.40	6.67	6.75
Over-all efficiency =	81.2	81.0	80.3	79.2	77.1	77.9	76.4	76.7	75.6

Still higher rates of driving and the corresponding efficiencies are given be these figures being taken from a test of Babcock & Wilcox boilers designed the United States warships "Cincinnati" and "Wyoming" (*Industrial E neering, March, 1911*). The results are as follows:

Equivalent evaporation per square foot =	8.42	8.75	9.03	9.58	10.1	10.5	13.7
Over-all efficiency =	70.4	70.6	72.1	68.2	70.1	71.0	64.5

These efficiencies are all exceptionally high for the given rates of driving, t the relative efficiencies for the different rates are representative of good rage practice.

Thickness of Fire and Efficiency. — Too thin a fire results in excess air and too thick a fire in a deficiency, unless sufficient draft is provided by ans of fans or tall chimneys (*see Draft, Mechanical*). There are so many tors to be considered that the proper thickness for maximum economy in any rticular case can be determined only from actual test. Under ordinary con- tions of hand-firing the thickness of fire for best efficiency ranges from 6 to 12 ches.

Air Supply and Efficiency. — The air supply for maximum efficiency, l other conditions remaining constant, is about 17 or 18 pounds per pound of rbon.

With an air supply lower than 17 pounds the efficiency is likely to fall off, i account of imperfect combustion. If the air supply is greater than 20 pounds e efficiency falls off very rapidly, the excess air supply causing a reduction temperature in the furnace and an increase of heat carried into the chimney.

Heat Balance and Distribution of Losses. — By the "heat balance" is ant a statement accounting for ultimate distribution of the B.t.u. in the el supplied to the boiler. Such a statement is usually made up as follows. he figures given illustrate the ordinary range for the various items.

HEAT BALANCE PER POUND OF COMBUSTIBLE

Item	B.t.u.	Per cent
1. Heat absorbed by the boiler	.....	80–50
2. Loss due to heating moisture in coal	.....	0.2–2.0
3. Loss due to heating moisture formed by the burning of hydrogen	.....	0.5–4.0
4. Loss due to heat carried away in the dry chimney gases	.....	12–30
5. Loss due to incomplete combustion of carbon (CO in flue gas)	.....	0.0–3.0
6. Loss due to		
a. Unconsumed hydrogen and hydrocarbons (smoke and soot)	.....	0.0–1.5
b. To heating the moisture in the air	.....	0.2–1.5
c. To carbon lost through grate	.....	0.5–3.0
d. To radiation	.....	1.0–3.0
e. Unaccounted for	.....	1.0–10.0
Total	11,000 to 15,500	100

The five items under 6 are frequently given as a single item.

TESTING OF BOILERS. — The principal observations made during an evaporation" test of a boiler are pounds of water evaporated, pounds of coal red, steam pressure and feed-water temperature. Records of the water aporated and the coal fired should be made for each hour of the test if possible. he steam pressures and feed-water temperatures are recorded every half-hour r oftener, and averaged for the whole test. All conditions should as nearly s possible be the same at the end as at the beginning of the test. When the rnaces are hand fired, tests of 8 to 10 hours duration are usually sufficient, but hen mechanical stokers are used it is difficult to obtain an equal quantity and ndition of the coal in the furnace at the beginning and end of the test, and a

large error in the results may be made if the test is much shorter than 24 hour The average moisture in the coal should be determined and the ash and refu should be weighed.

In all important tests the code of the American Society of Mechanical Eng neers (new code to be published shortly, 1922) should be followed. The princip data and results given in this code are as follows:

PRINCIPAL DATA AND RESULTS OF BOILER TEST.

1.	Grate surface (width ...., length ....)	sq. ft.
2.	Total heating surface	sq. ft.
3.	Date	
4.	Duration	hr.
5.	Kind and size of coal	
6.	Steam pressure by gauge	lb.
7.	Temperature of feed water entering boiler	° F.
8.	Percentage of moisture in steam or number of degrees of superheating	per cent or ° F.
9.	Percentage of moisture in coal	per cent
10.	Dry coal consumed per hour	lb.
11.	Dry coal consumed per sq. ft of grate surface per hour	lb.
12.	Equivalent evaporation per hour from and at 212°	lb.
13.	Equivalent evaporation per hour from and at 212° per sq. ft. of heating surface	lb.
14.	Rated capacity per hour, from and at 212°	lb.
15.	Percentage of rated capacity developed	per cent
16.	Equivalent evaporation from and at 212° per lb. of dry coal	lb.
17.	Equivalent evaporation from and at 212° per lb. of combustible	lb.
18.	Calorific value of 1 lb. of dry coal by calorimeter	B.t.u.
19.	Calorific value of 1 lb. of combustible by calorimeter	B.t.u.
20.	Efficiency of boiler, furnace and grate: $100 \times \left(\frac{\text{Item } 16 \times 970.4}{\text{Item } 18}\right)$	per cent
21.	Efficiency of boiler and furnace: $100 \times \left(\frac{\text{Item } 17 \times 970.4}{\text{Item } 19}\right)$	per cent

Flue Gas Analysis and Heat Balance. — See Kent's *Mechanical Engineer Pocket-Book* and Gebhardt's *Steam Power Plant Engineering*.

SPECIFICATIONS FOR STEAM BOILERS. — As nearly all stea boilers are now made by large manufacturing concerns who have their ow specifications as to details of construction, quality of material, etc., it is rare the case that an engineer of a power plant or a consulting engineer is called o to make an original design of a boiler or to furnish detailed specifications fo one. What is usually done is to call for bids on general specifications, namin the quality of coal to be used, the kind of furnace or stoker, the horse-power t be developed (34.5 pounds of water evaporated from and at 212° F. = 1 h.p. when the boiler is driven at a rate not to exceed 3.5 pounds per square foot o heating surface per hour, evaporated from and at 212° F., and the overload capa

y desired for higher rates of driving, or " the peak of the load." The bids re-ved are then tabulated as to the details, such as heating surface, grate surface, e of combustion chamber, size of tubes, diameter of shell, quality of steel, le of riveting, factor of safety, space occupied, guarantees of capacity and nomy, etc., and a selection made of the boiler that appears to be the most itable for the location. Of two boilers that have the same heating surface e one that has the largest grate surface is the one that has the greatest over-ad capacity, if the draft is the same in both cases. Guarantees of capacity id economy may be disregarded when bids are for ordinary forms of boilers id furnaces, for the capacity and economy of two boilers of the same size of ate and heating surface will be practically the same whatever the type or rm of the boiler, but they will vary greatly from causes independent of the ilers themselves, such as quality of coal, method of firing, kind of furnace, e of combustion chamber, etc.

OPERATION OF BOILERS. — To obtain the best results from boilers, nsiderable care must be paid to the firing and regulation of air supply.

Firing. — There are three common methods of hand firing: (1) the alternate which fresh coal is fired on one side of the grate at a time, the combustion of olatile matter being assisted by the heated air passing through the other side; 2) the spread-firing, in which small amounts are spread thinly over the entire re bed; and (3) the coking, in which a thick bed of fresh coal is fired directly n front of the door and allowed to coke, after which it is pushed back into the urnace. The best method for any particular kind of fuel, style of furnace nd rate of driving should be determined by experiment.

Mechanical stokers (*see Stokers, Mechanical*) afford the following advantages: ix., the uniform feeding of coal, the close regulation of the air supply at all imes, and consequently smokeless and efficient combustion with a wide range f loads, and a great reduction of labor cost in handling and firing fuel. In mall plants with poor load factors the expense of installation is generally con-idered prohibitive, but in plants of 1500 kilowatts or more a considerable net nnual saving can usually be obtained.

Air Supply. — (*See also Chimneys; Draft, Mechanical.*) The extent of the ue losses is determined by the amount of gas discharged, the temperature at hich it is discharged, the amount of incompletely burned gas discharged and he amount of latent heat carried away in water vapor. The minimum economic mount of flue gas would obtain with the amount of air supplied to the fire xactly equal to the theoretical requirements of complete combustion. The dmission of less air tends to the production of CO. More air dilutes the flue as, increases the total amount of gas rejected and, in the same ratio, increases he amount of heat rejected, the stack temperature remaining the same. The heoretical air supply per pound of combustible (*see Fuels*) is approximately .2 pounds, but since the air and fuel cannot be mixed with perfect intimacy it s necessary to considerably increase this amount to prevent the formation of CO. See above under *Air Supply and Efficiency.*

CO_2 Recorders. — The per cent of CO_2 in the flue gas is an index of the ir excess, provided combustion is complete. With perfect combustion and no xcess air 20.9 per cent CO_2 should be obtained with pure carbon as fuel, or 18.6 per cent with a fuel composed of 95 parts C and 5 parts H. In practice nore air must be supplied and 14 per cent CO_2 represents about the upper limit which should be attempted. 12 per cent CO_2 is good, 10 per cent fair and 8 per cent poor. Several types of CO_2 recorders have been devised. If prop-rly maintained and interpreted they form a valuable check on the regulation f the air supply. Their indications, however, give no clue to the presence of CO, and are directly significant only when the formation of CO is prevented.

Flue-gas Temperature. — Because of the great heating surface wh would be required it is not practicable to reduce flue-gas temperature to l than 75 degrees above the feed water. Economizers or flue-gas feed-wa heaters (*see Feed-water Heaters*) assist in lowering the temperature of disch but add considerably to the space required, increase the cost of installation a maintenance and increase the total draft required. Without economizers it seldom economical to attempt to reduce the gas temperature below 450° F.

Smoke represents a minor element of loss *per se*, seldom exceeding 1 per ce but it is generally an index of inefficient combustion. Smoke is usually due a poorly regulated air supply, an imperfect mixture of air and fuel, or the u rapid volatilization of hydrocarbons and their premature chilling in a h burned state. The absence of smoke, however, is not a final index of efficien for the air supply may be excessive. See also article on *Smoke Prevention*.

Feed Water. — (*See Feed-water Heaters; Pumps and Pumping Engines.*)

Cleaning Tubes. — The tubes of a boiler should be kept clean, both int nally and externally. For blowing the soot off the external surface the tu of water tube boilers or off the internal surface of the tubes of fire tube boil a steam jet blower is ordinarily used. For removing scale from the interior water tubes different forms of scrapers or chippers are used, also rotary cutti devices driven at a high speed by steam, water or other power. For removi scale from the water side of fire tubes of horizontal tubular boilers the usu method is the operation of chipping and hammering by a man working insi of the boiler. Sometimes the scale is softened by the use of soda or other chem cals, before chipping, and a strong jet of water from a hose assists in detachi the scale. In locomotive practice it is often necessary to cut the tubes out the boiler and run them through a cleaning machine, and then to weld a pie of each tube on one end to restore its original length, and to reset the tubes i the boiler.

DIMENSIONS OF BOILERS. — An ordinary fire tube boiler occupi a floor space of from 1.5 to 2.0 square feet per boiler horse-power (on th basis of 12 square feet of heating surface per horse-power). A water-tub boiler occupies from 0.5 to 1.0 square foot of floor space per boiler horse-p wer (on the basis of 10 square feet of heating surface per horse-power). Wit either type the height ranges from as low as 7 to as high as 30 feet dependin not only on the horse-power but also on the style, whether horizontal o vertical. One boiler is sometimes placed directly on top of another, making "double-deck" arrangement. For complete dimensions see the manufacturer catalogues.

COST OF BOILERS (Pre-war figures). — The selling price of boilers pe rated horse-power (10 square feet of heating surface = 1 horse-power) rang from about $8 to $25, depending upon the size, the pressure they are to sustain the style and design, etc. The lowest prices named are for large-sized ordinar horizontal tubular boilers (fire tube) for low pressures. For power plants o 1000 horse-power and over the price will range usually between $10 and $15 fo pressures not over 150 pounds per square inch. For higher pressures and in boilers provided with superheaters the prices will be higher. For boilers of les than 100 horse-power the price per horse-power increases as the size decreases The prices named are for the boilers with the usual fittings of grates, steam an water gauges, blow-off and stop valves, on board cars at the boiler works, an do not include the cost of erection nor of brickwork, flues or chimneys. (*See also Power Station.*)

The following approximate rules, in which P = boiler horse-power, may b used for determining the cost of boilers:

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) Horizontal return tubular boilers.
Cost f.o.b. factory ($) = 180 + 6.4*P*
Cost of setting ($) = 140 + 2*P*.

) Horizontal water-tube boilers, 125 lb. pressure.
Cost f.o.b. factory ($) = 425 + 9*P*.
Cost of setting ($) = 140 + 2*P*.

) High grade water-tube boiler, 160 lb. pressure.
Cost f.o.b. factory ($) = 1000 + 10*P*.

) High grade water-tube boiler, 200 lb. pressure.
Cost f.o.b. factory ($) = 1300 + 12*P*.

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BONDS, RAILWAY TRACK. — (*See also Third Rail Systems; Trolley Systems; Wires and Cables.*) Rail bonds are electrical conductors for bridging the joints of rails. They consist either of a series of thin strips of annealed copper, or of one or more cables of copper wire, the ends of which are usually pressed or cast into solid copper terminals. Ribbon is more compact, but stranded wire is more flexible; the latter should always be used if space permits. Sometimes the terminals are made by upsetting the ends of a stranded conductor, so as to form a crude bond head. The terminals of the headed bonds are then heated to a welding heat in furnaces, and pressed to the proper size and shape, the separate wires in the terminals becoming a solid mass of homogeneous copper. After being cleansed of all foreign substances the terminals are shaved to the proper size.

TYPES OF BONDS. — Bonds may be classified, according to the method of fastening them to the rail, as soldered bonds, brazed bonds and bonds applied by mechanical pressure.

Soldered Bonds (Figs. 1 and 2) usually consist of a series of thin strips of annealed copper with tinned terminals as shown in Figs. 1 and 2. They are

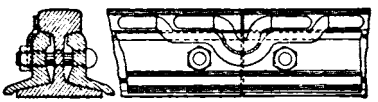


Fig. 1.

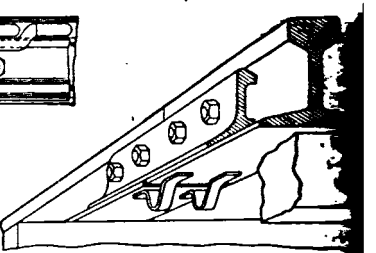


Fig. 2.

soldered direct to the head, foot or web of the rail. One or more bonds per joint may be used. A few companies employing well-trained workmen continue to install bonds of this type, but they have generally been abandoned.

Brazed Bonds resemble soldered bonds except that the terminals are enveloped in brass. They are brazed or welded to the rail by heat generated electrically in a carbon which constitutes one jaw of a clamp holding the bond against the rail. These are sometimes known as "electrically welded" bonds.

Expanded and Compressed Terminal Bonds. — Bonds fastened to the rail by mechanical pressure may be divided into two general classes, expanded terminal and compressed terminal bonds. Both kinds are called "stud terminal" bonds. The number of stud terminal bonds in use greatly exceeds that of any other kind, brazed bonds being second.

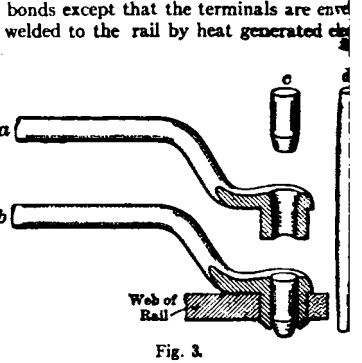


Fig. 3.

Pin-expanded Terminal Bonds (Fig. 3) have their heads drilled with an axial hole, through which a tapered steel pin *d* is driven, forcing the copper

tward and against the steel. This type of bond is fastened to the web of th
l.

Compressed Terminal Bonds (Figs. 4 and 5). — There are two kinds compressed terminal bonds, in one of which direct pressure is applied at both ds of the head, and in the other, at one end only. The first type of bond is ually applied to the web of the rail by means of a heavy screw or hydraulic ss (Fig. 8) which engages the bond head and causes it to compress longitudi-lly and expand laterally as the pressure is applied, bringing the copper into

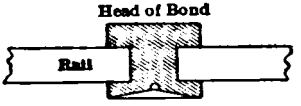
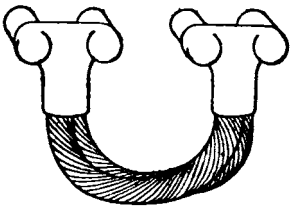


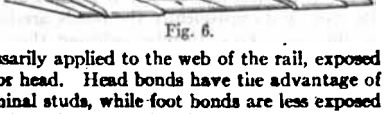
Fig. 4.


Fig. 5.

m contact with the steel and spreading the projecting end of the terminal into button-shaped rivet-head, as shown in Fig. 4. The second type of bond (Fig.) is applied only to the head of the rail, the terminal lugs being set in holes herein and expanded into contact by means of hammer blows.

Compressed Terminal Soldered Bond. — A type of bond which has been ound very successful at the Detroit River Tunnel for third-rail work is a com-ressed terminal head bond soldered to the rail. The combination of mechani-l adhesion and soldering has resulted in a bond of unusual durability. *J. B. P. Wrenn.*)

Exposed Versus Concealed Bonds. — Whether soldered, brazed, expanded r compressed, bonds may be either exposed or concealed (Fig. 6) under the ab-plates. The former condition is preferable, if there is no likelihood of heft, as it permits inspection to be asily made. Where the bonds are xposed to theft, as, for example, a track rails unprotected by pav-ng, concealed bonds are almost a ecessity.


Fig. 6.

While concealed bonds are necessarily applied to the web of the rail, exposed onds may be applied to the foot or head. Head bonds have the advantage of reater contact surface at the terminal studs, while foot bonds are less exposed o mechanical violence. Web bonds, unless concealed, have to be excessively ong in order to span the fish-plates.

USES OF VARIOUS TYPES OF BONDS. — Bonds are used for track ails, third rails and girders of elevated and subway lines. Soldered bonds and ompressed terminal head bonds find their best application in third-rail work, here good electrical contact is of greater importance than mechanical strength. Expanded terminal web bonds, especially of the concealed type with two stranded onductors, are regarded as the best for heavy track work, where mechanical trength and ease of installation are of the utmost importance.

SUBSTITUTES FOR BONDING. — Several efficient substitutes for bond-ng are now in use, such as electrical welding, cast welding and Thermit welding.

Electrical Welding is performed by clamping an iron bar to the web of the ails, and bringing the bar and the neighboring part of the rail to a white heat by

means of an electric current. Another process accomplishes the welding by means of a carbon electrode. A modification of the latter process makes use of a composition bar which is clamped against the fish-plate. A soft steel rod is placed in a groove between the rail and composition bar supplies the welding material.

Cast Welding is accomplished by setting a mold around the rail joint and pouring molten iron around it. The Thermit process is a modification of this, the iron being liberated at a white heat from a mixture of iron oxide and aluminum, which is ignited in a crucible.

SELECTION OF TYPE AND SIZE OF BOND. — Considerations determining the choice between concealed and exposed bonds are liability of theft, electrolytic corrosion, facility of inspection and injury to fish-plate bolts of old rails.

The choice between mechanical adhesion and soldering depends largely upon the importance of rapid installation, the mechanical stresses to be withstood in service, the type of labor available and the facilities for the use of drills, presses, etc.

Single vs. Double Bonding. — Joints are sometimes bonded with one bond, sometimes with two bonds. Double bonding has the advantages of less chance of complete failure and greater carrying capacity for a given cross-section of copper. It, however, has the disadvantages of being more expensive and giving uncertain results in testing.

Selection of Cross-sectional Area of Bond. — The cross-sectional area of a rail bond should, as a rule, be not greater than is necessary to keep its temperature at a safe working amount, unless greater area is required for mechanical strength. The resistance of the bonded joint is of secondary importance unless very high, because the resistance of the joints is usually a mere fraction of the total track-rail resistance (*see below*).

Carrying Capacity of Bonds. — The carrying capacity of rail bonds is not very well known as the manufacturers do not supply any data on this subject for their various products. The excellent heat conductivity of copper and the large heat storage capacity of steel rails tend to make the carrying capacity of bonds in cold weather considerably greater than that of free wire of the same size, especially if the bonds are short. In hot weather, however, the rails and consequently the bonds are likely to become hot from exposure to the sun's rays, thereby reducing the effective carrying capacity of the bonds.

Tests to determine the ultimate carrying capacity of soldered bonds indicate that a 500,000 circular mil bond of the type shown in Fig. 1 will carry 3500 amperes continuously without injury, but will melt in 5 or 10 minutes at 10,000 amperes. On the basis of this test assuming the cooling surface per unit length of a bond to be proportional to the square root of its cross-section, the safe carrying capacity of a bond of A circular mils cross-section is

$$I = \frac{A}{5.6\sqrt[4]{A}}.$$

Or, the cross-section required for a given current is

$$A = 10\, I \sqrt[3]{I}.$$

Resistance of Bonds. — The total resistance of a bond is the sum of the resistances of the copper in the bond and the contact resistance between the body of the bond and the terminals and the contact resistance between the

minals and the rail. The following table gives the resistance of a well-bonded nt at 75° F., including the body resistance and the two contact resistances each end.

RESISTANCE OF BONDED JOINT IN MICROHMS (10^{-6} OHMS)

Size . W. G. r B. & S. nd C. M.	Diameter of terminals, inches	Length of bond in inches, between centers of terminals							
		9	12	15	18	24	30	36	42
500,000	1	28	33	39	44	55	65	76	87
400,000	1	32	39	46	52	66	80	93	106
300,000	1	38	46	55	63	80	97	114	131
250,000	7/8	44	54	65	75	95	116	136	157
0000	7/8	50	62	75	87	111	136	160	185
000	3/4	60	75	91	107	137	169	200	230
00	5/8	72	91	112	131	171	210	250	290
0	5/8	87	112	137	162	211	260	310	360

Bonding Efficiency and "Equivalent" Length of Joint. — The onding efficiency* of a bonded rail system (having one bonded joint to ch rail length) is the ratio of its conductance to that of an equal length of rfectly continuous rail without any breaks or joints. By "equivalent" ngth of a joint is meant the length of continuous rail having a resistance ual to that of the bonded joint. Let

B = bonding efficiency,
l = distance in feet measured along the rail between centers of bond terminals,
l' = equivalent length of bonded joint in feet,
L = length in feet of a full rail section,
r = resistance of rail per foot,
R_j = resistance of bonded joint.

hen

$$l' = \frac{R_j}{r},$$

$$B = \frac{1}{1 + \frac{l' - l}{L}}.$$

For values of r see article on *Rails*. The equivalent length of a properly nded joint ranges from 1 foot to 6 feet, depending upon the size of rail, number nd cross-section of bonds, length of bond, etc. (See also section on *Rebonding*, elow.)

It is common practice to bond a joint with a bond having one-half the conductance of the rail. Hence for a 12-inch bond, and 30-foot rail section, assuming inches between terminals measured along the rail, $l = 0.75$ and $l' = 2$, giving a onding efficiency of 96 per cent.

Selection of Length of Bond. — The length of concealed bonds is necessarily determined by the dimensions of the rail and fish-plate, and by the bolt-ole drilling. The length should never be less than ten inches for single bonding

* The efficiency of individual bonds is sometimes stated as the ratio of the distance long the rail between centers of bond terminals to the equivalent length $= l/l'$.

and should generally be greater, it being usual practice to place the termina between the first and second bolt holes. In double bonding it is customa to place one terminal of each bond between the first and second bolt holes each rail, and the other terminals beyond the second bolt holes. It is n unusual to use concealed bonds 2 feet long for double-bonded rails on electr fied steam roads. Exposed bonds are usually made as short as is consiste with the flexibility requisite to withstand vibration and other rail movements.

Tests by H. H. George (E.R.J., 1914, Vol. 44, p. 487) on No. 0000 strande wire bonds showed the following relative number of vibrations to produce fra ture.

Length of Bond inches	Relative number of vibrations
7	1.0
8	5.2
10	31.2
14	194.0

Effect of Vibration and Expansion of Rails. — The continu bending of a copper wire or ribbon will cause local hardening and crystallizati of the metal, and eventually lead to fracture. It is, therefore, important save track bonds from vibration as much as possible, and they should be initial designed to withstand the vibration they are likely to experience in use. T best way to accomplish this is to use long thin wires of soft annealed copp entirely free from surface imperfections.

According to the A. S. W. Co., Cat. No. 3, wires of from 0.040 to 0.045 in diameter give the best general service for short bonds.

Concealed ribbon bonds, and to a less extent wire bonds, frequently bre at the loop between rail bolts, first, because the operation of crimping slight hardens the copper in the loop, and second, because the travel of the rails, d to their expansion and contraction, is wholly taken up in the loops, causing t copper to crystallize and break at this point. Of course this action is aggravat by any severe jarring or vibration of the joint.

SPECIFICATIONS. — (*See also article on Specifications and Contract*) Specifications for rail bonds should state the exact service conditions und which the bond is to be used, the style of adhesion desired, the part of the r they are to be applied to, the style of conductor (ribbon, solid wire or cabl the cross-sectional area, the contact area of the stud, the formed length betwe centers of terminals, and the fish-plate and bolt layout, if the bonds are to concealed.

INSTALLATION. — The foremost consideration in the installation bonds is the cleanliness of the bonds and bond holes, or other adhesion surfa Unless this is secured the bonds will be electrically defective whatever th mechanical strength may be.

Soldered Bonds. — The rail surface is brightened by means of a carboru dum or emery wheel, then tinned, using an acid flux. The bond is then clamp in place and the rail and bond heated by means of a blow-torch, to a temper ture at which the solder will melt and cause the bond to adhere firmly to the ra

Brazed Bonds. — The preliminary processes are the same as for solder bonds except that a special clamp is used, the terminals of which are the el trodes of an electrical circuit, one being of copper and the other of carbon.

The surface of the rail being previously ground bright at the point whe the weld is to be made, the brass-enveloped bond terminal is placed in positi against the rail at this point, held there and pressed against the rail by the carb

lectrode, the copper electrode being in contact with the opposite side of the ail. The current, on passing from one electrode to the other, traverses the ond terminal and rail, the carbon becoming incandescent. The incandescent arbon pressing the copper against the rail quickly transmits sufficient heat exactly the point where it is required, to produce the weld. To make a weld, he current is applied for a period of from 45 seconds to two minutes, depending n conditions.

Welding Outfit. — It is claimed by the manufacturers of one type of elding outfit that an average of over 100 bonds per day is readily installed y their car operating with four men, a bonder and three helpers. This car about 6 feet, 10 inches long by 5 feet, 10 inches wide, and carries an 18-kilowatt otary converter and transformer, with the necessary apparatus for their safe peration. To weld an average-size rail bond to the rail, an alternating current f about 2000 amperes at 5 volts is employed. On d-c. railways this is obtained y converting and transforming about 20 amperes at 500 volts taken from the rolley wire.

Pin-expanded Bonds. — The rail is drilled, usually through the web, with r without lubricant, using some form of drill especially adapted to this service.

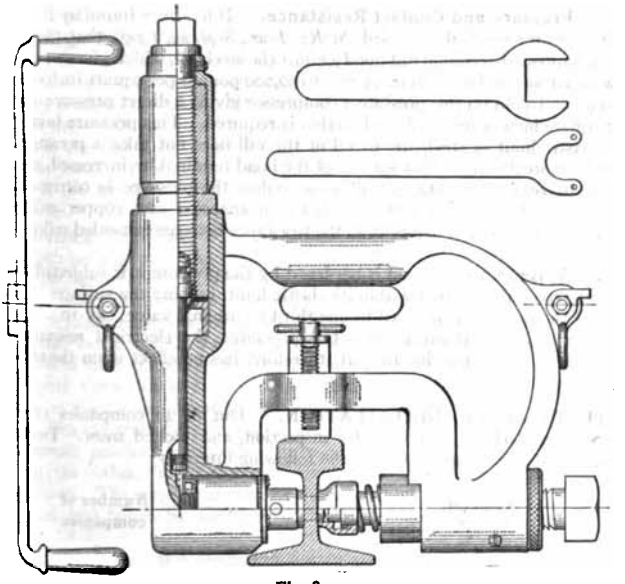


Fig. 8.

Drilling without lubricant has the advantage of giving a perfectly clean hole, nd is now generally preferred. Holes are drilled to the same diameter as the ond studs, and rust or scale on the web of the rail is removed around the hole. The bond head is then inserted into the hole, and a long taper punch lubricated with grease is driven entirely through the terminal. Then a short drift pin is driven home, as shown in Fig. 3. The diameter of the hole is usually increased

about ⅛ inch by the expansion process. From 100 to 200 bonds may be inst with one taper punch before it is worn down to an appreciable extent.

This type of bond requires a smaller equipment in tools and materials t most other types and does not necessitate the use of any apparatus w obstructs the track and thereby endangers traffic.

Compressed-terminal Web and Foot Bonds. — The drilling and cleaning having been performed as for a pin-expanded bond, and the bond h inserted into their respective holes, a screw or hydraulic compressor, as sho Fig. 8, is applied at both ends of the bond head, the conical point of the p fitting into the conical depression of the bond. Pressure is applied, either u collar on the ram touches the rail, or until the head of the bond acquires proper shape. Where no collar is used the point of the press (if of the s type) sometimes cuts into the bond head; this may be avoided by placi small amount of flake graphite mixed with oil in the depression of the bond h

Compressed-terminal Head Bonds. — A four-spindle drill is used to four holes simultaneously in the rail heads. It is important to avoid dri the holes too deep lest the copper should not touch bottom and therefore unable to expand laterally. If, on the other hand, the hole is too sha expansion will occur too soon.

Pressure and Contact Resistance. — It has been found by P. M. H P. C. Smith and C. B. Starbird (*St. Ry. Jour., Sept. 14, 1907*) that the pres of a compressed-terminal rail bond against the steel rail, which gives a reaso low-resistance value, is from 25,000 to 30,000 pounds per square inch of co surface. To obtain this pressure a compressor giving a direct pressure of 25 per square inch of terminal steel section is required. This pressure being w the elastic limit of steel, the metal of the rail does not take a permanent Furthermore, if the contact surface of the bond terminal be increased, no ap ciable decrease of resistance will occur unless the pressure is correspondi increased. The contact resistance between annealed cast copper and ste from 30 to 60 per cent higher than the resistance between annealed rolled cop and steel.

The copper of a bond head is hardened by the pressure it is subjected to, a like the steel, is distorted within its elastic limit, causing the surfaces to ad even if the pressure is reduced to one-third its original value, say 10,000 po per square inch. Between these two pressures, the electrical resistance d not vary. Expansion due to heat, therefore, has no effect upon the resista of bonds.

TESTS AFTER INSTALLATION. — Out of 42 companies 15 do inspect regularly, 6 test only by inspection, and melted snow. Twenty- companies which inspect, test at the following intervals

Interval, months	Number of companies
3	2
6	10
12	12
18	1

Twenty-three of these companies use portable bond testers; four use a graphic test cars.

Resistance Test. — The usual method of testing is to measure the drop potential across the bonded joint and find simultaneously the length of c tinuous rail in which the same drop occurs, i.e., the "equivalent" length of t

led joint. Several ingenious instruments have been devised for making comparison with ease and accuracy.

Differential Voltmeter Method. — The most accurate type consists differential voltmeter and three contact pieces for attachment to the rail. winding of the differential voltmeter is connected to a pair of contact es *A* and *B*, which are placed ntact with the rail just over centers of the bond termi-, see Fig. 9, and the other ding to a pair of contact es *B* and *C*, which span a able length of continuous The distance *BC* is varied moving the contact *C* until voltmeter shows no deflec-. This indicates that the ential drop between *A* and *B* qual to that between *B* and *C*, or in other words, that a length of continuous has been found which has the same resistance as the bonded joint. The ter should make sure that there is current in the rail while he is making test.

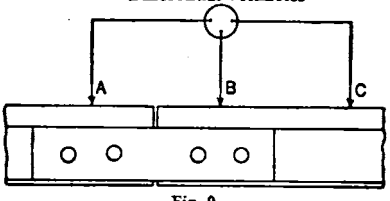
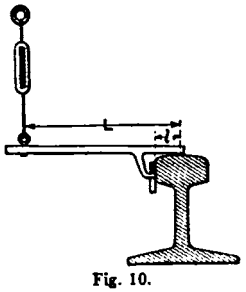


Fig. 9.

Conant Bond Tester. — R. W. Conant (Cambridge, Mass.) makes a nd tester in which the balancing is done by sound. A clockwork interrupter, induction coil, and a telephone receiver is connected across a Wheatstone dge (*see Bridges, for Electric Measurements*). The interrupted current causes nds in the telephone receiver, which sounds diminish and disappear when drop in the rail is balanced, by the bridge adjustment, to equal the drop oss the joint. This type of apparatus has the advantage of being indeident of the traction current in the rails, and is, therefore, constant in its sitiveness.

Herrick Test Car. — A. B. Herrick has devised a recording instrunt, which being placed on a car, is able to test the bonding of a railroad while ning the car over it. The Herrick test car carries autographic recording aratus, which measures by means of millivoltmeters, the potential drop oss each joint, recording on sensitized paper by an electric spark, the scale the record being usually about 1 inch to 60 feet of track. Wire-brush conis made of steel of composition similar to that of the rail measure the drop ss joints through which low-voltage current irculated from a small motor generator set on car The car trucks are insulated from each er. current passing through the rail from one ck to the other, while the bond is under asurement. The apparatus can also automatly mark bad bonds by squirting paint on the


Fig. 10.

The advantages of this method of testing are follows: 1. Uniform impressed low-voltage rent through joints while testing; 2. Heavy passing over joint breaks any transient conion made by fish-plate; 3. Autographic record duced by the bonds themselves of their conion.

Mechanical Strength. — The mechanical adhesion of soldered bonds may tested by means of a lever as shown in Fig. 10. It may be used as soon

as the terminals are cool. The operation of testing consists simply in s mitting each bond terminal to a predetermined pull. A properly solde bond should stand a shearing force of 1200 pounds per square inch of cont Calling S this shearing force per square inch, A the square inch of cont and P the pull, as registered on the balance, then

$$P = \frac{ASl}{L}.$$

REBONDING. — The resistance at which a joint should be rebon depends upon how much potential drop is permissible in the tracks, and up the relative cost of the energy loss and the cost of rebonding. The latter, turn, depends upon the probable life of a new bond. If the energy loss is t primary consideration, the resistance at which rebonding becomes economic is given by the formula below.

Let

R = amount by which the resistance of the existing bond has increas over that of a new bond, ohms,

B = cost of rebonding once, dollars, allowing credit for scrap material,

I = root-mean-square current in the bond, amperes,

C = cost of an increment of energy, dollars per kw. hour,

T = expected life of the bond in days, i.e., the number of days in wh its resistance is expected to increase R ohms, or in which it is be removed for any reason whatsoever. This may be estimat from previous experience on the railway under considerati the usual limitations being the life of the rails to which they a attached, corrosion by electrolysis, fracture due to crystalli tion and loosening of the terminals.

Then it is economical to rebond if R is equal to or greater than

$$\frac{B}{0.024\,I^2CT}.$$

It is usual to state the resistance of bonds in terms of the number of feet rail having the same resistance. Let r be the resistance of the rail in ohms p foot; then the increased resistance R will be represented by an increased leng expressed in feet, equal to $\frac{R}{r}$.

It should also be noted that bonds in different parts of a railway system car different amounts of current, those nearer the station bus carrying more th those at comparatively remote points. Hence, the economical resistance which to rebond is less the nearer the bond is to the bus, a consideration th complicates the use of the above formula. Furthermore, as the economic resistance is inversely proportional to the square of the current, a slight err in the estimation of the root-mean-square current will lead to a considerabl error in the resistance. Such errors are unavoidable, a circumstance that, take in conjunction with the probable error in the estimated life, renders the abov formula a mere approximation. It is, therefore, usual for railway companie to select some arbitrary total resistance at which to replace their bonds, th resistance being expressed in terms of equivalent length of rail. For urba lines this length varies from 3¼ feet to 20 feet with an average of about 8 feet for suburban lines, a length of 12 feet or more is common.

REPAIRS. — If a soldered bond becomes loose, it may often be resoldered but defective bonds of other types are usually scrapped, unless the defect is o a very trivial nature. Pin-expanded bonds may, however, be reexpanded int

ger holes, but with some loss in efficiency. Soldered bonds entail a comratively large and increasing expense for repairs when applied to track rails, spite of the fact that no failures may occur for several months after installation. ost bond failures are due to loose rail joints.

COSTS. — The cost of bonding is extremely variable, depending upon the pe and size of bond, cost of labor, etc. The following cost data should therere be used with caution.

COST OF BONDING

	Cost per joint		
	Labor	Material	Total
a. 2-500,000 C.M. bonds soldered to head of third rail	$0.66	$1.23	$1.89
b. 2-500,000 C.M. pin-expanded concealed bonds applied to track rail.	0.69	2.05	2.74
c. 2-400,000 C.M. compressed terminal concealed bonds applied to track rail	....	....	1.90
d. 2-0000 bonds of same type as *c*	0.50	1.00	1.50

Note.—In *a* and *b* the item for material includes inspection and the labor item includes foreman's salary; solder, acids and tools, not included.

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BRAKES AND BRAKING SYSTEMS. — (*See also Cars, Electric; Railways, Energy Requirements for.*) In order to stop a car or train a torque must be applied to the wheels in a direction opposite to the direction of motion of the car. This may be accomplished by applying a frictional retarding force to the wheel rims, by applying a retarding force to the axle by means of a magnetically operated friction clutch, by applying a reverse torque to the axles by operating the motors as generators, or by applying a frictional force to the rails directly by a "track brake." The method of applying a retarding frictional force to the wheel rims is the most general one and lends itself most readily to the system of manipulating the brakes by compressed air. This system has done much to improve the safety of travel on railroads. The other methods have all been tried and some have been put into practical operation, but only to meet special local conditions.

FRICTIONAL RESISTANCES IN BRAKE-SHOE SYSTEM. — The application of the usual brake-shoe system makes use of the frictional adhesion between the wheels and the track and between the brake shoes and the wheels. Both these quantities vary throughout a considerable range and it is therefore necessary to adjust the pressure between the various members so that it is possible to rely on a definite minimum value.

Adhesion between Wheel Rim and Rails. — The coefficient of adhesion between the wheel rims and rails varies from less than 15 per cent to over 30 per cent depending upon the condition of the track and the relative motion between the track and wheel rim. (*See Railways, Energy Requirements for.*) An adhesion of 15 per cent can usually be depended upon with normal track, and this can be increased to 25 per cent by the use of sand. But these values only obtain while the wheels are rolling on the track. If they begin to slide the coefficient decreases considerably. For this reason the braking effort must always be controlled so that the wheels do not slip.

Adhesion between Brake Shoe and Wheel Rim. — When the brakes are applied, the retarding force is applied below the center of gravity of the car body. The latter is therefore subjected to a couple and tends to press downward at the forward end and upward at the rear end, thus changing the distribution of weight on the axles and decreasing the adhesion on some axles or trucks. It is therefore not possible to figure on using for braking purposes the same weight per axle as exists at standstill. For this reason the brake-shoe adhesion must be less than the track adhesion. The coefficient of adhesion between the customary cast-iron brake shoe and the steel tire of the wheel varies with the speed, and decreases as the time of application increases. As the speed increases the coefficient drops off, being a maximum of from 30 to 25 per cent at speeds from 0 to 5 mi. per hr., 20 per cent at 20 mi. per hr., 14 per cent at 40 mi. per hr., and 7.5 per cent at 60 mi. per hr. Thus at high speeds a heavy pressure may be applied without stopping the wheels, while as the speed of the car diminishes the pressure on the brake shoes must be decreased in order to prevent gripping the wheels and causing them to slide on the track.

Effect of Angular Momentum. — In addition to overcoming the linear momentum of the cars the brakes must overcome the angular momentum of the gears and motor armatures. The effect of the latter is to introduce a tendency of the whole motor to rotate around the car axle and introduce additional strains on the gears and on the trucks. For this reason brake shoes hung between the wheels of a truck are better than those hung on the outside of the wheels.

HAND BRAKES are always provided on cars and locomotives whether power brakes are employed or not, as they are necessary to hold a car left out of service on a grade, because the air brakes will not hold a car standing idle for any

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ngth of time. When a car is descending a very steep grade it is customary
set the hand brakes to hold the speed of the car and reserve the power brakes
emergency or for stopping the car. In hand braking equipment the "foun-
ation" brakes (*see next paragraph*) are actuated through a drum or lever
stem which is hand operated.

POWER BRAKES. — The "foundation" brakes are that part of the brake quipment usually furnished separately from the power-braking equipment, and onsist of the brake shoes, hangers, equalizers, levers, etc., back to the brake ylinder. To this is attached the desired form or make of power brake. Of he various forms of power brakes in use, viz., air, electric, regenerative and lectro-pneumatic, the air-brake is the most generally used.

Air-Brakes. — In electric railway practice there are three systems of air-rakes in use, each of which is best suited to a definite type of service and has its articular field, as follows: (1) straight air-brake system for cars always operated ingly; (2) emergency straight air-brake system for cars operated in trains of wo or three but never more than three cars; (3) automatic air-brake system or cars operated in trains of any number of cars.

Straight Air-brake System. — The equipment for the straight air-rake system consists essentially of a motor-driven compressor, a reservoir, a brake cylinder, a motorman's valve, a train pipe, and the foundation brakes. The brakes are applied by direct pressure, that is by admitting air from the reservoir directly to the cylinder. The advantages of the system are that it is quick-acting and the braking effort is easily controlled to any value desired. Its disadvantage is that in trains a leak in the train pipe renders the brakes ineffective so that there is no means of applying the brakes on the trail-cars if the train should break apart. Sometimes instead of a compressor the motor-car carries a large reservoir which is charged at stations.

Emergency Straight Air-brake System. — This system involves a special valve and an extra pipe on each car so arranged that if the air pressure in the train pipe drops, due to cars breaking apart, this valve automatically turns the pressure of the reservoir into the brake cylinders and applies the brakes. The equipment of the motor car includes an extra pipe and each trail car has a reservoir, two pipes, automatic valve, brake cylinder and foundation brakes. The usual operation in service is like that of the straight air-brake.

Automatic Air-brake System. — This system involves the use of an auxiliary reservoir and a "triple valve" on each car. Whenever the air pressure in the train pipe is reduced, either intentionally or accidentally, this triple valve turns the air pressure of the auxiliary reservoir on each car into the brake cylinders. The brakes are applied by the motorman by opening the service pipe to the air by means of the engineer's valve. The engineer's valve has three positions, "off," "lap," and "on." By turning the handle to the "on" position the train pipe is opened to the atmosphere and the air continuously escapes. This applies the brakes with a continuously increasing pressure. When the desired pressure has been reached the handle is turned to the "lap" position, when the pressure of air in the train pipe and the pressure of the brakes on the wheels remains constant. By turning the handle to the "off" position pressure is restored in the train pipe, the brakes are released, and the reservoirs recharged.

Quick-action Triple Valve. — In any air-brake system an appreciable time elapses between the action of turning the engineer's valve and the actual application of the brakes. If there are many cars in a train the brakes may be applied on the leading cars sometime before they are applied on the rear cars and the result is that the rear cars bump into the forward cars, and may cause a derailment, particularly if this happens on a curve. To guard against this, the

"quick-action triple valve" is used on long trains. This consists of a special form of valve which causes a local intensification of the change in pressure in the train pipe on each car. The action is somewhat similar to a relay which is affected by slight changes in pressure and causes greater changes, and thus applies or releases the brakes more quickly.

Electromagnetic Brakes. — Any braking system making use of the electric current is not as reliable as the air system since if either the trolley comes off or the motors fail to pick up as generators the brakes are inoperative. Electromagnetic braking may be applied either to the axles or directly to the track.

Disc Brakes. — This system comprises two cast-iron discs mounted concentrically on the car axle. One is keyed to the axle and the other anchored to the truck frames. A coil is placed in one of these discs and when a current flows in the coil the two discs are attracted to each other by the magnetism and the friction between them retards the car. The current for the coils may be taken from the trolley or from the motors operating as generators. In the latter case the motors supply an additional retarding force. The braking effort is controlled by resistance in series with the magnet coils.

Track Brakes. — The principle of electromagnetic braking may also be applied to a track brake in which a magnet coil when energized draws a shoe against the rail, the pressure being regulated by a resistance in series with the magnet coil.

Regenerative Braking. — By supplying the field circuits of the motors with a current of proper value and direction by means of separate excitation they may be operated as generators and made to exert a strong retarding effort on the car axles. This separate excitation may be obtained by connecting the field windings of all the motors on a car in series with themselves and with a regulating resistance to the trolley, or by means of a motor generator set (on a locomotive) supplying a low potential of the proper value. The energy developed by the motors when acting as generators may be dissipated in rheostats or may be returned to the distributing system. In the latter case the voltage generated by the motors must be accurately controlled. Ordinarily, if the energy is returned to the line, the braking effort can only be obtained at speeds in the proximity of full speed. Very special means must be provided to make it possible to return energy to the line at low speeds.

This system has had its most elaborate application in the locomotives of the C. M. & St. P. Ry. of U. S. A., where experience over a considerable period of time shows a saving of approximately 15 per cent in the energy consumption with grades varying from 0.7 per cent to 2 per cent. Of greater importance than the saving of energy, is the saving in wear on wheel tires, brake shoes and track and the ease of control, as these features have reduced the number of derailments to a marked extent. In the early St. Paul locomotives, a special motor generator was provided to serve as an exciter. In the later locomotives, two of the main traction motors are used to supply the exciting currents for the rest of the motors when they act as generators.

Three-phase induction motors will provide regenerative braking at rated speed without auxiliary devices.

Electro-pneumatic Brakes. — This system has been proposed as an improvement over the quick-acting air-brake system. It involves controlling the application of the brakes on each car by means of an electromagnet receiving current from the locomotive cab. By energizing this circuit the motorman can set the air brakes on all cars practically simultaneously. Each car would be equipped with the usual brake cylinders and reservoir and merely the application of the brakes would be controlled electrically.

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BRICKS AND BRICK MASONRY. — (*See also Buildings, Allowable Unit Stresses in; Cement; Concrete.*) Brick construction may be made more ornamental than concrete, but is generally more expensive to place on account of the necessity of handling each brick as an individual unit. The proportion of building and engineering construction in which bricks are used, although still extensive, has been falling off in recent years with the increasing use of plain and reinforced concrete.

Kinds of Bricks. — Ordinary or clay bricks are made by moulding a rectangular block of nearly pure clay, or clay and clean sand, and subsequently burning it in a kiln for from one to two weeks. Pressed bricks are machine molded clay bricks used for facing work in high-class construction. Sand lime bricks are also used to some extent. They are made from sand cemented by lime and are hardened by being subjected to steam pressure at from 100 to 150 pounds per square inch for about one-half a day. Fire bricks are a special kind of clay bricks, which are made to stand high temperatures. The refractory properties of fire bricks depend chiefly upon the amount of silicon contained. The amount of iron oxide in fire bricks should not exceed 6 per cent. Vitrified bricks are very hard burned clay bricks which have been annealed by slow cooling; used in pavement work.

Physical Properties. — A common, practical test for a good brick is that it will give a clear, ringing sound when struck with a hammer. The color of a brick is not a reliable indication of its strength or properties. The water absorbed in a specified time by a number of bricks is sometimes considered to indicate their relative strengths, as water acts as a lubricant on the material and causes crushing to occur more readily than when dry, but there is considerable difference of opinion as to the value of this test.

The compressive strength of dry bricks ranges from 500 pounds per square inch for soft bricks to over 10,000 pounds per square inch for pressed bricks. The strength of the individual bricks, however, is of little importance except for comparing various kinds, as the strength of brick masonry is usually limited by the strength of the mortar used.

The specific gravity of bricks ranges from 1.6 to 2.6. See also paragraph below on *Brick Masonry* and article on *Weights of Materials*.

Several foreign countries have adopted legal standard sizes for brick, but the only standard sizes in the United States are those specified by the National Brick Mfg. Assoc. as follows:

Common brick	8¼ by 4 by 2¼ inches
Pressed brick	8⅛ by 4 by 2⅛ inches
Paving brick	8½ by 4 by 2½ inches

BRICK MASONRY. — Bricks are laid in lime or cement mortar, the mortar forming a cushion which fills the interstices and keeps out water. Joints, i.e., the spaces between adjacent bricks which are filled with mortar, are usually made from ¼ to ⅝ inch thick in outside walls, and from ⅜ to ½ inch thick in inner walls. In ordinary building work, where the weight of the wall itself is the greater part of the load, lime mortar is usually used because it is cheap. Where strength is required of brickwork, a rich Portland cement mortar should be used; see article on *Cement*. Tests upon the ultimate compressive strength of brick piers are quoted in detail in Johnson's *Materials of Construction*, and Baker's *Masonry Construction*. The values of loads allowed upon brick masonry in various localities range from 100 to 300 pounds per square inch; see *Buildings, Allowable Unit Stresses in*. A brick wall itself weighs from 100 to 145 pounds per cubic foot, depending somewhat upon the quality of the brick and the thickness of joints.

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Measurement of Brickwork. — Bricks are usually sold by the thousand. Brickwork is commonly measured by the cubic yard in place, but the units of per thousand brick and per square yard of surface area are also used. The relation between the number of bricks used and the volume of finished brickwork depends upon the size of brick, thickness of joints and shape of the structure. For solid brick walls the number of bricks per cubic yard ranges from about 400 with $\frac{3}{8}$-inch joints to about 500 with $\frac{1}{4}$-inch joints. An allowance of 3 or 4 per cent excess should be made in estimating to provide for waste and breakage.

Cost of Brickwork (Pre-war figures). — Hudson River common bricks cost prior to the war about $6.00 per thousand. Lime for mortar was quoted at $0.97 to $1.10 per 200-pound barrel. The total cost of brick masonry including labor and materials was from $6.00 to $15.00 per cubic yard, depending upon the locality, type of construction and quality of brick and mortar. An average figure for ordinary brick walls was from $8.00 to $10.00 per cubic yard.

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BRIDGES FOR ELECTRICAL MEASUREMENTS. — (*See also Inductance and Inductive Reactance; Resistance and Conductance, Electric; Resistors, Standard; Wires and Cables, Insulated.*) Numerous arrangements of electric circuits, known under the general term of "bridges," are used for the comparison of unknown with known resistances, capacities and inductances. The fundamental principle of an electric bridge is the adjustment of the component circuits or arms of the bridge in such a manner that the drop in potential V in the arm formed by the circuit to be tested is to the drop of potential V_r in an arm having known constants as the drop of potential V_a in one "ratio" arm is to the drop V_b in the second "ratio" arm.

A bridge may be made up of separate resistance boxes (*see Resistors, Standard*), but where frequent tests are to be made it is more desirable to have all the resistances, keys, etc., mounted together in a single box. Complete bridges of this kind can be obtained from instrument manufacturers.

SLIDE-WIRE BRIDGE (Fig. 1). — This is the simplest form of bridge but is seldom used in commercial testing, as its range is limited. In principle it is the same as a Wheatstone bridge (*see below*), the difference being a structural one only, in that a wire is used for the "ratio" arms.

The slide wire, AB in Fig. 1, is generally a wire of uniform cross-section stretched along a meter scale which is divided into millimeters. All connections in the X and R circuits are made of heavy low-resistance material. A slider is provided for sliding over and making contact on the wire. When the bridge is balanced (i.e., no current through the galvanometer),

$$X = \frac{AR}{1000 - A},$$

where A is the distance in millimeters between the slider and the left-hand end of the bridge. The slide wire can be made uniform to $\frac{1}{10}$ per cent and the error in observation may be even smaller than this. When using a ratio greater than 1 to 1 and when a low resistance is being measured, the errors are greater. It is possible when using an even ratio to make very exact comparisons of the standard and unknown resistances by reversing them and taking the mean of the two measurements.

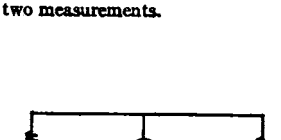


Fig. 1. Slide-wire Bridge

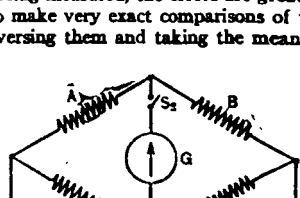


Fig. 2. Wheatstone Bridge

WHEATSTONE BRIDGES. — Fig. 2 shows the arrangement of resistances in the ordinary type of Wheatstone bridge used for comparing resistances. A and B represent two coils or sets of coils, usually referred to as the "ratio" coils, whose relative resistances must be known but whose actual resistance values are unnecessary; R is a standard variable resistance, or resistance box (*see Resistors, Standard*); X is the unknown resistance; G is a sensitive galvanometer connected across two points of the diamond and B is a battery connected across the other two points of the diamond.

For no deflection of the galvanometer when the switches S_1 and S_2 are closed, i.e., when the bridge is balanced,

$$X = \frac{A}{B} \cdot R,$$

where the letters represent the resistances of the four arms.

Construction. — Wheatstone bridges having the various parts mounted in one box may be divided into three classes: (1) **portable bridges**, in which not only the resistance coils and keys but also the battery and galvanometer are mounted in one box; (2) **laboratory bridges**, in which the coils and in some cases the keys are mounted in one box, but for which separate galvanometers and batteries must be provided; and (3) precision bridges, arranged in the same manner as laboratory bridges but made with greater care and capable of greater precision.

Since the construction of the resistance coils, blocks, plugs and other minor details of bridges is practically the same as for resistance boxes (*see Resistors, Standard*); only the arrangement of coils and connections will be described here.

Rheostat Arrangements. — The coils forming the rheostat (the variable resistance R in Fig. 2) may be arranged on the 1, 2, 3, 4 plan as shown in Fig. 3, on the 1, 2, 2, 5 plan, on the decade plan of Fig. 4, or on any other plan. (*See Resistors, Standard.*)

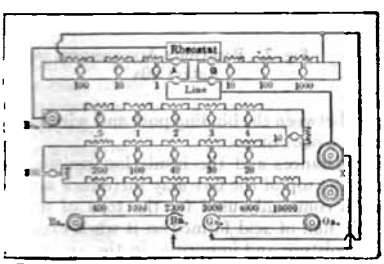


Fig. 3. Wheatstone Bridge (Post Office Type)

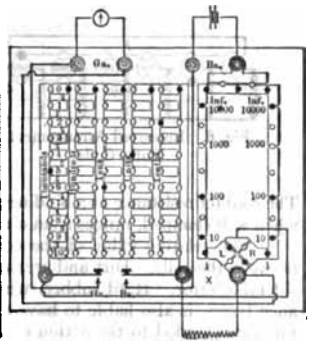


Fig. 4. Wheatstone Bridge (Anthony Type)

The advantage of the decade arrangement is that few plugs are required, and, therefore, there is less likelihood of error due to the contact resistance. A very good form of the decade type of rheostat is used in the Anthony type of Wheatstone bridge, shown in Fig. 4. In this bridge the coils may be joined in series or multiple or in any desired combination of series and multiple.

Plug and Dial Arrangements. — The resistances of the various arms of the bridge may be varied either by the insertion of plugs between the heavy metal terminals of the coils provided on the top of the box, or a dial arrangement similar to that employed on ordinary rheostats (but more carefully made to reduce the contact resistance) may be used.

Ratio Coils (Figs. 5 to 7). — The connections of the ratio arms in a common construction of dial bridge is shown in Fig. 5. The values of the coils are so chosen that the ratio of these coils is always that given by the stamping for various settings of the contact S. An advantage of this type of ratio coils is

that there is no error due to contact resistance in the ratio coils, as the contact is in series with the battery.

The arrangement of an improved form of ratio coils is shown diagrammatically in Fig. 6. This arrangement of ratio coils has the advantage over the old post-office arrangement shown in Fig. 7, in that there are but two plugs to operate and the coils can be checked by reversal.

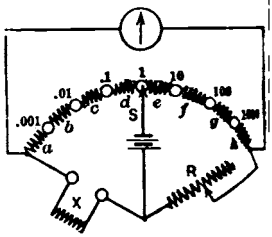


Fig. 5. Dial Type Ratio Coils

Precision of Measurements by Wheatstone Bridge. — The degree of accuracy with which a resistance can be measured by means of a Wheatstone bridge is determined by the following conditions:

1. The accuracy to which the resistances of the various coils is adjusted. The range of accuracy is from about 0.1 per cent for portable bridges to 0.02 per cent for precision bridges.

2. The relative value of the coil resistances and the contact resistances at plugs and terminals. A well-fitting, clean plug has a resistance of from 0.0001 to 0.00005 ohm; a poorly fitting or greasy plug a resistance of 0.01 ohm or higher.

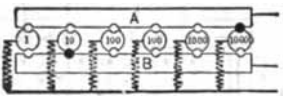


Fig. 6. Improved Arrangement of Ratio Coils

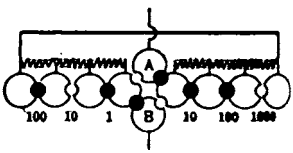


Fig. 7. Post-Office Arrangement of Ratio Coils

The contact resistance at a binding post between the binding post and wire, even when well clamped, ranges from 0.001 to 0.0001 ohm.

3. The relative value of the coil resistances and the insulation resistances between the coils. Dirt and grease on the top of the box may introduce a considerable error. Hard rubber, which is commonly used for the tops of resistance boxes, is also liable to have a thin film of acid formed on it when exposed for a long period to the action of the moisture and impurities in the air, which attack the sulphur in the rubber. Such a film will greatly reduce the insulation resistance between the lugs on top of the box.

4. The effect of changes of temperature in changing the resistances of the coils and in producing thermoelectric effects. The thermal e.m.f. in a copper-brass-copper circuit is about 2×10^{-6} volts per degree C. difference in temperature between the two junctions. Thermoelectric troubles can usually be avoided by reversing the connections of the battery to the bridge and taking the mean of the values of the resistances corresponding to the balance when the battery current flows through the bridge first in one direction and then in the other.

5. The maximum current that the coils will safely carry; this ranges from about 0.5 ampere for 1-ohm coils down to 0.005 ampere for a 5000-ohm coil.

6. The resistances of the galvanometer and battery, particularly the former. The battery resistance is usually small.

7. The relative resistances of the various arms of the bridge.

8. The sensitiveness of the galvanometer, i.e., the deflection per unit current.

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Best Galvanometer Resistance. — Referring to Fig. 2, the best galvanometer resistance is

$$G = \frac{(A + X)(B + R)}{A + B + R + X},$$

where the letters designate the resistances of the various branches.

Best Location of Galvanometer. — Knowing the galvanometer and battery resistances (the galvanometer resistance is usually the larger), connect the one having the higher resistance so that it joins the junction of the two arms of the bridge having the highest resistances to the junction of the two arms having the lowest resistances.

Precautions in Making Measurements. — The following rules should be observed in using a Wheatstone bridge:

1. Do not employ a battery having an e.m.f. of over 5 volts; a lower value is desirable if sufficient sensitiveness can be obtained.
2. Always shunt the galvanometer during preliminary adjustments. The shunt circuit should be opened when the final balance is made.
3. See that all binding posts are screwed up tightly and all plugs firmly inserted. After withdrawing a plug those adjacent to it should be retightened.
4. For a preliminary balance use a 1 to 1 ratio.
5. In manipulating the keys be careful not to touch the metal work, as the heat and moisture of the hand is likely to set up appreciable electromotive forces.
6. Always close the battery switch first and then the galvanometer switch, to avoid momentary deflections of the galvanometer due to the transient e.m.f.'s set up while the currents are establishing themselves.
7. If the contact or lead resistances are appreciable relative to the resistances of the coils with which they are in series, these resistances should be separately determined.

Care of Bridge. — In order that a bridge or resistance box may remain in first-class condition, it must be carefully protected from dust and moisture by being covered when it is not in use. To insure high insulation the top must be kept clean, especially between the blocks. The plugs must be kept free from grit, grease or from contact with mercury. Grease may be removed by the use of a little benzol. Never use sand or emery paper for cleaning the plugs or holes, for the surfaces of the taper will be spoiled by this treatment. These materials work into the metal and cannot be removed, thus causing the plugs to "cut." If it becomes absolutely necessary to clean the plugs and sockets, a little of the very finest whiting may be employed. Extra holes of the proper taper bored in the brass blocks are convenient for holding the plugs when they are not in use, and also for attaching a movable terminal. Never apply undue force in inserting the plugs.

KELVIN BRIDGE. — The ordinary form of Wheatstone bridge is not suitable for measuring with accuracy a resistance of 0.1 ohm or less, due to the contact resistances introduced at the binding posts, this contact resistance being of the order of 0.0001 to 0.001 ohm. An arrangement of circuits to avoid these contact resistances devised by Lord Kelvin (*Wm. Thomson*) is shown in Fig. 8, and is known as the Kelvin or Thomson bridge. There will be no current in the galvanometer when

$$X = \frac{A}{B} \cdot R + \frac{bd}{a + b + d}\left(\frac{A}{B} - \frac{a}{b}\right).$$

If $\frac{a}{b}$ is made equal to $\frac{A}{B}$, then

$$X = \frac{A}{B} \cdot R.$$

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It is also well to make the resistance of d extremely low in comparison with X or R, since the lower the resistance of d the less an error in $a/b = A/B$ will affect the accuracy of measurement.

In the above formulas X and R are the resistances between the arrowheads which represent the "potential terminals." Such terminals are always provided on low-resistance standards (*see Resistors, Standard.*)

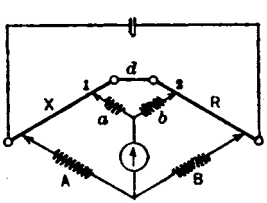


Fig. 8. Kelvin Bridge

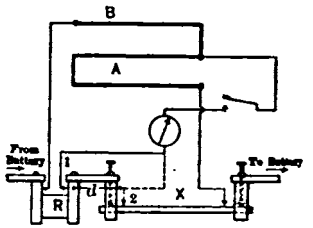


Fig. 9. Modification of the Kelvin Bridge

Simple Modification of the Kelvin Bridge. — When suitable resistances are not available for a and b, these resistances may be omitted and the galvanometer terminal be connected first at 1 and then at 2, and A adjusted for a balance in each case; let A_1 and A_2 be the corresponding values of A. Then

$$X = R\frac{A_1(B + A_2)}{B(B + A_1)}.$$

This method is very convenient for measuring the resistance X of a low-resistance shunt (*see Shunts*). The only standard resistances required are a low-resistance standard R and a resistance box with three terminals (or two separate resistance boxes). Fig. 9 shows such an arrangement.

HOOPES' CONDUCTIVITY BRIDGE. — This bridge is also a modification of the Kelvin bridge, designed for the rapid determination of the relative conductivity (*see Resistance and Conductance*) of samples of wire. It is extensively used in wire factories. A diagram of the connections is shown in Fig. 10.

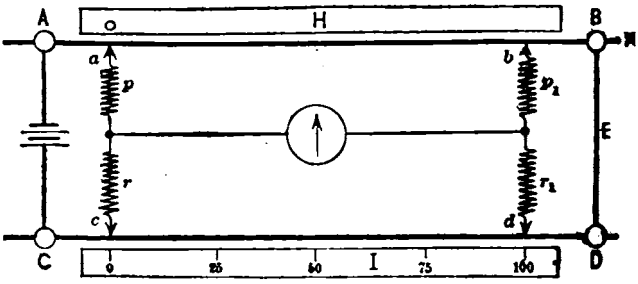


Fig. 10. Hoopes' Conductivity Bridge

The standard A–B and the unknown C–D are of the same metal; consequently if care be taken that they are at the same temperature, all corrections due to temperature are avoided. The arms p, r, p_1, r_1 are in the same case and are made of material of low temperature coefficient so that their relative values will not change. They are adjusted so that $p = r$ and $p_1 = r_1$; consequently at balance the resistance of c–d equals the resistance of a–b.

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The sample *C–D* is placed alongside a scale *I* divided into 100 parts, so that the graduations represent percentages of the total length of the scale. Accompanying the standard wire *A–B* is a scale *H*, on which are laid off a number of points corresponding to the weights of the standard length (38 inches) of a range of sizes of sample wires.

To make a conductivity reading, the weight of the standard length of the sample *C–D* is found to within an accuracy of $\frac{1}{10}$ per cent. The contact *b* is set at the point on scale *H* corresponding to this weight, the contacts *a* and *c* being at the zero points of their respective scales. After the case has been closed a sufficient length of time to allow both the standard and sample to assume the same temperature, the contact *d* is moved until the galvanometer shows no deflection; this will occur when the resistance between *a* and *b* is equal to that between *c* and *d*. The scale reading corresponding to the position of *d* for a balance is equal to the per cent conductivity.

The Hoopes' bridge is so designed that the standard wire with its scale is removable from the bridge and so that a single standard covers a range of sizes equal to 3 numbers of B. & S. gauge. Any number of standards can be supplied with a bridge, so that it can cover an extensive range of sizes and can also be used for wires of different materials. In order to keep the standard wire and the test wire at the same temperature the bridge is mounted in a metal-lined case and the scale read through a glass window in the case, the window being closed by a metal screen when readings are not being taken.

Resistance of Electrolytes. — The resistance of an electrolyte can be measured by using the Wheatstone bridge principle with an a-c. source substituted for the battery and an a-c. detector in place of the a-c. galvanometer. Alternating current must be used on account of the polarizing action of a direct current. A convenient source of alternating current is an induction coil with the secondary winding in place of the battery, as in an ordinary set-up. A telephone receiver makes a very good detector when an induction coil is used. The current from an induction coil gives a very clear and sharp sound in the telephone, making accurate balancing of the bridge quite simple. If a sinusoidal alternating current is used, a vibration galvanometer may be used to better advantage than a telephone. To measure merely the resistance of an electrolyte it is only necessary to place the electrolyte in a vessel provided with two electrodes, preferably of gold or platinum, and connect this vessel into one arm of a Wheatstone bridge and balance for alternating current. The other arms of the bridge are resistances which must be strictly non-inductive.

To determine the resistivity it is necessary to place the electrolyte in a vessel whose length and cross-section can be accurately measured. Such a vessel may be made from a glass tube, whose internal diameter is known, and in the two ends of which metal plugs are inserted. These plugs may be any convenient distance (say 20 cm.) apart. There should be several small holes in the side of the tube. The tube is then immersed in a vessel containing the electrolyte and the bridge balanced as before. The resistivity is then the product of the cross-sectional area of the tube and the resistance, divided by the length of the tube.

COSTS (Pre-war prices). — A good slide-wire bridge costs about $20, a portable Wheatstone bridge from $50 to $125, depending upon the design, a laboratory Wheatstone bridge from $25 to $75 and a high-precision standard bridge from $700 to $400. A Hoopes' conductivity bridge with a single standard, covering 3 sizes of B. & S. gauge wire, costs about $500; additional standards cost about $50.

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BUILDINGS, ALLOWABLE UNIT STRESSES IN. — (*See also Brick; Cement; Concrete; Iron, Pig and Cast; Iron, Wrought; Steel; Structures Simple; Timber.*) The following tables give the allowable unit stresses and loads in accordance with the building laws of the respective cities, as corrected to recent dates (*see Bibliography*).

TABLE I.—STEEL AND IRON

Loads in pounds per square inch

	New York	Chicago	Philadelphia	St. Louis	Boston
Compression:					
Rolled steel	16,000	14,000	16,250	14,000	20,000(*b*)
Cast steel	16,000	14,000	.....	14,000	.....
Wrought-iron	.....	10,000	12,500	10,000	.....
Cast iron (in short blocks)	16,000	10,000	11,700	10,000	16,000(*b*)
Steel pins and shop or power driven rivets (bearing)	24,000	25,000	22,000	24,000	24,000
Steel field rivets, hand driven in (bearing)	16,000	.....	17,600	18,000	20,000
Wrought-iron pins and rivets (bearing)	.....	.....	18,000	.....	.....
Tension:					
Rolled steel	16,000	16,000	16,250	16,000	.....
Cast steel	16,000	16,000	.....	16,000	.....
Wrought iron	.....	12,000	12,500	12,000	.....
Cast iron	3,000	.....	.....	.....	.....
Bending (extreme fiber stress):					
Rolled-steel beams	16,000	16,000	16,250*	16,000	16,000(*c*)
Rolled-steel pins, rivets and bolts	20,000	25,000	.....	25,000	24,000
Riveted steel-beams	16,000(*a*)	16,000	16,250*	.....	16,000(*c*)
Riveted wrought-Iron beams (net flange section)	.....	.....	12,500	.....	.....
Rolled wrought-iron beams	.....	.....	12,500	12,000	.....
Riveted wrought-iron pins	.....	.....	.....	.....	.....
Cast-iron compression side	16,000	10,000	17,500	10,000	10,000(*c*)
Cast iron, tension side	3,000	3,000	3,750	3,000	4,000
Shear:					
Steel, web plates	10,000	10,000	10,000	10,000	10,000
Steel, shop rivets and pins	12,000	12,000	11,000	12,000	10,000
Steel, field rivets	8,000	10,000	8,800	9,000	.....
Wrought iron, web plates	.....	.....	7,500	.....	.....
Wrought-iron, shop rivets and pins	.....	.....	9,000	.....	.....
Wrought iron, field rivets	.....	.....	7,200	.....	.....
Cast iron	3,000	.....	.....	.....	2,000

* 14,500 for mild steel.

(*a*) Net flange section. (*b*) Bearing.

(*c*) Where top flange is stayed laterally at distance not greater than 20 times the width of flange $\left(\frac{L}{b} < 20\right)$. When this ratio is between 20 and 70 this formula applies up to $\frac{L}{b} = 70$. $f = 19{,}200 - 160\frac{L}{b}$.

(*d*) $\frac{L}{b}$ not greater than 20

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TABLE II—TIMBER

Loads in pounds per square inch

	New York	Chicago	Philadelphia	St. Louis	Boston
Compression (short lengths):					
Oak, with grain	1400	900	.....	1000	900
Oak, across grain	1000	500	.....	500	500
Yellow pine, with grain.	1600 *L*	1100 *L*	750 *L*	1100 *L*	1200 *D*
	1000 *S*	800 *S*		800 *S*	900 *So*
Yellow pine, across grain	1000 *L*	250	550 *L*	250 *L*	350 *D*
	800 *S*			250 *S*	250 *So*
White pine, with grain	1000	700	.....	700	700
White pine, across grain	800	200	.....	200	200
Spruce, with grain	1200	.....	500	.....	750
Spruce, across grain	800	.....	300	.....	200
Hemlock, with grain	800	500	350	500	.....
Hemlock, across grain	800	150	250	150	.....
Tension:					
Yellow pine	1200 *L*	1300 *L*	1800 *L*	1800 *L*	.....
	900 *S*	1000 *S*	.....	1000 *S*	.....
White pine	700	800	.....	800	.....
Spruce	800	.....	1250	.....	1000
Oak	1200	1200	.....	1800	.....
Hemlock	600	600	1000	600	.....
Bending (extreme fiber stress):					
Yellow pine	1600 *L*	1300 *L*	1600 *L*	1100 *L*	1600 *D*
	1000 *S*	1000 *S*	.....	800 *S*	1200 *So*
White pine	1200	800	.....	700	1000
Spruce	1200	.....	1100	.....	.....
Oak	1200	1200	.....	1000	1400
Hemlock	800	600	900	500	.....
Shear:					
Yellow pine, with grain.	150 *L*	130 *L*	100 *L*	150 *L*	150 *D*
	100 *S*	120 *S*	.....	120 *S*	100 *So*
Yellow pine, across grain	1000 *L*	.....	1125 *L*	.....	.....
	1000 *S*				
White pine, with grain	100	80	.....	80	80
White pine, across grain	500	.....	.....	.....	.....
Spruce, with grain	100	.....	75	.....	100
Spruce, across grain	500	.....	750	.....	.....
Oak, with grain	200	200	.....	200	200
Oak, across grain	1000	.....	.....	.....	.....
Hemlock, with grain	100	60	62	60	.....
Hemlock, across grain	600	.....	625	.....	.....

F.S. = Factor of Safety. *L* = Longleaf Yellow Pine. *S* = Shortleaf Yellow Pine, *D* = Dense Grade. *So* = Sound Grade.

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TABLE III.—STEEL AND IRON COLUMNS

Loads in pounds per square inch *

City	Medium steel	Wrought iron	Cast iron
New York....	$16{,}000 - 70\frac{L}{R}$ (a)	no values given	$9{,}000 - 40\frac{L}{R}$ (b)
Chicago.....	$16{,}000 - 70\frac{L}{R}$ (a)	$12{,}000 - 60\frac{L}{R}$	$10{,}000 - 60\frac{L}{R}$ (b)
Philadelphia..	$\frac{16{,}250}{1 + \frac{L^2}{11{,}000\,R^2}}$	$\frac{12{,}500}{1 + \frac{L^2}{15{,}000\,R^2}}$	$\frac{11{,}700}{1 + \frac{L^2}{400\,D^2}}$
St. Louis....	$16{,}000 - 70\frac{L}{R}$ (a) with maximum of 14,000	$12{,}000 - 60\frac{L}{R}$ with maximum of 10,000	$10{,}000 - 60\frac{L}{R}$ (b)
Boston.....	$20{,}000 - 100\frac{L}{R}$ (c) with maximum value of 12,000	.....	$9{,}000 - 40\frac{L}{R}$ (d)

* All values obtained either by formulas or from tables shall be reduced for eccentr loading.

L = unsupported length in inches.
D = diam. or least side in inches.
R = least radius of gyration in inches.
S = stress in lb. per sq. in.

(a) $L/R > 120$ not allowed.
(b) $L/R > 70$ not allowed.
(c) $L/R > 160$ not allowed.
(d) $L/R > 96$ not allowed.

TABLE IV.—TIMBER COLUMNS

Loads in pounds per square inch

City	Yellow pine (b)	White pine	Oak
New York....	$1200 - 20\frac{L}{D}$ (a)	$900 - 17\frac{L}{D}$ (a)	$1200 - 20\frac{L}{D}$ (a) for white oak
Chicago.....	$1100\left(1 - \frac{L}{80\,D}\right)$	$700\left(1 - \frac{L}{80\,D}\right)$	$900\left(1 - \frac{L}{80\,D}\right)$
Philadelphia.	$750\left(1 - \frac{L}{100\,D}\right)$	.....	.....
Boston (a)..	$1200 - 20\frac{L}{D}$ (c) with maximum value of 1000	$S = 585$ for $\frac{L}{D} = 10$ $S = 230$ for $\frac{L}{D} = 40$	$900 - 15\frac{L}{D}$ (c) with maximum values of 750
St. Louis.....	$1100\left(1 - \frac{L}{80\,D}\right)$	$700\left(1 - \frac{L}{80\,D}\right)$	$1000\left(1 - \frac{L}{80\,D}\right)$

L = unsupported length in inches.
D = diam. or least side in inches.
S = stress in lb. per sq. in.

(a) $L/D > 30$ not allowed.
(b) Longleaf.
(c) $L/D > 40$ not allowed.

TABLE V.—LIVE LOADS ON FLOORS AND ROOFS

Pounds per square foot

Kind of building	New York	Chicago	Philadelphia	St. Louis	Boston
Dwellings, hotels	40	40 to 50	70	50	50 to 100
Office buildings:					
First floor	60	50	100	100	125
Above first floor	60	50	100	60	75
Schools	75	75 to 100	.....	75	50 to 100
Buildings for public assembly	100	100	120	100	100
Stores	120	100	120	150	125
Factories	120	100	150	150	125 to 250
Roofs:					
Pitch < 20 degrees	40	25 (*a*)	30	30 (*b*)	40 (*b*)
Pitch > 20 degrees	30 (*a*)	25 (*a*)	30	.....	.....

(*a*) Measured in horizontal plane. (*b*) Flat.

TABLE VI.—MASONRY AND BUILDING MATERIALS

Loads (compression) in pounds per square inch

Item	New York	Chicago	Philadelphia	St. Louis	Boston
Concrete (P), 1 : 2 : 4	500	400 M 350 H	208 (*b*)	500 (*d*)	450 (*e*)
Concrete (P), 1 : 2½ : 5 (*f*)	400	350 M 300 H	.....	.....	361 (*g*)
Rubble stonework:					
Portland cement mortar	140	200 C 100 NC	139 (*b*)	.....	.....
Lime mortar	no value given	120 C 60 NC	70		
Brickwork:					
Portland cement mortar, 1 : 3	250 (*c*)	250 (*a*)	209 (*b*)	300 (*d*) 250 (*d*)	278
Lime mortar, 1 : 4	110 (*c*)	100	111 (*c*)	100 (*c*)	111 (*c*)
Granite	1000	.....	.....	.....	1000 (*h*)
Limestone	700	.....	.....	.....	556 (*h*)
Marble	600	.....	.....	.....	556 (*h*)
Sandstone	400	.....	.....	.....	417 (*h*)

P = Portland cement.
M = Machine mixed.
H = Hand mixed.
NC = Not coursed.
C = Coursed.

a = Pressed.
b = Kind of concrete not specified.
c = Mixture not specified.
d = Vitrified paving brick, 300: hard pressed brick, 250.
e = Mixture 1 : 6.
f = Mixture 1 : 2 : 5 for Chicago.
g = Mixture 1 : 7½.
h = Portland cement mortar 1 : 2 and not more than ½-inch joints.

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TABLE VII.—BEARING CAPACITY OF SOILS

Tons per square foot

Item	New York	Chicago (a)	Philadelphia	St. Louis	Bos
Clay, soft	1	.....	...	According to test;	2
Clay, hard, dry	4	2.25 (a)	3.5	maximum not	5
Sand, firm and coarse	4	2.5 (a)	3.5	to exceed 2½	5
Sand, fine and dry, firm	3	2.5 (a)	...	tons on "solid natural clay"	4
Clay and sand, wet	2	1.5	...	unless satisfactory tests are	4
Clay and gravel, well cemented	..	.....	6	made	6

(a) In relatively thick beds protected against lateral displacement.

BIBLIOGRAPHY. — *The Building Code of The City of New York, amendments to July 17, 1910; Revised Building Ordinances, Chicago; Am ments to May 26, 1920; Laws and Ordinances Relating to the Bureau of Bui Inspection, Philadelphia, July 1, 1920; Building Laws of the City of St. L 1917; The Building Law of the City of Boston, with amendments to Oct., 191*

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JS-BARS AND BUS-BAR STRUCTURES. — (*See also Circuit akers; Power Stations; Substations; Switches; Switchgear Equipment for wer Stations; Wires and Cables.*) Bus-bars, or "omnibus bars," as they were ginally called, are the common circuits into which the various generators de- r their output and from which the different feeders draw their supply of wer. In large-capacity, moderate-voltage a-c. plants the bus-bars are usually ced in structures and connected to the various generators, feeders, etc., by table wiring. The bus-bars and their connections, together with the bus-bar uctures, form one of the most important parts of large plants, as the entire rgy of the station is usually concentrated thereon.

BUS-BAR SYSTEMS. — Where there is only a single set of bus-bars ber in d-c. or a-c. stations the connections are said to be arranged on the ingle-throw" system; when the connections can be made to either of two ts of bus-bars the system is spoken of as "double-throw"; but if the connec- ns can be made to both sets of bus-bars instead of only to either set, the stem is spoken of as the "selector system." Occasionally three or more ts of bus-bars are used.

If there is only one set of bus-bars, but with switches provided for divid- g it into two or more sections, it is spoken of as a "sectioned bus." Where ere are two sets of these sectioned bus-bars connected together at the ds, the system forms a "ring bus." In many high-voltage plants having ep-up transformers each generator normally connects to the low-tension de of its own transformers, but switches are provided so that any transformer r generator can connect to a bus; such a bus is spoken of as a "relay bus." here a number of feeders connect to a bus which in turn connects to the ain bus through a switch or breaker, such a bus is spoken of as a "group us."

BUS-BAR MATERIAL. — Depending on the current and voltage, bus- ars may be made of wire, rod, tubing, cable or strap, either bare or insulated. olid wire is seldom used for more than 200 amperes, rod is used for less than 000 amperes, tubing for 300 to 600 amperes, cable up to 1000 amperes, while trap is used up to any capacity.

Strap for bus-bars, particularly for heavy current, possesses several advan- ages over other shapes, the chief one being the ease with which additional straps ay be added and the excellent radiating surface secured. Straps of different ections are in use, a typical one being 3 inches × ¼ inch. Where more than ne strap is required, a space is left between adjacent bars making the so-called aminated bus. The usual spacing left with 3 inches × ¼ inch bars is ½ inch. The connections from switches, circuit breakers, etc., to the bus are made of ne or more similar straps suitably interleaved and clamped together.

With this construction and due to the large surface exposed in comparison to he section of copper used comparatively high current density may be employed or a small number of straps without exceeding a safe temperature rise. The xact amount of current to be carried for a given rise depends somewhat on local onditions, ventilation, etc., and whether the bus is being used for direct current, 5-cycle, or 60-cycle service, and the temperature rise is not the same for differ- nt parts of the bar. A typical test under average conditions, 60-cycle service, 5° rise, indicated that one bar would carry 650 amperes, two bars 1150, three 1500, four 1800, five 2000, six 2160, showing that due to skin effect, lack of venti- lation, etc., the permissible current density falls off rather rapidly as the number of bars increases.

It is usually necessary to interleave the phases or to adopt special arrangements of the strap connections to balance the mutual induction, to secure proper cur-

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rent distribution in the various straps for 60-cycle service to carry 3000 ampere or more without an excessive amount of copper.

Tubing for Small Currents and High Voltages. — For extremely high voltages with their correspondingly small currents, copper tubing for bus-bars and connections has many advantages over rods, cable or wire. These advantages are principally increased stiffness for the same amount of material, large and effective radiating surface, and the facility of making connections by flattening out the tubing at the point desired and bolting the tubing together at such points. On extremely high-voltage circuits tubing of approximately 1 inch outside diameter is not apt to be troubled by the brush discharge or corona effect that is sometimes noted with small wires or straps having sharp edges. In some plants iron piping is used for bus-bars and connections.

BUS-BAR STRUCTURES. — (*See also Power Stations; Substations; Switchgear.*) In large-capacity a-c. plants of 13,000 volts or less, with generators connected directly to the bus, the current that can be developed on a short circuit is something enormous, and every precaution has to be taken to prevent trouble from spreading if it ever starts. For this reason it has become customary to employ masonry compartments and cellular construction for the oil circuit breakers and bus-bars. In higher-voltage plants open wiring possesses several decided advantages. The vertical walls and septums of the circuit-breaker and bus-bar structures are usually built of brick or concrete, and the horizontal shelves between the bus-bars are ordinarily made of concrete, sandstone, soapstone, slate or marble. These substances are named in the order of their increasing cost. In some instances the bus-bar structures have been made of asbestos lumber, transite or similar material.

Low tension bus-bars when not too heavy can be supported by the wall bushing for the lead. For heavier work, or where bushings are not used, the bus-bars are supported on porcelain pillars, petticoat insulators, and similar devices resting on the bus-bar shelf, or attached to the wall.

In the larger generating stations due to the mechanical stress caused by the magnetic effects of the tremendous short-circuit current resulting from the size and number of turbo generators represented in present day station practice, close attention must be given to the adequacy of the bus-bar supports. Various curves and formulæ have been deduced for the purpose of calculating the mechanical strain on bus-bar supports at the instant of short-circuit. A typical formula is the following:

$$F = .27\ K.V.A.^2 \text{ divided by } A \times V^2 \times Z^2 \quad \text{where}$$

F = Maximum force exerted in pounds per foot of bus.
$K.V.A$ = Normal rating of the station including all synchronous apparatus.
A = Distance between buses in inches.
z = Impedance in per cent expressed in decimals to the point of short-circuit.
V = Line voltage.

In using this formula a typical example with 150,000 K.V.A. station capacity at 6600 volts, 8 per cent reactance, gives a maximum force on the bus-bars per foot of length, 735 pounds with 30 inch spacing between bars, 1470 pounds with 15 inch spacing between bars. With 4 feet between bus supports, each bus support would have to stand a strain of 2940 pounds if the buses are 30 inches on centers; 5880 pounds if the buses are 15 inches on centers. For heavy duty of this kind, multi-point supports are frequently used.

For supports for high tension bus-bars and connections it is customary to employ high-tension insulators of the pillar type, pin type, or suspension type, depending on the voltage.

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he open system of wiring is preferable for any voltage higher than that for ch generators can be conveniently wound. This opinion is based on the wing reasons:

For the same kilovolt-ampere capacity back of an arc the current estab- ed is approximately inversely proportional to the voltage, and consequently violence of the arc and its destructive effects are less on a high-voltage n on a low-voltage system.

. The distance from wire to ground has to be greatly reduced from what ld be obtained with open wiring in the same space, as the conductivity of the proof barriers is sufficiently good to permit large currents to flow with high tages, in case an arc or a dead ground is established.

. A more expensive building and more costly construction are usually needed inclosed bus-bars and wiring than are required for open wiring.

. Inspection and repairs are more difficult when bus-bars, wiring, disconnect- switches and similar appliances are boxed in masonry compartments, and conductors are visible and accessible only by the removal of doors. Inspec- n will be more frequent and thorough and incipient trouble will be noticed sooner with open wiring than with inclosed, as the station attendant can everything in a walk of a few minutes, and will not have to remove many rs and visit two or three floors to examine the condition of the apparatus.

CONNECTIONS TO BUS-BARS. — Where the currents exceed 600 or 0 amperes, it is usual to employ laminated copper straps for connecting to s-bars; for smaller currents, cable, wire, rod or tubing is used. Cable and, a certain extent, bare wire are used for connections involving bends or long ns through conduits, but for straight runs or simple bends rod or tubing can used. Tubing, though more costly than rod or wire, is stiffer for the same tion, and can often be flattened out for making connections to studs, bars, :, without the necessity of additional terminals.

BIBLIOGRAPHY. — Billhimer, F. M., *Current Capacity of Copper Bus-* rs, El. Jour. 1918, Vol. 15, p. 94; Leonard S. G. and Riker C. R., *Repulsion* ween *Bus-Bars*, El. Jour. 1917, Vol. 14, p. 491.

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CALORIMETERS, FUEL. — (*See also Fuel.*) A fuel calorimeter is an instrument for determining the heating value of a fuel. Its essential features are a closed chamber in which a weighed sample of the fuel can be quickly and completely burned, a vessel of water surrounding this chamber, into which the heat generated by the combustion is transferred, a delicate thermometer for measuring the rise of temperature of the water, means for igniting the fuel, and provisions for preventing loss of heat from the apparatus by radiation or by the escape of the gases and vapors produced by the combustion. The most approved form of the instrument is Mahler's modification of Berthelot's calorimeter. The combustion chamber is a strong cylindrical steel vessel enameled on the inside, called a "bomb," into which about 1 gram of pulverized coal, contained in a small platinum dish, is placed. Oxygen under a pressure of 20 to 25 atmospheres is introduced, and the coal is ignited by an electric spark and burned explosively. The bomb is set in a water pail of thin brass, which is heavily felted and surrounded by a double-walled vessel filled with water of the temperature of the room. A stirring apparatus is used in the pail to circulate the water around the bomb. The thermometer is finely graduated. Readings of the temperature are made and recorded every minute until the maximum is reached, and a few minutes afterward to obtain a correction for radiation. The weight of the water, together with the water equivalent of the bomb and pail, multiplied by the rise in temperature, corrected for radiation and other minor errors, gives the number of heat units generated by the combustion of the coal.

The Junker calorimeter is commonly used to determine the heating value of fuel gas. A measured volume of gas is burned with air or oxygen in a vessel which is surrounded with water, and the calculations are made in the same way as those for the Mahler calorimeter.

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ORIMETERS, STEAM. — (*See also Steam.*) For the purpose of
mining the percentage of moisture in the steam, in a boiler or engine test, a
calorimeter is used. Several forms of this instrument have been used
he most common is that of Professor Peabody, known as the throttling
meter. The action of this instrument depends upon the fact that the
of saturated steam is greater the greater the pressure, and consequently
pressure is reduced by throttling, the heat rendered available will convert
oisture into steam and in general produce more or less superheating.
½-inch pipe, closed at the end and perforated with several ⅛-inch holes in
alls, is inserted into the main steam pipe so that steam may enter these
. The other end of the calorimeter pipe is throttled by an orifice 1/16 inch
eter through which the steam escapes into a chamber which has an outlet
e atmosphere. The temperature and pressure of the steam on each side
e orifice are observed. The steam in the chamber is superheated more or
according to the amount of moisture contained in the sample drawn from
steam main.
he per cent of moisture in the steam is then

$$W = 100\,\frac{H - h - K\,(T - t)}{L},$$

re H = total heat and L = the latent heat of saturated steam at the pressure
he steam in the main pipe; h = total heat of saturated steam at the pressure
the discharge chamber of the calorimeter (= 1150.4, corresponding to a
sure of 14.7, when this chamber opens directly to the atmosphere); K =
ific heat of superheated steam (= 0.48 approximately); T = actual temper-
re in the discharge chamber; t = temperature of saturated steam at the
sure in the discharge chamber (= 212 when this chamber opens directly
he atmosphere). The above formula becomes

$$W = 100\,\frac{H - 1150.4 - 0.48\,(T - 212)}{L},$$

n the discharge chamber opens directly to the atmosphere, and when the
ospheric pressure is 14.7 pounds per square inch.
When the steam is very moist, so as to reduce the superheating on the dis-
rge side to 0°, the instrument fails, and a separating calorimeter, which is
ply a small steam separator (q.v.), must be used between the throttling calorim-
r and the steam pipe to collect the greater quantity of moisture. The
isture collected in the separator is then added to that determined by the
rimeter. The instrument must be thoroughly felted to reduce the error
to radiation. There is also usually a considerable error in obtaining steam
a average quality from the main pipe by the perforated tube.

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port of Committee on Power Tests, A.S.M.E.

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CAMBRIC, VARNISHED. — (*See also Insulating Materials, Wires, Cables, Insulated.*) Varnished muslin, variously known as varnished cloth, varnished cambric is an insulating material for cables, which consists of tapes of cotton fabric coated with insulating varnish, wound helically around the conductor with a thin layer of plastic compound between turns. This compound prevents the absorption of moisture, precludes air spaces and permits the layers of fabric to slide upon each other when the cable is bent. It is also used for machine coils without the plastic compound.

The fabric is prepared by coating it with a mixture whose principal constituents are boiled linseed oil, resin, gilsonite, and benzine. This mixture dries and the oil is oxidized by contact with air, leaving a hard smooth surface. Three such coats are usually applied. The plastic material between layers is usually a mixture of petrolatum and resin.

The varnished fabric usually has a thickness between seven and thirteen mils, the thinner cambric being used on smaller cables. There are usually between 65 and 70 threads to an inch.

The tensile strength of the varnished tape should be not less than 2000 pounds per square inch.

After the varnished cambric has been placed in hot petrolatum having a temperature of 150° C., removed from petrolatum and allowed to cool, the film of varnish should not become soft or tacky.

Specific Resistance. — The value of K in the formula $M = K \log \frac{D}{d}$ (See article on rubber) ranges from $K = 300$ to $K = 1000$, the usual value being between 400 and 600.

The resistance of varnished cambric is more affected by temperature changes than that of rubber or impregnated paper. The amount of variation differs in different makes and in different batches of the same make, so that the accompanying table should be considered as an approximation only.

Temperature		Per cent of resistance at 60° C
C.°	F.°	
15.5	60	100
18.3	65	61
21.1	70	37
24.0	75	24
26.7	80	15
29.4	85	11
32.2	90	8
35.0	95	6
37.8	100	5

Dielectric Strength. — The dielectric strength of varnished cambric depends greatly upon the size and shape of electrodes used for testing. Using the equipment described below, the puncture voltage per mil at 25° C. is between 800 and 1000 volts. This decreases rapidly as the temperature rises, being between 300 and 600 volts per mil at 75° C.

Farmer, Kennelly and Wiseman have shown that the apparent dielectri

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rength of 0.33 mm. varnished cambric decreased more than 50 per cent in anging from very small discs to discs exceeding 15 inches in diameter.

Tests are most readily made between the rounded edge of a strip of brass inch thick and 6 inches long, which constitutes the upper electrode, and a ip of brass about $\frac{1}{8}$ inch wide and 8 inches long, which is placed directly below e strip of varnished cambric to be tested, and forms the lower electrode. The ctrodes may be attached to a strip of wood about 16 inches long and 4 inches ide. Also the top electrode may be fastened to supports with revolving arms that it can be thrown out of the way when the test has been completed. In der to prevent flash-overs from one electrode to another, a wide strip of varshed cambric is placed underneath the lower electrode and petrolatum smeared er this strip of varnished cambric before the strip to be tested is placed over e lower electrode. The test strip of varnished cambric is pressed firmly against e lower strip so that the petrolatum makes a seal between the two strips thus eventing flash-overs from the top electrode to the bottom one.

Power Factor. — The power factor of varnished cambric insulation in cables much higher than that of impregnated paper. The following values are pical:

Temperature Deg. Cent.	Power factor, Per Cent
20	6.0
30	8.0
40	10.5
50	14.0
60	19.0
70	49.0
80	33.0
90	43.0
100	56.0

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CAPACITY AND CHARGING CURRENTS. — (*See also Alternating Currents; Condensers, Electric; Insulating Materials, Testing of; Transient Electric Phenomena and Oscillations; Transmission Lines; Wires and Cables, Insulated.*) In the section on *Capacity and Condensers*, in the article on *Electricity and Magnetism, Principles of*, are given the formulas for capacities in series and in parallel and for the energy stored in a charged condenser. For units and their interrelations see the articles *Units, Practical Electrical*, and *Units and Conversion Factors*. Commercial forms of condensers are described in the article on *Condensers, Electric*. The following is a brief table of contents of this article.

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GENERAL RELATIONS AND DEFINITIONS. — Consider any number of conductors 0, 1, 2, 3, etc., either (1) at a great distance from all other conductors or (2) completely surrounded by a hollow conducting shell, the inside surface of which shell is to be considered as one of the conductors, say No. 0, of the system. The electrostatic condition of such a system of conductors is uninfluenced by any electrostatic effects produced outside the system; it may therefore be called an "electrostatically independent system."

Potential Coefficients (A). — Any conductor of an electrostatically independent system may be chosen as a conductor of reference; let this reference conductor be designated as conductor No. 0. Let v_{10}, v_{20}, v_{30}, etc., represent the potential drop from No. 1 to No. 0, from No. 2 to No. 0, from No. 3 to No. 0, etc., and let q_0, q_1, q_2, q_3, etc., represent the charges on No. 0, No. 1, No. 2, No. 3, etc. Then, if the relative positions of the various conductors and insulators in the field remain unaltered and the specific inductive capacities (*see Electricity and Magnetism, Principles of*) of the various insulating materials between the conductors are *constant* (not necessarily the same for each insulating material, however), the following relations hold for all values of the charges on and potential drops between conductors irrespective of how the conductors may be connected: *

$$\left.\begin{aligned} v_{10} &= A_{11}q_1 + A_{12}q_2 + A_{13}q_3 + \text{etc.},\\ v_{20} &= A_{12}q_1 + A_{22}q_2 + A_{23}q_3 + \text{etc.},\\ v_{30} &= A_{13}q_1 + A_{23}q_2 + A_{33}q_3 + \text{etc.},\\ q_0 &= -(q_1 + q_2 + q_3 + \text{etc.}), \end{aligned}\right\} \quad (1)$$

where the A's are all *constants* depending upon the distances apart of the con-

* By wires of small cross-section and length compared with the dimensions of the conductors.

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luctors and the nature of the insulating medium between them. The coefficients A in these equations may be called the "potential coefficients" of he system of conductors. It should be noted particularly that *these coefficients are independent of how the conductors may be charged and of how they may be interconnected* (provided the connecting wires are small compared with urfaces of the conductors). In certain simple cases these coefficients A are eadily calculated; see below.

Electrostatic Induction Coefficients (B). — The above equations may lso be written

$$\left.\begin{aligned} q_1 &= B_{11}v_{10} + B_{12}v_{20} + B_{13}v_{30} + \text{etc.},\\ q_2 &= B_{12}v_{10} + B_{22}v_{20} + B_{23}v_{30} + \text{etc.},\\ q_3 &= B_{13}v_{10} + B_{23}v_{20} + B_{33}v_{30} + \text{etc.},\end{aligned}\right\} \qquad (1)$$

tc.

$$q_0 = -(q_1 + q_2 + q_3 + \text{etc.}),$$

here the B's are also constants and may be expressed directly in terms of the otential coefficients A by solving equations (1) for q_1, q_2, q_3, etc. The conants B are called the "electrostatic induction coefficients," and like the conants A are independent of how the conductors may be charged and of how ey may be interconnected. The B's may be expressed directly in terms of the normal and grounded capacities of the various conductors; see below.

Normal Capacity of Two Conductors (C). — By the normal capacity beeen any two conductors is meant the capacity of the condenser formed by ese two conductors when all the other conductors are connected to one anher and to the conductor of reference, the two conductors of course being sulated therefrom. The normal capacity between any two conductors of a stem, say Nos. 1 and 2, is, then, from equation (2),

$$C_{12} = \frac{B_{11}B_{22} - B_{12}^2}{B_{11} + B_{22} + 2B_{12}}. \qquad (2a)$$

When the arrangement of the conductors is perfectly symmetrical (as in a three-conductor cable), $B_{11} = B_{22}$ and the normal capacity between 1 and 2 is

$$C_{12} = \frac{1}{2}(B_{11} - B_{12}). \qquad (2b)$$

Grounded Capacity (C_g). — By the grounded capacity of any conductor of a system is meant the capacity of the condenser formed by this conductor as one "plate" and all the other conductors, including the conductor of reference, connected together as the other plate.* The grounded capacity of conductor No. 1, say, is then, from equation (2),

$$C_{1g} = B_{11}. \qquad (2c)$$

That is, the "electrostatic coefficient of self-induction" of any given conductor is the same as the grounded capacity of this conductor.

Capacity to Neutral (C_0). — In calculating the charging current, voltage drops, etc., in a single-phase or balanced three-phase transmission line it is sometimes convenient to consider the actual capacity between wires as made up of two capacities in series, each of twice the actual capacity between wires. This double capacity, viz.,

$$C_0 = 2C_{12}, \qquad (2d)$$

is called the capacity to neutral, since this capacity multiplied by the voltage to neutral, in either a single-phase or balanced three-phase line, gives the charge per wire, which charge is also in phase with the voltage to neutral. This prod-

* The term "grounded" arises from the fact that the conductor of reference is usually the ground.

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uct, however, does not give the charge per wire when the system is unbalanced the general equations (2) must then be used.

Charging Current and Capacity Susceptance. — The charging current taken by the various conductors of a system are found by differentiating equations (2) with respect to time; this gives the instantaneous values of the charging currents. In the case of sine-wave voltages all of frequency f, the effective values and phase relations of the charging currents in each conductor, in terms of the voltage drops to the conductor of reference, *all expressed in vector notation* (*see Alternating Currents*), are as follows:

$$\left.\begin{aligned} I_1 &= j\,2\pi f\,(B_{11}V_{10} + B_{12}V_{20} + B_{13}V_{30} + \dots\dots\dots\dots) \\ I_2 &= j\,2\pi f\,(B_{12}V_{10} + B_{22}V_{20} + B_{23}V_{30} + \dots\dots\dots\dots) \\ I_3 &= j\,2\pi f\,(B_{13}V_{10} + B_{23}V_{20} + B_{33}V_{30} + \dots\dots\dots\dots) \end{aligned}\right\}$$

etc.,

$$I_0 = -(I_1 + I_2 + I_3 + \dots\dots\dots\dots)$$

Note that the quantities in the brackets are to be added *vectorially*.

In the case of a system of but two conductors, i.e., a simple condenser, the relations reduce to

$$I = j\,2\pi fCV,$$

when V is the voltage drop through the condenser, I the current in the direction of this drop, and C the capacity of the condenser. That is, the charging current of a simple condenser leads the voltage drop by 90° and is equal numerically to the product of this voltage by $2\pi fC$. The factor

$$b = 2\pi fC$$

is called the capacity susceptance * of the condenser. Capacity susceptance is expressed in mhos or micromhos, being of the same dimensions as conductance. Numerically, the charging current of a simple condenser may be then expressed as

$$I = bV.$$

When V is in volts and b in mhos, the current I is in amperes. For either a single-phase or balanced three-phase line the charging current per wire may also be expressed as $I = b_0V_0$, where $b_0 = 2\pi fC_0 = 2b$, and may be called the "capacity susceptance to neutral." When b_0 is in micromhos (see tables below) and V_0 is in volts to neutral, the charging current per wire is

$$I = 10^{-6}b_0V_0.$$

In a single-phase line $V_0 = V/2$ and in a balanced three-phase line $V_0 = V/\sqrt{3}$ when V in each case is the voltage between wires.

FORMULAS FOR THE CAPACITY OF SIMPLE CONDENSERS — Let

K = specific inductive capacity of medium between conductors; medium assumed uniform; for air $K = 1$,

C = capacity of the condenser formed by the two conductors,

$C_0 = 2C$ = capacity to neutral.

Two Concentric Spheres. — Let r' = internal radius of outer sphere and r = external radius of inner sphere, both in centimeters, and R' and R the corresponding dimensions in inches.

$$C = \frac{Krr'}{r' - r} \qquad \text{statfarads,}$$

$$= 2.822 \times 10^{-4}\,\frac{KRR'}{R' - R} \qquad \text{microfarads.}$$

* The inductive susceptance of a condenser is $-2\pi fC$; see *Alternating Currents*.

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Two Parallel Plates. — Unless the plates are large compared with their distance apart no simple formula can be deduced, since the electrostatic field at the edge of the plates is not uniform. Let S = surface, in square inches, of contact between the metal plate and dielectric (the dielectric sheet is usually larger than the metal sheet, hence S is generally the surface, one side only, of the metal plate); D = thickness of dielectric in inches, K = specific inductive capacity, and let s and d be the dimensions in centimeters corresponding to S and D respectively. Then for D small compared with S, the capacity of two parallel plates is

$$C = \frac{Ks}{4\pi d} \quad \text{statfarads}$$

$$= 2.246 \times 10^{-7} \frac{KS}{D} \quad \text{microfarads.}$$

Stack of Plates. — Let N = the number of *metal* plates in the stack; there will then be $N-1$ effective dielectric sheets or $N-1$ parallel plate condensers in series. Using the same notation as above, the capacity of a stack of N metal plates, *connected in series*, is

$$C = \frac{Ks}{4\pi d\,(N-1)} \quad \text{statfarads}$$

$$= 2.246 \times 10^{-7} \frac{KS}{D\,(N-1)} \quad \text{microfarads.}$$

Round Wire in Concentric* Sheath. — Dimensions as in Fig. 1; since the *ratio* only is involved, it is immaterial what units are used for D and d provided *both* are expressed in the *same* unit. For a length of cable long compared with its diameter,

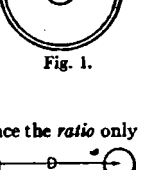


Fig. 1.

$$C = \frac{K}{2 \log_e \frac{D}{d}} \quad \text{statfarads per centimeter}$$

$$= \frac{7.354 \times 10^{-8} K}{\log_{10} \frac{D}{d}} \quad \text{microfarads per 1000 ft.}$$

Two Parallel Round† Wires. — Dimensions as in Fig. 2; since the *ratio* only is involved, it is immaterial what units are used for D and d provided *both* are expressed in the *same* unit. For length of line large compared with the distance apart of the wires, the exact formula‡ for the capacity *between wires* is

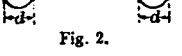


Fig. 2.

* When the wire is off center by a distance m (center of wire to center of sheath),

$$C = \frac{K}{2 \cosh^{-1}\alpha} \quad \text{statfarads per centimeter}$$

$$= \frac{16.93 \times 10^{-8} K}{\cosh^{-1}\alpha} \quad \text{microfarads per 1000 ft.,}$$

where

$$\alpha = \frac{D^2 + d^2 - 4m^2}{2Dd}.$$

† When the wires are far apart compared with the linear dimensions of their cross-section, the second group of formulas also applies approximately to wires of any shape of cross-section provided d is taken equal to the perimeter of the cross-section divided by π, i.e., equal to the "equivalent" diameter of the cross-section.

‡ Taking into account the non-uniform distribution of the charge on each wire; see Snider and Osborne, *Elec. World*, 1910, *Vol.* 56, *p.* 667.

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$$C = \frac{K}{4 \cosh^{-1} \frac{D}{d}} \quad \text{statfarads per centimeter}$$

$$= \frac{8.467 \times 10^{-3} K}{\cosh^{-1} \frac{D}{d}} \quad \text{microfarads per 1000 feet.}$$

When D is greater than 10 d the following formulas for the capacity of *wires* may be used instead of the above with an error of less than 0.1 per cent:

$$C = \frac{K}{4 \log_e \frac{2D}{d}} \quad \text{statfarads per centimeter}$$

$$= \frac{3.677 \times 10^{-3} K}{\log_{10} \frac{2D}{d}} \quad \text{microfarads per 1000 feet}$$

$$= \frac{19.41 \times 10^{-3} K}{\log_{10} \frac{2D}{d}} \quad \text{microfarads per mile.}$$

The *capacity to neutral* in all cases is $C_0 = 2C$. Tables of capacity to neut for various sizes of wires and various spacings, when separated by air ($K =$ are given in the tables below. Note that these tables and the above formu are strictly applicable to ordinary overhead lines only when the distance b the wires to other conductors, particularly the earth, is large compared wi their distance apart. However, the effect of the earth is usually small in m practical cases (see below), and the formulas and tables give a very fair a proximation to the actual capacities.

The capacities of standard strands given in the following tables are calcula by the same formula as for smooth round wires using for the diameter d t diameter of the strand; see *Wires and Cables, Bare*. The values as thus c culated are therefore not exact, but the error is probably less than 3 per c for all practical cases.

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CAPACITY TO NEUTRAL* OF SMOOTH ROUND WIRES

Microfarads per 1000 FEET of each wire of a single-phase or of a symmetrical three-phase line

Size of wire, A.W.G.	Diam. of wire, inches	Inches between wires, center to center							
		1	3	6	9	12	18	24	30
0000	0.4600	0.01199	0.006608	0.005192	0.004618	0.004282	0.003884	0.003643	0.003477
000	0.4096	0.01099	0.006317	0.005013	0.004477	0.004161	0.003783	0.003555	0.003396
00	0.3648	0.01016	0.006055	0.004847	0.004344	0.004045	0.003688	0.003470	0.003319
0	0.3249	0.009458	0.005812	0.004692	0.004218	0.003936	0.003597	0.003390	0.003245
1	0.2893	0.008855	0.005587	0.004546	0.004100	0.003833	0.003511	0.003313	0.003174
2	0.2576	0.008332	0.005381	0.004408	0.003988	0.003735	0.003428	0.003239	0.003107
4	0.2043	0.007455	0.005010	0.004157	0.003781	0.003553	0.003274	0.003102	0.002980
6	0.1620	0.006753	0.004688	0.003933	0.003595	0.003388	0.003134	0.002975	0.002863
8	0.1285	0.006177	0.004406	0.003732	0.003426	0.003238	0.003005	0.002859	0.002755
10	0.1019	0.005693	0.004155	0.003551	0.003273	0.003100	0.002886	0.002751	0.002655
12	0.08081	0.005277	0.003931	0.003386	0.003132	0.002974	0.002776	0.002651	0.002562
14	0.06408	0.004921	0.003730	0.003235	0.003003	0.002858	0.002675	0.002558	0.002475
16	0.05082	0.004611	0.003549	0.003099	0.002885	0.002750	0.002580	0.002472	0.002394

Size of wire, A.W.G.	Feet between wires, center to center								
	3	4	5	6	8	10	15	20	25
0000	0.003351	0.003171	0.003043	0.002947	0.002806	0.002706	0.002542	0.002436	0.002361
000	0.003276	0.003103	0.002981	0.002889	0.002753	0.002657	0.002498	0.002396	0.002323
00	0.003204	0.003039	0.002922	0.002833	0.002702	0.002610	0.002456	0.002358	0.002287
0	0.003135	0.002977	0.002864	0.002779	0.002653	0.002564	0.002416	0.002320	0.002251
1	0.003069	0.002917	0.002809	0.002727	0.002606	0.002520	0.002376	0.002284	0.002217
2	0.003006	0.002860	0.002756	0.002677	0.002560	0.002477	0.002338	0.002249	0.002184
4	0.002887	0.002752	0.002656	0.002582	0.002474	0.002396	0.002266	0.002182	0.002121
6	0.002777	0.002652	0.002563	0.002494	0.002392	0.002319	0.002197	0.002118	0.002061
8	0.002676	0.002559	0.002476	0.002412	0.002317	0.002248	0.002133	0.002059	0.002004
10	0.002581	0.002473	0.002395	0.002335	0.002245	0.002181	0.002073	0.002002	0.001951
12	0.002493	0.002392	0.002319	0.002262	0.002178	0.002118	0.002016	0.001949	0.001900
14	0.002411	0.002316	0.002247	0.002194	0.002115	0.002058	0.001961	0.001898	0.001852
16	0.002334	0.002245	0.002180	0.002130	0.002056	0.002002	0.001910	0.001850	0.001806

* The capacity *between* wires equals one-half the values given in this table.

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CAPACITY TO NEUTRAL* OF SMOOTH ROUND WIRES

Microfarads per MILE of each wire of a single-phase or of a symmetrical three-phase line

Size of wire, A.W.G.	Diam. of wire, inches	Inches between wires, center to center							
		1	3	6	9	12	18	24	30
0000	0.4600	0.06332	0.03490	0.02741	0.02438	0.02261	0.02051	0.01924	0.01836
000	0.4096	0.05802	0.03336	0.02647	0.02361	0.02197	0.01998	0.01877	0.01793
00	0.3648	0.05366	0.03198	0.02559	0.02293	0.02136	0.01947	0.01832	0.01752
0	0.3249	0.04995	0.03069	0.02477	0.02227	0.02078	0.01899	0.01790	0.01713
1	0.2893	0.04676	0.02951	0.02400	0.02165	0.02024	0.01854	0.01749	0.01676
2	0.2576	0.04400	0.02842	0.02328	0.02106	0.01972	0.01810	0.01710	0.01640
4	0.2043	0.03937	0.02645	0.02195	0.01997	0.01876	0.01729	0.01638	0.01573
6	0.1620	0.03566	0.02475	0.02077	0.01898	0.01789	0.01655	0.01571	0.01512
8	0.1285	0.03262	0.02326	0.01971	0.01809	0.01710	0.01587	0.01510	0.01455
10	0.1019	0.03006	0.02194	0.01875	0.01728	0.01637	0.01524	0.01453	0.01402
12	0.08081	0.02787	0.02076	0.01788	0.01654	0.01570	0.01466	0.01400	0.01353
14	0.06408	0.02599	0.01970	0.01709	0.01586	0.01509	0.01412	0.01351	0.01307
16	0.05082	0.02434	0.01874	0.01636	0.01523	0.01452	0.01362	0.01305	0.01264

Size of wire, A.W.G.	Feet between wires, center to center								
	3	4	5	6	8	10	15	20	25
0000	0.01769	0.01674	0.01607	0.01556	0.01482	0.01429	0.01342	0.01286	0.01246
000	0.01730	0.01639	0.01574	0.01525	0.01454	0.01403	0.01319	0.01265	0.01227
00	0.01692	0.01604	0.01543	0.01496	0.01427	0.01378	0.01297	0.01245	0.01207
0	0.01656	0.01572	0.01512	0.01467	0.01401	0.01354	0.01275	0.01225	0.01189
1	0.01621	0.01540	0.01483	0.01440	0.01376	0.01330	0.01255	0.01206	0.01171
2	0.01587	0.01510	0.01455	0.01413	0.01352	0.01308	0.01235	0.01187	0.01153
4	0.01525	0.01453	0.01402	0.01363	0.01306	0.01265	0.01196	0.01152	0.01120
6	0.01467	0.01400	0.01353	0.01317	0.01263	0.01225	0.01160	0.01118	0.01088
8	0.01413	0.01351	0.01307	0.01273	0.01223	0.01187	0.01126	0.01087	0.01058
10	0.01363	0.01306	0.01264	0.01233	0.01186	0.01152	0.01094	0.01057	0.01030
12	0.01316	0.01263	0.01224	0.01194	0.01150	0.01118	0.01064	0.01029	0.01003
14	0.01273	0.01223	0.01187	0.01159	0.01117	0.01087	0.01036	0.01002	0.00977
16	0.01232	0.01185	0.01151	0.01125	0.01085	0.01057	0.01008	0.009768	0.00953

* The capacity *between* wires equals one-half the values given in this table.

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CAPACITY TO NEUTRAL* OF STANDARD STRANDS

Microfarads per 1000 FEET of each conductor of a single-phase or of a symmetrical three-phase line

ize of able, M. or .W.G.	Diam. of strand, inches	Inches between conductors, center to center							
		1	3	6	9	12	18	24	30
000,000	1.152	.....	0.0105	0.00725	0.00617	0.00558	0.00492	0.00454	0.00428
750,000	0.998	.....	0.00959	0.00683	0.00586	0.00533	0.00472	0.00437	0.00414
500,000	0.814	0.0254	0.00856	0.00630	0.00547	0.00501	0.00447	0.00415	0.00394
350,000	0.681	0.0181	0.00783	0.00591	0.00517	0.00476	0.00427	0.00398	0.00378
250,000	0.575	0.0147	0.00725	0.00558	0.00492	0.00454	0.00409	0.00383	0.00364
0 000	0.528	0.0135	0.00699	0.00542	0.00480	0.00444	0.00401	0.00376	0.00358
000	0.470	0.0122	0.00666	0.00523	0.00465	0.00431	0.00390	0.00366	0.00349
00	0.418	0.0112	0.00637	0.00504	0.00450	0.00418	0.00380	0.00357	0.00341
0	0.373	0.0103	0.00610	0.00488	0.00437	0.00407	0.00371	0.00349	0.00333
1	0.332	0.00958	0.00586	0.00472	0.00424	0.00396	0.00361	0.00341	0.00326
2	0.292	0.00891	0.00561	0.00456	0.00411	0.00384	0.00352	0.00332	0.00318
4	0.232	0.00790	0.00520	0.00429	0.00389	0.00365	0.00336	0.00318	0.00305
6	0.184	0.00712	0.00486	0.00405	0.00369	0.00348	0.00321	0.00304	0.00293

ize of able, M. or W.G.	Feet between conductors, center to center								
	3	4	5	6	8	10	15	20	25
000,000	0.00410	0.00383	0.00365	0.00351	0.00331	0.00317	0.00295	0.00281	0.00271
750,000	0.00396	0.00371	0.00354	0.00341	0.00322	0.00309	0.00288	0.00274	0.00265
500,000	0.00378	0.00355	0.00339	0.00327	0.00310	0.00298	0.00278	0.00266	0.00257
350,000	0.00363	0.00342	0.00328	0.00316	0.00300	0.00289	0.00270	0.00258	0.00250
250,000	0.00351	0.00331	0.00317	0.00307	0.00292	0.00281	0.00263	0.00252	0.00244
0 000	0.00345	0.00326	0.00312	0.00302	0.00287	0.00277	0.00260	0.00249	0.00240
000	0.00337	0.00318	0.00306	0.00296	0.00282	0.00272	0.00255	0.00245	0.00237
00	0.00329	0.00312	0.00299	0.00290	0.00276	0.00267	0.00251	0.00240	0.00233
0	0.00322	0.00305	0.00293	0.00284	0.00271	0.00262	0.00247	0.00237	0.00229
1	0.00315	0.00299	0.00288	0.00279	0.00266	0.00257	0.00242	0.00233	0.00226
2	0.00308	0.00292	0.00281	0.00273	0.00261	0.00252	0.00238	0.00229	0.00222
4	0.00295	0.00281	0.00271	0.00263	0.00252	0.00244	0.00230	0.00222	0.00215
6	0.00284	0.00271	0.00261	0.00254	0.00244	0.00236	0.00223	0.00215	0.00209

* The capacity between conductors equals one-half the values given in this table.

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CAPACITY TO NEUTRAL* OF STANDARD STRANDS

Microfarads per MILE of each conductor of a single-phase or of a symmetrical three-phase line

Size of cable, C.M. or A.W.G.	Diam. of strand, inches	Inches between conductors, center to center							
		1	3	6	9	12	18	24	30
1,000,000	1.152	.....	0.0554	0.0383	0.0325	0.0294	0.0260	0.024c	0.02
750,000	0.998	.....	0.0506	0.0361	0.0309	0.0281	0.0249	0.0231	0.02
500,000	0.814	0.134	0.0452	0.0333	0.0289	0.0264	0.0236	0.0219	0.02
350,000	0.681	0.0955	0.0413	0.0312	0.0273	0.0251	0.0225	0.0210	0.02
250,000	0.575	0.0776	0.0383	0.0295	0.0260	0.0240	0.0216	0.0202	0.01
0 000	0.528	0.0713	0.0369	0.0286	0.0253	0.0234	0.0212	0.0198	0.01
000	0.470	0.0644	0.0352	0.0276	0.0245	0.0227	0.0206	0.0193	0.01
00	0.418	0.0590	0.0336	0.0266	0.0238	0.0221	0.0201	0.0189	0.01
0	0.373	0.0544	0.0322	0.0258	0.0231	0.0214	0.0196	0.0184	0.01
1	0.332	0.0506	0.0309	0.0249	0.0224	0.0209	0.0191	0.0180	0.01
2	0.292	0.0470	0.0296	0.0241	0.0217	0.0203	0.0186	0.0175	0.01
4	0.232	0.0417	0.0275	0.0227	0.0205	0.0193	0.0177	0.0168	0.01
6	0.184	0.0376	0.0256	0.0214	0.0195	0.0184	0.0169	0.0161	0.01

Size of cable, C.M. or A.W.G.	Feet between conductors, center to center								
	3	4	5	6	8	10	15	20	25
1,000,000	0.0216	0.0202	0.0193	0.0185	0.0175	0.0168	0.0156	0.0148	0.01
750,000	0.0209	0.0196	0.0187	0.0180	0.0170	0.0163	0 0152	0.0145	0.01
500,000	0.0200	0.0188	0.0179	0.0173	0.0164	0.0157	0.0147	0.0140	0.01
350,000	0.0192	0.0181	0.0173	0.0167	0.0159	0.0153	0.0143	0. 0136	0.01
250,000	0.0185	0.0175	0.0168	0.0162	0.0154	0.0148	0.0139	0.0133	0.01
0 000	0.0182	0.0172	0.0165	0.0160	0.0152	0.0146	0.0137	0.0131	0.01
000	0.0178	0.0168	0.0161	0.0156	0.0149	0.0143	0.0135	0.0129	0.01
00	0.0174	0.0165	0.0158	0.0153	0.0146	0.0141	0.0132	0.0127	0.01
0	0.0170	0.0161	0.0155	0.0150	0.0143	0.0138	0.0130	0.0125	0.01
1	0.0166	0.0158	0.0152	0.0147	0.0141	0.0136	0.0128	0.0123	0.01
2	0.0162	0.0154	0.0149	0.0144	0.0138	0.0133	0.0126	0 0121	0.01
4	0.0156	0 0148	0.0143	0.0139	0.0133	0.0129	0.0122	0.0117	0.01
6	0.0150	0.0143	0.0138	0.0134	0.0129	0.0125	0.0118	0.0114	0.01

* The capacity *between* conductors equals one-half the values given in this table.

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25-CYCLE CAPACITY SUSCEPTANCE TO NEUTRAL* SMOOTH ROUND WIRES

Charging current in amperes per mile = (susceptance from table) × (volts to neutral) × 10^{-6}

Micromhos per MILE of each wire of a single-phase or of a symmetrical three-phase line

Size of wire, A.W.G.	Diam. of wire, inches	Inches between wires, center to center							
		1	3	6	9	12	18	24	30
0000	0.4600	9.948	5.483	4.306	3.830	3.552	3.222	3.023	2.884
000	0.4096	9.115	5.241	4.158	3.714	3.451	3.139	2.949	2.817
00	0.3648	8.430	5.024	4.020	3.602	3.356	3.059	2.878	2.752
0	0.3249	7.847	4.821	3.891	3.499	3.265	2.983	2.812	2.691
1	0.2893	7.346	4.636	3.770	3.401	3.180	2.913	2.748	2.633
2	0.2576	6.912	4.465	3.657	3.309	3.098	2.844	2.686	2.576
4	0.2043	6.185	4.155	3.448	3.137	2.947	2.716	2.573	2.471
6	0.1620	5.602	3.888	3.263	2.982	2.811	2.600	2.468	2.375
8	0.1285	5.125	3.654	3.096	2.842	2.686	2.493	2.372	2.286
10	0.1019	4.722	3.447	2.946	2.715	2.572	2.394	2.283	2.203
12	0.08081	4.378	3.261	2.809	2.598	2.466	2.303	2.199	2.126
14	0.06408	4.083	3.095	2.685	2.492	2.371	2.218	2.122	2.053
16	0.05082	3.824	2.944	2.570	2.393	2.281	2.140	2.050	1.986

Size of wire, A.W.G.	Feet between wires, center to center								
	3	4	5	6	8	10	15	20	25
0000	2.779	2.630	2.525	2.444	2.328	2.245	2.108	2.020	1.957
000	2.718	2.575	2.473	2.396	2.284	2.204	2.072	1.987	1.928
00	2.657	2.520	2.424	2.350	2.242	2.165	2.038	1.956	1.896
0	2.602	2.470	2.375	2.305	2.201	2.127	2.003	1.924	1.868
1	2.547	2.419	2.330	2.262	2.162	2.089	1.972	1.895	1.840
2	2.493	2.372	2.286	2.220	2.124	2.055	1.940	1.865	1.811
4	2.396	2.283	2.203	2.141	2.052	1.987	1.879	1.810	1.760
6	2.305	2.199	2.126	2.069	1.984	1.924	1.822	1.756	1.709
8	2.220	2.122	2.053	2.000	1.921	1.865	1.769	1.708	1.662
10	2.141	2 052	1.986	1.937	1.863	1.810	1.719	1.661	1.618
12	2.067	1.984	1.923	1.876	1.807	1.756	1.672	1.617	1.576
14	2.000	1.921	1.865	1.821	1.755	1.708	1.628	1.574	1.536
16	1.935	1.862	1.808	1.767	1.705	1.661	1.584	1.535	1.498

* The susceptance between wires equals one-half the values given in this table.

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25-CYCLE CAPACITY SUSCEPTANCE TO NEUTRAL* STANDARD STRANDS

Charging current in amperes per mile = (susceptance from table) × (volts to neutral) ×

Approximate micromhos per MILE of each conductor of a single-phase or d
symmetrical three-phase line

Size of cable, C.M. or A.W.G.	Diam. of strand, inches	Inches between conductors, center to center							
		1	3	6	9	12	18	24	30
1,000,000	1.152	.....	8.70	6.01	5.10	4.62	4.08	3.77	3.55
750,000	0.998	.....	7.94	5.67	4.85	4.41	3.91	3.63	3.43
500,000	0.814	21.0	7.10	5.23	4.54	4.14	3.71	3.44	3.27
350,000	0.681	15.0	6.48	4.90	4.29	3.94	3.53	3.30	3.14
250,000	0.575	12.2	6.01	4.63	4.08	3.77	3.39	3.17	3.02
0 000	0.528	11 2	5.79	4.49	3.97	3.67	3.33	3.11	2.97
000	0.470	10.1	5.53	4.33	3.85	3.57	3.24	3.03	2.89
00	0.418	9.26	5.28	4.18	3.74	3.47	3.16	2.97	2.83
0	0.373	8.54	5.06	4.05	3.63	3.36	3.08	2.89	2.76
1	0.332	7.94	4.85	3.91	3.52	3.28	3.00	2.83	2.70
2	0.292	7.38	4.65	3.79	3.41	3.19	2.92	2.75	2.64
4	0.232	6.55	4.32	3.57	3.22	3.03	2.78	2.64	2.53
6	0.184	5.90	4.02	3.36	3.06	2.89	2.65	2.53	2.42

Size of cable, C.M. or A.W.G.	Feet between conductors, center to center								
	3	4	5	6	8	10	15	20	25
1,000,000	3.39	3.17	3.03	2.90	2.75	2.64	2.45	2.32	2.25
750,000	3.28	3.08	2.94	2.83	2.67	2.56	2.39	2.28	2.20
500,000	3.14	2.95	2.81	2.72	2.57	2.47	2.31	2.20	2.12
350,000	3.02	2.84	2.72	2.62	2.50	2.40	2.25	2.14	2.07
250,000	2.90	2.75	2.64	2.54	2.42	2.32	2.18	2.09	2.02
0 000	2.86	2.70	2.59	2.51	2.39	2.29	2.15	2.06	1.99
000	2.79	2.64	2.53	2.45	2.34	2.25	2.12	2.03	1.96
00	2.73	2.59	2.48	2.40	2.29	2.22	2.07	1.99	1.93
0	2.67	2.53	2.43	2.36	2.25	2.17	2.04	1.96	1.90
1	2.61	2.48	2.39	2.31	2.22	2.14	2.01	1.93	1.87
2	2.54	2.42	2.34	2.26	2.17	2.09	1.98	1.90	1.84
4	2.45	2.32	2.25	2.18	2.09	2.03	1.92	1.84	1.78
6	2.36	2.25	2.17	2.10	2.03	1.96	1.85	1.79	1.73

* The susceptance *between* conductors equals one-half the values given in this tabl

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60-CYCLE CAPACITY SUSCEPTANCE TO NEUTRAL* SMOOTH ROUND WIRES

Charging current in amperes per mile = (susceptance from table) × (volts to neutral) × 10^{-6}

Micromhos per MILE of each wire of a single-phase or of a symmetrical three-phase line

Size of wire, A.W.G.	Diam. of wire, inches	Inches between wires, center to center							
		1	3	6	9	12	18	24	30
0000	0.4600	23.87	13.16	10.33	9.191	8.524	7.732	7.253	6.922
000	0.4096	21.87	12.58	9.979	8.912	8.263	7.532	7.076	6.760
00	0.3648	20.23	12.06	9.647	8.645	8.053	7.340	6.907	6.605
0	0.3249	18.83	11.57	9.338	8.396	7.834	7.159	6.748	6.458
1	0.2893	17.63	11.13	9.048	8.162	7.630	6.990	6.594	6.319
2	0.2576	16.59	10.71	8.777	7.940	7.434	6.824	6.447	6.183
4	0.2043	14.84	9.972	8.275	7.529	7.073	6.518	6.175	5.930
6	0.1620	13.44	9.331	7.830	7.155	6.745	6.239	5.923	5.700
8	0.1285	12.30	8.769	7.430	6.820	6.447	5.983	5.693	5.485
10	0.1019	11.33	8.271	7.069	6.515	6.171	5.745	5.478	5.286
12	0.08081	10.51	7.827	6.741	6.236	5.919	5.527	5.278	5.101
14	0.06408	9.798	7.427	6.443	5.979	5.689	5.323	5.093	4.927
16	0.05082	9.176	7.065	6.168	5.742	5.474	5.135	4.920	4.765

Size of wire, A.W.G.	Feet between wires, center to center								
	3	4	5	6	8	10	15	20	25
0000	6.669	6.311	6.058	5.866	5.587	5.387	5.059	4.848	4.697
000	6.522	6.179	5.934	5.749	5.482	5.289	4.973	4.769	4.626
00	6.379	6.047	5.817	5.640	5.380	5.195	4.890	4.694	4.550
0	6.243	5.926	5.700	5.531	5.282	5.105	4.807	4.618	4.483
1	6.111	5.806	5.591	5.429	5.188	5.014	4.731	4.547	5.415
2	5.983	5.693	5.485	5.327	5.097	4.931	4.656	4.475	4.347
4	5.749	5.478	5.286	5.139	4.924	4.769	4.509	4.343	4.222
6	5.531	5.278	5.101	4.965	4.762	4.618	4.373	4.215	4.102
8	5.327	5.093	4.927	4.799	4.611	4.475	4.245	4.098	3.989
10	5.139	4.924	4.765	4.648	4.471	4.343	4.124	3.989	3.883
12	4.961	4.762	4.614	4.501	4.336	4.215	4.011	3.879	3.781
14	4.799	4.611	4.475	4.369	4.211	4.098	3.906	3.778	3.686
16	4.645	4.467	4.339	4.241	4.090	3.985	3.800	3.683	3.595

* The susceptance between wires equals one-half the values given in this table.

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60-CYCLE CAPACITY SUSCEPTANCE TO NEUTRAL*
STANDARD STRANDS

Charging current in amperes per mile = (susceptance from table) × (volts to neutral) × 10^{-7}

Approximate micromhos per MILE of each conductor of a single-phase or of a symmetrical three-phase line

Size of cable, C.M. or A.W.G.	Diam. of strand, inches	Inches between cables, center to center							
		1	3	6	9	12	18	24	30
1,000,000	1.152	.....	20.9	14.4	12.3	11.1	9.80	9.05	8.52
750,000	0.998	.....	19.1	13.6	11.6	10.6	9.39	8.71	8.22
500,000	0.814	50.5	17.0	12.6	10.9	9.95	8.90	8.26	7.84
350,000	0.681	36.0	15.6	11.8	10.3	9.46	8.48	7.92	7.54
250,000	0.575	29.3	14.4	11.1	9.80	9.05	8.14	7.62	7.24
0 000	0.528	26.9	13.9	10.8	9.54	8.82	7.99	7.46	7.13
000	0.470	24.3	13.3	10.4	9.24	8.56	7.77	7.28	6.94
00	0.418	22.2	12.7	10.0	8.97	8.33	7.58	7.13	6.79
0	0.373	20.5	12.1	9.73	8.71	8.07	7.39	6.94	6.63
1	0.332	19.1	11.6	9.39	8.44	7.88	7.20	6.79	6.48
2	0.292	17.7	11.2	9.09	8.18	7.65	7.01	6.60	6.33
4	0.232	15.7	10.4	8.56	7.73	7.28	6.67	6.33	6.07
6	0.184	14.2	9.65	8.07	7.35	6.94	6.37	6.07	5.81

Size of cable, C.M. or A.W.G.	Feet between cables, center to center								
	3	4	5	6	8	10	15	20	25
1,000,000	8.14	7.62	7.28	6.97	6.60	6.33	5.88	5.58	5.39
750,000	7.88	7.39	7.05	6.79	6.41	6.15	5.73	5.47	5.28
500,000	7.54	7.09	6.75	6.52	6.18	5.92	5.54	5.28	5.09
350,000	7.24	6.82	6.52	6.30	5.99	5.77	5.39	5.13	4.98
250,000	6.97	6.60	6.33	6.11	5.81	5.58	5.24	5.01	4.86
0 000	6.86	6.48	6.22	6.03	5.73	5.50	5.16	4.94	4.79
000	6.71	6.33	6.07	5.88	5.62	5.39	5.09	4.86	4.71
00	6.56	6.22	5.96	5.77	5.50	5.32	4.98	4.79	4.64
0	6.40	6.07	5.84	5.66	5.39	5.20	4.90	4.71	4.56
1	6.26	5.96	5.73	5.54	5.32	5.13	4.83	4.64	4.49
2	6.11	5.81	5.62	5.43	5.20	5.01	4.75	4.56	4.41
4	5.88	5.58	5.39	5.24	5.01	4.86	4.60	4.41	4.30
6	5.66	5.39	5.20	5.05	4.86	4.71	4.45	4.30	4.18

*. The susceptance *between* conductors equals one-half the values given in this table.

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Single Round* Wire Parallel to the Ground. — Dimensions as in Fig. 3. The dotted circle represents the "image" of the wire in the plane. The capacity of the actual condenser formed by the wire and the earth (assumed equivalent to an infinite conducting plane parallel to the wire) is the same as the capacity to neutral of the fictitious condenser formed by the wire and its image, the distance between the two wires of this fictitious condenser being $D = 2H$. Hence using the approximate expressions, since the wire is practically always more than 10 times its diameter above the other, the capacity *between the wire and the earth* is

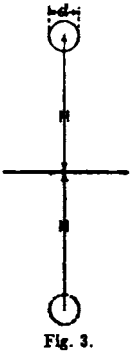


Fig. 3.

$$C = \frac{K}{2\log_e \frac{4H}{d}} \quad \text{statfarads per centimeter}$$

$$= \frac{7.354 \times 10^{-4} K}{\log_{10} \frac{4H}{d}} \quad \text{microfarads per 1000 feet}$$

$$= \frac{38.83 \times 10^{-3} K}{\log_{10} \frac{4H}{d}} \quad \text{microfarads per mile.}$$

SYSTEMS OF THREE CONDUCTORS. — Three practical examples of an electrostatically independent system consisting of three conductors only are: (1) three parallel overhead wires at a distance above the earth large compared to their distances apart, (2) two wires in a lead sheath and (3) two overhead wires and the earth. In the first case any one of the three wires may be considered as the conductor of reference; in the second case it is convenient to choose the sheath of the cable as the conductor of reference, whether grounded or not, and in the third case to choose the earth as the conductor of reference. The general equations (1) and (2) are applicable to either case. Designating the reference conductor as No. 3 instead of No. 0, and the other two conductors as No. 1 and No. 2 respectively, the general equations may be written

$$\left.\begin{aligned} v_{13} &= A_{11}q_1 + A_{12}q_2, \quad & q_1 &= B_{11}v_{13} + B_{12}v_{23}, \\ v_{23} &= A_{12}q_1 + A_{22}q_2, \quad & q_2 &= B_{12}v_{13} + B_{22}v_{23}, \\ & & q_3 &= -(q_1 + q_2). \end{aligned}\right\} \qquad (5)$$

v_{13} and v_{23} indicate the potential drop from 1 to 3 and from 2 to 3 respectively. Solving the first set of equations for q_1 and q_2 gives

$$B_{11} = \frac{A_{22}}{A_{11}A_{22} - A_{12}^2}, \quad B_{22} = \frac{A_{11}}{A_{11}A_{22} - A_{12}^2}, \quad B_{12} = \frac{-A_{12}}{A_{11}A_{22} - A_{12}^2}. \qquad (5a)$$

Possible Combinations of Three Conductors which may be used as a Condenser — "Part Capacities." — The following combinations are possible:

No. 1 against † No. 2 with No. 3 insulated,
No. 2 against No. 3 with No. 1 insulated,
No. 3 against No. 1 with No. 2 insulated,
No. 1 against No. 2 and No. 3 connected together,
No. 2 against No. 3 and No. 1 connected together,
No. 3 against No. 1 and No. 2 connected together.

* When the wire is at a height large compared with the linear dimensions of its cross-section these formulas also apply approximately to wires of any shape of cross-section provided d is taken equal to the perimeter of the cross-section divided by π.

† By "against" is here meant that the source of e.m.f. is connected between the two conductors designated, e.g., in the fourth case No. 1 is charged positively say, and an equal and opposite charge divides between 2 and 3.

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The capacities corresponding to these various combinations may be called "part capacities," and may be designated by subscripts thus: C_{12} = capacity of No. 1 against No. 2 with No. 3 insulated (= normal capacity between 1 and 2), $C_{1(3)}$ = capacity of No. 1 against No. 2 and No. 3 connected together (= grounded capacity of No. 1), and so on for the others. The values of these part capacities can be deduced directly from equations (5), viz.,

$$\left.\begin{aligned} C_{12} &= \frac{1}{A_{11} + A_{22} - 2A_{12}}, & C_{1(23)} &= B_{11} \\ C_{23} &= \frac{1}{A_{22}}, & C_{2(31)} &= B_{22} \\ C_{31} &= \frac{1}{A_{11}}, & C_{3(12)} &= -(B_{11} + B_{22} + 2B_{12}) \end{aligned}\right\} \quad (6)$$

Three Overhead Parallel Wires, Effect of Earth Neglected. — Arrangement of wires and dimensions as in Fig. 4; distance apart of wires and diameters both in the *same* unit of length, but this unit may be either centimeters or inches. From equation (20c) in the article on *Electricity and Magnetism, Principles of*, the following closely approximate values of the A's (accurate to within less than 0.1 per cent when the distance apart of the wires is greater than 10 diameters) may be deduced, taking K as unity, since the dielectric in the case under consideration is air:

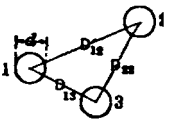


Fig. 4.

$$A_{11} = 2\log_e \frac{4D_{12}^2}{d_1 d_2}, \quad A_{22} = 2\log_e \frac{4D_{23}^2}{d_2 d_3}, \quad A_{12} = 2\log_e \frac{2D_{12}D_{23}}{d_2 D_{13}}, \quad (7)$$

all in c.g.s. electrostatic units for a length of one centimeter.*

From these relations the values of the coefficients B may be calculated for any arrangement of three parallel wires.

Equilateral Triangle Arrangement. — A common arrangement of the three wires of a three-phase transmission line is to place them so that their centers form the three vertices of an equilateral triangle. In this case $D_{12} = D_{23} = D_{13} = D$, say; and if all three wires are of the same diameter $d_1 = d_2 = d_3 = d$, say, then $A_{11} = A_{22} = 4\log_e \frac{2D}{d}$ and $A_{12} = 2\log_e \frac{2D}{d}$ in c.g.s. electrostatic units, and therefore, from equation (6) the normal capacity between any two of the wires with the third wire insulated is

$$C_{12} = \frac{1}{4\log_e \frac{2D}{d}} \quad \text{statfarads per centimeter,}$$

$$= \frac{3.677 \times 10^{-8}}{\log_{10} \frac{2D}{d}} \quad \text{microfarads per 1000 ft.,}$$

which is the same as the capacity between two parallel wires by themselves see above.

Equilateral Triangle Arrangement with Balanced Three-phase Voltages. — For sine-wave voltages between the wires equal in effective value to V and differing in phase by 120 degrees, the above equations for the charges and

* To find the values of the B's in microfarads per 1000 feet change 2 $\log_e$ in these formulas to 1.36 $\log_{10}$ and apply equations (5a).

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charging currents give the following relations between the *effective* values of the voltages, charges and charging currents, for each of the three wires:

$$Q = C_0 V_0, \qquad I = 2\pi f C_0 V_0,$$

where

$$V_0 = \frac{V}{\sqrt{3}} = \text{voltage to neutral},$$

$$C_0 = 2\,C_{12} = \text{capacity to neutral}.$$

When the C's are in microfarads the charge Q is in microcoulombs and the charging current in micro-amperes.

The charge on any particular wire is in phase with the voltage between that wire and the neutral (*see Alternating Currents*) and the charging current for that wire is 90 degrees ahead of the voltage drop from that wire to the neutral. For the same voltage V between wires in a single-phase system as in a three-phase balanced system, the charging current per wire in the three-phase system with the equilateral triangle arrangement of wires is $\frac{2}{\sqrt{3}} = 1.155$ times the charging current per wire in the single-phase system.

For any other arrangement of wires and for an unbalanced three-phase system, the general equations (5) and the general formulas for A_{11}, A_{22} and A_{12} given above must be used.

Two-conductor Cable. — Arrangement of wires and dimensions as shown in Fig. 5. The sheath forms the conductor of reference and when designated as conductor No. 3, general equations (5), (5a) and (6) apply directly to this case also. For the symmetrical arrangement of the wires shown in the figure, $A_{11} = A_{22}$ whence, dropping the first subscript,

$$B_1 = \frac{A_1}{A_1^2 - A_2^2}, \qquad B_2 = \frac{-A_2}{A_1^2 - A_2^2}.$$

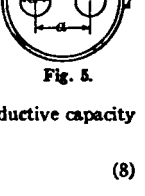


Fig. 5.

Russell (*Alternating Currents, Vol. 1*) gives the following values of A_1 and A_2, assuming a dielectric filling the space between the wires and the sheath to have the *same** specific inductive capacity throughout:

$$A_1 = \frac{2}{K}\log_e \frac{D^2 - a^2}{Dd}, \qquad A_2 = \frac{2}{K}\log_e \frac{D^2 + a^2}{2Da}, \tag{8}$$

both in c.g.s. electrostatic units for a length of one centimeter. To reduce to practical units for a length of 1000 ft. change $2\log_e$ to $1.36\log_{10}$.

Normal Capacity of a Two-conductor Cable. — Substituting Russell's values for A_1 and A_2 in equation (6) gives

$$C_{12} = \frac{K}{4\log_e\left(\frac{2a}{d}\cdot\frac{D^2 - a^2}{D^2 + a^2}\right)} \quad \text{statfarads per centimeter}$$

$$= \frac{3.677 \times 10^{-1} K}{\log_{10}\left(\frac{2a}{d}\cdot\frac{D^2 - a^2}{D^2 + a^2}\right)} \quad \text{microfarads per 1000 ft.}$$

Grounded Capacity of a Two-conductor Cable. — The capacity in this case, from equations (6), is

$$C_{1(2)} = B_{11} = \frac{A_1}{A_1^2 - A_2^2}.$$

*This is seldom realized in practice, since the dielectric is made up of insulation, fillers and braids having different specific inductive capacities; see *Wires and Cables, Insulated.*

By substituting Russell's values of the A's an approximate value for this capacity may be obtained; it will be greater than the normal capacity C_{12}.

Effect of the Earth on the Capacity of Two Overhead Wires. — As a fair approximation the earth may be considered as a conducting plane of infinite extent and the wires as parallel to this plane. Such a combination is electrostatically equivalent to two wires and their two "images" at a distance below the earth equal to the distance of the actual wires above the earth, see Fig. 6. Let q_1 and q_2 represent the charges on the actual wires and q_3 the actual charge on the earth, and V_{12} and V_{32} the potential differences between the two wires and the earth respectively (the p.d. between the two wires $v_{12} = v_{13} - v_{23}$); equations (5), (5a) and (6) then apply to this case also. The values of the A's in this case are (putting $K = 1$, since the dielectric is air)

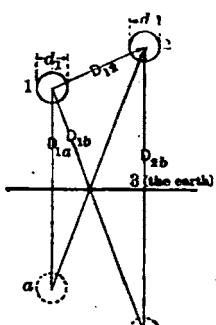


Fig. 6.

$$A_{11} = 2\log_e \frac{2D_{1a}}{d_1},\ A_{22} = 2\log_e \frac{2D_{2b}}{d_2},\ A_{12} = 2\log_e \frac{D_{1b}}{D_{12}}, \tag{9}$$

all in c.g.s. electrostatic units per centimeter length. To find the values of the B's directly in microfarads for a length of 1000 feet change 2 $\log_e$ to 136 $\log_{10}$.

Consider the special case where both wires are at the same height H, say, and both of the same diameter d; then from equation (9), putting D for the distance between their centers,

$$A_{11} = A_{22} = 2\log_e \frac{4H}{d},\quad A_{12} = 2\log_e \frac{2H}{D'}, \tag{9a}$$

where

$$D' = \frac{D}{\sqrt{1+\left(\frac{D}{2H}\right)^2}} = \text{"equivalent" distance apart.}$$

Then from equations (6)

$$C_{12} = \frac{1}{4\log_e \frac{2D'}{d}} \quad \text{statfarads per centimeter.} \tag{10}$$

Comparing the formula for C_{12} with that for two wires by themselves, equation (4), it is evident that the effect of the earth in this case is to increase the capacity by an amount equal to the increase in capacity which would result from decreasing the distance between the wires from the actual distance D to the "equivalent" distance D'. For D small compared with the height H, which is usually the case, the equivalent distance D' is practically equal to D and the effect of the earth is therefore negligible.

Effect of the Earth When One Wire is Grounded. — Let No. 2 be grounded. Consider the same case as in the preceding paragraph, i.e., both wires at the same height H and of the same diameter d. From equation (5a)

$$B_{11} = B_{22} = 2C_{12}\left(\frac{A_{11}}{A_{11}+A_{12}}\right),\qquad B_{12} = -2C_{12}\left(\frac{A_{12}}{A_{11}+A_{12}}\right),$$

where C_{12} has the value given by equation (10) and the A's the values given by (9a). The charge taken by conductor No. 1 is then $B_{11}v$, the charge taken

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y conductor No. 2 is $B_{12}v$, and the charge taken by the earth $(B_{11} + B_{12})v$, here v is the drop of potential from No. 1 to No. 2.

Effect of the Earth When Middle or Neutral Point of the System s Grounded. — In this case $v_{23} = -v_{13} = v_0$, where v_0 = voltage to neutral. rom equation (5) it is then evident that grounding the middle point of the ystem has no effect upon the charging current.

SYSTEMS OF FOUR OR MORE CONDUCTORS. — The method of lculating the capacities for a three-conductor system, described in detail bove, may be readily extended to a system of any number of circuits, inde-endent or otherwise, made up of any number of conductors.

Relations Between the *A*'s and *B*'s for a Four-conductor System. — or a four-conductor system the relations are as follows: put

$$M = A_{11}A_{22}A_{33} + 2A_{12}A_{13}A_{23} - (A_{11}A_{23}^2 + A_{22}A_{13}^2 + A_{33}A_{12}^2),$$

hen

$$\left.\begin{aligned} B_{11} &= \frac{A_{22}A_{33} - A_{23}^2}{M}, & B_{12} &= -\frac{A_{12}A_{33} - A_{13}A_{23}}{M}, \\ B_{22} &= \frac{A_{11}A_{33} - A_{13}^2}{M}, & B_{23} &= -\frac{A_{22}A_{11} - A_{12}A_{13}}{M}, \\ B_{33} &= \frac{A_{11}A_{22} - A_{12}^2}{M}, & B_{13} &= -\frac{A_{12}A_{23} - A_{13}A_{22}}{M}, \end{aligned}\right\} \quad (11)$$

here are 32 part capacities in the general case of a four-conductor system ut in cases of symmetry they reduce to a lesser number.

Three-conductor Cable. — Arrangement and dimensions as shown in Fig. 7. The sheath forms the conductor of reference; let it be designated as nductor No. 0. From symmetry $A_{11} = A_{22} = A_{33} = A_1$, say, nd $A_{12} = A_{23} = A_{13} = A_2$, say. Equations (11) then reduce to

$$B_{11} = B_{22} = B_{33} = \frac{A_1 + A_2}{(A_1 - A_2)(A_1 + 2A_2)} = B_1, \text{ say},$$

$$B_{12} = B_{23} = B_{13} = \frac{-A_2}{(A_1 - A_2)(A_1 + 2A_2)} = B_2, \text{ say},$$

nd the capacity between any pair of wires is

$$C_{12} = \tfrac{1}{2}(B_1 - B_2).$$

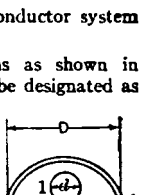


Fig. 7.

For sine-wave voltages equal in effective value and differing in phase by 120 egrees, the effective value of the charging current per wire is then, from quation (3),

$$I = 2\pi f (B_1 - B_2) V_0 = 2(2\pi f C_{12}) V_0,$$

here $V_0 = \frac{V}{\sqrt{3}}$, the voltage V being the p.d. between wires. This current ads the voltage drop to neutral, V_0, by 90 degrees.

Calculated Value C_{12} for a Three-conductor Cable. — Russel (*Alternating Currents, Vol. 1*) gives the following approximate values for A_1 and A_2, ssuming the insulation fillers and braids to have the same specific inductive apacity (which is not usually the case),

$$A_1 = \frac{0.1360 \times 10^9}{K} \log_{10}\left(\frac{D^2 - 1.33\,d^2}{Dd}\right) \text{ and } A_2 = \frac{0.0680 \times 10^9}{K} \log_{10}\left(\frac{0.75\,D^4 - 1.78\,d^4}{d^2D^2(3D^2 - 4d^2)}\right)$$

in practical units for a length of 1000 feet. Using these values the normal capacity between wires is

$$C_{12} = \frac{3.677 \times 10^{-8} K}{\log_{10} \frac{2a\rho}{d}} \quad \text{microfarads per 1000 feet,}$$

where

$$\rho = \sqrt{\frac{(3D^2 - 4a^2)^2}{(3D^2)^2 - (4a^2)^2}}.$$

That is, the capacity is the same as that of two parallel wires by themselves but at a distance ρa between centers instead of the actual distance a.

Effect of the Earth on the Capacity of Three Overhead Wires. — For any kind of arrangement, as shown in Fig. 8 (the dotted circles are the "images" of the actual wires), the general expressions for the A's in c.g.s. electrostatic units* for a length of one centimeter are as follows:

$$A_{11} = 2 \log_e \frac{2 D_{1a}}{d_1}, \quad A_{22} = 2 \log_e \frac{2 D_{2b}}{d_2}, \quad A_{33} = 2 \log_e \frac{2 D_{3c}}{d_3},$$

$$A_{12} = 2 \log_e \frac{D_{1b}}{D_{12}}, \quad A_{13} = 2 \log_e \frac{D_{1c}}{D_{13}}, \quad A_{23} = 2 \log_e \frac{D_{2c}}{D_{23}}.$$

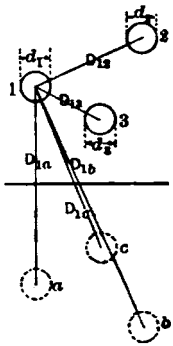


Fig. 8.

The values of the B's may then be calculated from equation (11) and the charging currents from equation (3). For any numerical case the calculations are tedious, but not difficult. Ordinarily the formulas given above neglecting the effect of the earth are sufficiently accurate for all practical purposes; compare with the effect of the earth on a two-wire line.

Electrostatic Induction From One Circuit to Another. — The general equations (1), (2) and (3) together with the method of calculation of the A's given in the last paragraph make it possible to calculate the induced voltages from one line to another, e.g., the voltages induced from a high-tension line to a telephone line. The method is straightforward, but tedious. The discussion given above indicates how such a problem may be attacked; space is not available for a detailed discussion here.

MEASUREMENT OF CAPACITY. — See the article on *Condensers, Electric.*

BIBLIOGRAPHY. — Russell, Alex., *Alternating Currents;* Ferguson, *Elements of Electrical Transmission;* Deutsch., W., *Graphical Method of Calculating the Capacity of Cylindrical Combinations,* Archiv f. Elektrotechnik, 2, p. 435, 1914, gives a method for calculating the capacity of parallel conductors of any form of cross-section whatever.

* To find from these A's the values of the B's in microfarads per 1000 feet change $2 \log_e$ in these formluas to $136 \log_{10}$ and apply equations (11).

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CAR BARNS AND INSPECTION SHEDS. — (*See also Cars, Electric; Locomotives, Electric; Railways.*) In every electric railway system it is necessary to provide car barns and inspection sheds where the cars may be taken regularly for a systematic inspection. In some cases these barns are used for the storage of cars and in special cases are equipped as regular repair shops. Provision for inspection is necessary, provision for storage is optional, although it is customary to provide storage at least for those cars which are idle during the daytime. The expense of providing for the storage under cover of all the cars that are idle between midnight and 6 a.m. is of doubtful value, for the deterioration of the cars left in the open is likely to be less than the fixed charges on the increased capacity of the sheds.

Location. — The location of the car barn may be determined by several considerations. It may be located in the city on account of the convenience of the employees, the possibility of placing the general offices in the same building, and on account of the fact that the city service is an important part of the whole system. It may be located in the suburbs where real estate is cheap and ample space available. It may be located at a convenient point such as the center of gravity of the system, so that the dead mileage of the cars will be a minimum. Finally, it may be located adjacent to the power station, so that the repair shops of the two departments may be combined and thus become more efficient.

Construction. — Preparatory to designing a car house it is necessary to become acquainted with municipal and underwriters' regulations and conforming with these, to provide space for car storage, inspection, administration offices, line department, road department, car employees' lobby, car sign storage, sand drying and storage, salt storage, oil storage, wash-room and toilets.

The standard construction consists of a concrete foundation and brick walls, but many of the smaller railroads have mill frame buildings with 2-inch cement curtain walls. The floors are made of concrete with cement finish and sloped for drainage.

Illumination. — The illumination of a car barn should be both general and local. The general illumination should consist of incandescent lights, suspended from overhead between the tracks and spaced about a car length apart. These may be run five in series on the trolley circuit, although an ungrounded system is better. The intensity of illumination on the floor should be from 1 to 1.5 foot-candles or lumens per square foot. Frequent sockets for drop lights must also be provided for many portions of the car equipment are in dark corners.

Inspection Pits. — Inspection pits between the rails are usually 4 ft. 6 in. deep below the top of rails. It is important to have these pits thoroughly drained and well illuminated.

Tracks. — Tracks should be spaced not less than 11 feet between centers where there are no posts between tracks and not less than 13 feet where there are posts. The tracks at the entrance to the car house should be designed to permit the rapid movement of cars with the least interruption to traffic.

Fire Risks. — Attention should be given to the prevention of fire by the adoption of the following precautions:

1. Use of automatic sprinklers.
2. Provision of two sources of water supply such as mains and tank.
3. Division of building by fire-proof walls. The underwriters stipulate that no section shall contain cars to the value of over $200,000.
4. Avoiding proximity to inflammable buildings.

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5. Having ample provision of water pails, sand pails, chemical extinguishers and short hoses, the last being usually 2 ½ inches in diameter and provided with 1¼ inch nozzles.
6. Locating car house near a fire station.
7. Building tracks on a grade so that cars may be easily pushed out by hand.
8. Having numerous auxiliary fire alarms.
9. Consulting underwriters when planning.

Repair Shops. — It is usual to provide about 200 sq. ft. of repair shop floor per car owned. This area is usually divided about equally between departments, with, and those without car tracks. Where tracks are installed the usual spacing is from 15 to 16 feet between centers. Cars and car parts are usually lifted by travelling cranes, but in the smallest shops it is common practice to use jacks, hydraulic lifts, screw hoists and chain hoists. Transfer tables are preferred to ladder tracks for moving cars between departments.

Shop buildings should be surrounded with sufficient ground for storage of trucks, lumber, scrap material, etc.

BIBLIOGRAPHY. — Electric Railway Engineering Association, *Engineering Manual* and Proceedings.

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CARS, ELECTRIC. — (*See also Control Systems for Railway Motors; Collectors, Current; Locomotives, Electric.*) The cars used on electric railways may be divided into two classes, viz., single-truck and double-truck. Each of these classes may be subdivided into types according as the cars are open or closed.

SINGLE-TRUCK CARS have a seating capacity as high as 32 passengers. Their characteristics are given in the accompanying table.

Item	Dimension
Over-all length	28 to 31 ft.
Rigid wheel base	5 to 7 ft.
Weight loaded and equipped	12 to 20 tons
Maximum speed	25 m.p.h
Maximum motor capacity, total	80 h.p.
Number of motors	2

They are only used in city service with frequent stops and usually have a cylinder-type controller at each end with hand brakes, although there are cases where these cars have been fitted with remote control and air brakes.

Considerable attention is being given at present to the subject of equipping these cars so that during the hours of heavy traffic they may be run in trains of two, controlled by one motorman. This causes less congestion in the streets for a given service and obviates the waste of operating throughout the day cars of large capacity designed to meet rush-hour conditions.

DOUBLE-TRUCK CARS.— The double-truck type of car has an over-all length of from 30 to 70 feet, a seating capacity of from 32 to 70 passengers and a maximum speed of from 40 to 70 m.p.h. One of these cars consists of a body mounted on two, four-wheel trucks. The car body under-frame is supported on a cross piece in the truck known as the bolster and is kept in position by a king-pin fitted into a king-pin center plate on the car body. The truck may swivel around this king-pin through quite an angle, guided by curved plates on each member.

Construction of Trucks. — The truck consists of axles, carried in journal boxes in side frames, transoms which connect the side frames, and the bolster which is carried by the transoms by means of springs (either spiral or elliptical) and a spring plate swung from the transoms. Coil springs are inserted between the journals and the side frames. The bolster may be of the "rigid," "floating" or "swinging" type depending upon the amount of play in the bolster. The rigid bolster is employed in locomotives only. The swinging bolster is most generally used for passenger cars, particularly in high-speed service, as it makes a much more easy riding construction. The three-axle truck is common in high-speed steam railroad practice, but the two-axle truck is generally used in electric railway practice as it allows more room for the motors. Four-wheel trucks are sometimes called "bogie" trucks or "swiveling" trucks to distinguish them from the "pony" or "radial" trucks having two wheels, which are used on steam locomotives.

Motor-car trucks have wheels of from 33 to 36 inches in diameter, and usually weigh from 10,000 to 15,000 pounds depending upon the size of the motors and body they are intended to carry. The rigid wheel base is from 6 to 8 feet. The problem of making a motor-driven truck guide properly is considerably more difficult than guiding the trucks of a car that is hauled, as there is a tendency for the motor-driven truck to get out of line and become cramped between the

rails. On this account and on account of the weight of the motors, trucks for a motor car must be stronger and heavier than for a trailer car.

Suspension of Motors. — The motors are usually hung between the axles on a single-truck car and between each axle and the transom on a double-truck car. In the "nose" suspension a lug is cast on the side of the motor frame away from the axle and this is attached to the transom with or without springs. The other side of the motor is carried by arms containing bearings which encircle the car axles. Thus about one-half of the weight of the motor is carried as a dead weight on the car axle, and the rest by the truck framing. In the "cradle" suspension both motors of a truck are carried by a cradle which is suspended from the car axles by springs. By this arrangement the entire weight of the motors is spring supported and carried by the axles, thus relieving the transom and side frames of the weight of the motors.

Maximum Traction Truck. — This is a special form of bogie truck with two axles having wheels of different diameters. The equalizing arrangements in this truck are such that about three-quarters of the total weight comes on the main axle which has the larger wheels and carries the motor, and the balance comes on the other axle which has small wheels. This arrangement gives a double-truck car with only two motors and yet provides that about three-quarters of the total weight shall be on driving axles, thus yielding "maximum traction." This type of truck is used on cars which are too long and heavy to use the two-axle rigid truck but which have such slow speed that only two motors are required. It is not adapted to high-speed work.

CAR BODIES may be classified as closed, convertible, semi-convertible and open.

Closed Cars.— The small closed type for city service is always of wood and has longitudinal seats. The general dimensions are given in the table below. Large closed cars with double trucks for interurban or rapid-transit service have both transverse and longitudinal seats, the proportion depending upon the proportion of long-haul traffic. The longitudinal seats give an arrangement permitting convenience of movement into and out of the car and allow more room for standing, but are not comfortable for long trips. Transverse seats are more comfortable for a long trip and for a service employing a high rate of acceleration.

Convertible Cars are constructed so that all the side panels of the body may be folded either up into the roof, or down to the floor leaving only the upright posts carrying the weight of the roof, thus converting a closed car into an open car at will.

Semi-convertible Cars. — A semi-convertible car, as its name implies, is arranged so that it may be partly opened in the summer time. It makes a very good car for high-speed interurban service because it is not advisable to operate open cars in high-speed service.

Open Cars usually have the transverse seats extending clear across the car. Access is obtained by steps running the length of the car on each side. They may be of the single- or double-truck type. They provide the maximum seating capacity for a given weight.

Cars for Rapid Handling of Traffic. — In large cities where the service is congested special means must be provided to aid and direct the rapid loading and unloading of cars. In a rapid transit service having stations this is accomplished by placing doors in the sides of the cars at the center and at or near the ends, and requiring all passengers to enter by the end doors and leave by the center doors. Both center and end doors are operated by compressed air and controlled by a guard at one end of the car. For street service the pre-payment or "pay as you enter" car is employed. This is built with extra long platforms

at each end. The passengers are required to deposit their fare in a box as they enter the car from the rear platform, where the conductor stands, and to leave by the front door and platform. The rear platform is made roomy to take care of congestion while the conductor is making change. Cars of this type recently installed in Chicago and Philadelphia are arranged for both entrance and exit of passengers at the front end, the conductor's station also being at this end.

The "One Man Safety Car" was introduced in 1914 to give more frequent service with decreased expense and in 1919, more cars of this type were built than of all other types combined. The principal data on a typical car are: Seats 32, single truck, length overall 28 feet, two 25 h.p. motors, wheel base 8 feet, wheels 24 inches, total weight equipped 7 tons, maximum speed 18 to 20 m.p.h., energy consumption 0.75 kw.-hr. per car mile. The car is equipped with air brakes, control system automatically interlocked with brakes and car doors and other special safety devices making it possible for one man to operate it with minimum possible chance of mistakes.

Construction of Car Bodies. — Most of the car bodies used on electric railways are constructed of wood, but for underground roads or for roads operating a high-class suburban service of multiple-unit trains the cars are preferably constructed of steel to reduce the dangers from collision and fire. This construction is demanded by consideration of safety, but it is directly contrary to the general tendency of the present day to reduce the weight of cars as much as possible. The proportion of weight of car to weight of load is very high and it entails a considerable waste of energy to propel this dead weight. The weight of car per passenger or seat capacity is a figure that should receive careful consideration and it should be kept at the minimum value compatible with strength and safety.

DIMENSIONS AND WEIGHTS OF TYPICAL EQUIPMENTS. — There are indicated in the following table the principle data for electric cars which are being operated in various typical services.

Service	City	City	City	City P. A. Y. E.	Suburban	Interurban	Subway	N. Y. C. R.R.	W. S. R.R.
Seating capacity	14	24	32	32	38	40	52	64	52
Number of trucks	1	1	1	2	2	2	2	2	2
Length over-all, ft.	22	30	32	41	38	40	50	60	49
Length of body, ft.	16	20	21	28	28	29	41	50	38
Number of motors	2	2	2	2	2	4	2	2	4
H.p. of each motor	40	40	40	70	70	50	200	200	75
Weight of body, lb.	6,000	9,530	7,500	15,800	15,670	19,200	34,300	55,000	35,110
Weight of trucks, lb.	4,600	4,800	4,500	10,400	10,600	16,000	22,500	14,940	23,000
Weight of electric equipment, lb.	5,990	6,962	7,062	9,500	8,350	16,542	21,510	25,460	21,680
Weight, total, lb.	16,590	21,292	19,062	35,700	34,620	51,742	78,310	95,400	79,790
Weight per passenger, lb.	1,185	887	594	1,118	911	1,293	1,506	1,490	1,534
Weight of load, lb.	2,240	3,640	4,760	4,760	5,600	5,889	7,560	9,240	7,560

BIBLIOGRAPHY. — Buck, A. M., *The Electric Railway*, New York, 1915; Burch, E. P., *Electric Traction for Railway Trains*, N. Y., 1911; Jackson, W., *Electric Car Maintenance*, New York, 1914; Master Car Builders Assn., *Car-Builders' Dictionary*, New York, 1916; *Electric Railway Journal*, Numerous places; *Electric Journal*, Oct. 1916, Oct. 1918.

CASTINGS, IRON AND STEEL. — These are made by pouring the molten material into sand or iron molds of the desired shape and allowing it to cool. Sand molds are generally used, and are made by packing molding sand about a wooden pattern having the shape of the desired casting and somewhat larger dimensions to allow for the contraction of the metal in cooling. The removal of the pattern leaves a hollow in the sand of the shape of the object to be cast. In order to have sufficient consistency the sand should either contain some clay and be somewhat moist, giving a "green sand" mold, or it should be mixed with a binding material giving a "dry sand mold."

Simple patterns may be made in one piece, but if the pattern be at all complicated it must be made in two or more pieces to permit withdrawal from the sand without disturbing the latter.

Steel castings are more difficult to make than iron castings, as they are more porous; thin steel sections should be avoided for such castings, as the steel cools too rapidly when thin.

In all castings sudden changes in the thickness of the metal should be avoided, as the unequal cooling of sections of different thicknesses causes temperature stresses and may crack the metal. This is particularly true in steel castings.

Care should be exercised in designing castings to make them such that the patterns can be readily removed from the sand molds.

Process of Making a Mold. — A wooden or iron box called a flask, consisting of sides only, is used in making the molds. This is divided into a bottom portion called the drag, and an upper portion called the cope; see Fig. 1. Intermediate portions, called checks, are used for complicated patterns.

A hole is made through the cope to convey the metal to the mold. Molds made of "dry sand" should be baked in an oven before pouring. The surface of the mold is frequently coated with "blacking."

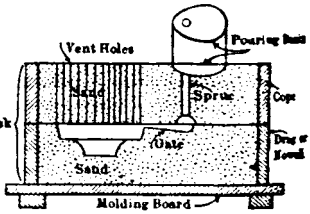


Fig. 1.

If holes are to be made in the casting they are formed by cores of hard-baked sand inserted after the pattern is removed and are held in place by studs of metal, called "chaplets," and by impressions in the mold made by projections on the pattern called "prints."

Cost of Iron and Steel Castings (Pre-war prices). — The cost of an iron casting, exclusive of the pattern, depends somewhat upon the intricacy of the pattern; representative costs in 1914 were for simple patterns of moderate size, 3 to 5 cents per pound; for large engine and dynamo castings 3 to 4.25 cents per pound; for small intricate castings 6 to 10 cents per pound. Malleable iron and steel castings about 50 to 100 per cent more.

BIBLIOGRAPHY. — See bibliographies in the articles on *Iron, Pig and Cast; Steel.*

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CELLS, STANDARD. — (*See also Batteries, Primary; Electrochemistry, Principles of; Potentiometers.*) The need of a standard of electromotive force was recognized in the early days of the electrical industry, and the Daniell cell (*see Batteries, Primary*) was largely used for this purpose. This cell is readily prepared from ordinary chemicals, and is still used to some extent as a rough and ready standard. Such a cell, however, deteriorates quite rapidly, and has therefore been supplanted, for all accurate measurements, by other cells which possess to a greater degree the necessary characteristics of permanence and reproducibility. There are at present two types of standard cells in general use, the Clark and the Weston cells. The latter is the more generally used at the present time.

Pure Chemicals Required. — In order that the e.m.f. of any form of primary standard cell may accord with the stated value, great care must be exercised in the preparation of the materials, the processes for which have been carefully worked out by Kahle and later by Wolff and Waters (*Bull. Bureau of Standards, 1907, Vol. 4, p. 1*).

CLARK CELL. — In Fig. 1 is shown the Kahle's H-form of the Clark cell, which is one of the most satisfactory of the several forms in which the Clark cell is made. The container is of glass, which is mounted in a metal case with insulated binding posts connected to the two platinum terminals. The saturated solution of zinc sulphate forms the electrolyte, the paste of mercurous sulphate and zinc sulphate acts as a depolarizer, the mercury forms the positive pole and the zinc the negative pole. Detail directions for the preparation of the cell are given in the Bulletin of the Bureau of Standards, 1907, Vol. 4, p. 1.

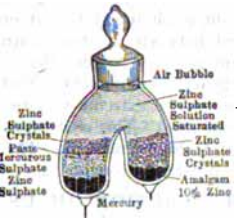


Fig. 1. Kahle's H-form of Clark Cell

Electromotive Force of Clark Cell. — The e.m.f. of the Clark cell, as determined at the time of the adoption of the international units (*see Units, Practical Electrical*), was given as 1.434 volts at 15° C. Subsequent investigations have shown that its true value is 1.4328 international volts at 15° C. At any other temperature $t°$ C. its e.m.f. is

$$E_t = 1.4328\,[1 - 0.00077\,(t - 15)].$$

The chief objections to the Clark cell are its relatively high temperature coefficient and the length of time required for the e.m.f. to attain a constant value after a change in the temperature of the cell.

Carhart-Clark Cell. — To reduce the temperature coefficient and time lag of the saturated or "normal" Clark cell, Carhart devised a form of Clark cell in which the zinc sulphate solution was just saturated at 0° C. with no excess of crystals. The e.m.f. of this type of cell is approximately

$$E = 1.440\,[1 - 0.00039\,(t - 15)].$$

For accurate work, however, such cells must be calibrated, as the e.m.f. of individual cells may differ appreciably.

WESTON OR CADMIUM CELL. — In Fig. 2 is shown the construction of the "normal" Weston or cadmium cell. The container is of glass suitably mounted in a case provided with binding posts to which the platinum wires are attached. This cell differs from the Clark cell chiefly in the use of cadmium amalgam and cadmium sulphate in place of the zinc amalgam and zinc sulphate

for the negative pole and electrolyte respectively. The particular advantag in the use of cadmium instead of zinc arises from the low temperature coefficien and small temperature lag thus obtainable. It also has a longer life and polarizes less rapidly than the Clark cell.

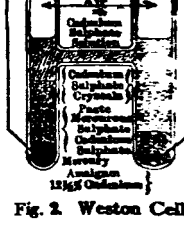


Fig. 2. Weston Cell

Electromotive Force of Weston Normal Cell. — The e.m.f. at 20° C. of the Weston normal cell (the word normal designating that the cadmium sulphate solution is saturated) is 1.01830 international volts. At any other temperature $t°$ C. its e.m.f. is

$$E_t = 1.01830 - 10^{-6}[40.6\ (t - 20) + 0.95\ (t - 20)^2 + 0.001\ (t - 20)^3].$$

(*See Bulletin Bureau of Standards, 1909, Vol. 5, p. 309.*) The e.m.f.'s of normal cadmium cells as set up by various observers following the same specifications differ among each other by less than 1 part in 10,000.

Portable Cadmium Cell. — A portable form of cadmium cell is made, which differs from the normal cadmium cell chiefly in that the cadmium sulphate solution is just saturated at 4° C., and therefore does not contain an excess of cadmium sulphate crystals at ordinary temperatures. This type of cell is to be used between the temperatures of 4° and 40° C. The temperature coefficient is much smaller than that of the normal cell and is negligible for any ordinary measurements; each cell is accompanied by a certificate stating its e.m.f. The extreme variation among 145 cells of this type was found to be 0.0009 volt. This is at present the best form of secondary standard cell, being remarkably permanent. The e.m.f. is approximately 1.0186 international volts; the resistance, roughly, 200 ohms.

PRECAUTION IN USING STANDARD CELLS. — No appreciable current can be taken from a standard cell without alteration of its e.m.f., due to polarization. It is found that the change is not permanent, for the cell gradually recovers its original e.m.f.; of course the cell is unreliable until the recovery is complete. Consequently standard cells should be used only where their e.m.f. is opposed to an equal p.d., as in connection with potentiometers. They should always be protected by a key, which is closed only momentarily, and for preliminary adjustments a high resistance, several thousand ohms at least, should be in series with the cell. When an approximate balance has been obtained this resistance should be cut out and the final balance then made.

COSTS (Pre-war prices). — A normal Clark cell costs about $12, a normal cadmium cell $15, a portable Weston cell $15.

BIBLIOGRAPHY. — Laws, F. A., *Electrical Measurements;* . Wolff and Waters, *Bull. Bur. of Stand.*, 1907, Vol. 4, p. 1; Wolff, *Bull. Bur. of Ltd.*, 1909, Vol. 5, p. 309.

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CEMENT. — (*See also Concrete.*) The cements used in engineering construction are Portland, natural and Puzzolan (or slag) cements. Of these Portland cement is the most reliable and should always be used in reinforced concrete construction. The processes of manufacture and general characteristics of these cements are given in the following paragraphs, the descriptions being copied from the report of the Joint Committee as published in *Trans. Am. Soc. C. E.*, 1917.

PORTLAND CEMENT. — This is the finely pulverized product resulting from the calcination to incipient fusion of an intimate mixture of properly proportioned argillaceous and calcerous materials. Portland cement should be used in reinforced concrete construction and in any other construction that will be subject to shocks or vibrations or stresses other than direct compression.

Specifications. — The following specifications are taken by permission from the *Am. Soc. Test. Mat. Standards*, 1918.

The following limits shall not be exceeded:

Chemical Limits. — Loss on ignition, 4 per cent; insoluble residue, 0.35 per cent; sulfuric anhydride (SO_3), 2 per cent; magnesia (MgO), 5 per cent.

Specific Gravity. — The specific gravity of cement shall be not less than 10 (3.07 for white Portland cement). Should the test of cement as received fall below this requirement a second test may be made upon an ignited sample. The specific gravity test will not be made unless specifically ordered.

Fineness. — The residue on a standard No. 200 sieve shall not exceed 22 per cent by weight.

Soundness. — A pat of neat cement shall remain firm and hard, and show no signs of distortion, cracking, checking or disintegration in the steam test for soundness.

Time of Setting. — The cement shall not develop initial set in less than 45 minutes when the Vicat needle is used or 60 minutes when the Gillmore needle is used. Final set shall be attained within ten hours.

Tensile Strength. — The average tensile strength in pounds per square inch of not less than three standard mortar briquettes composed of one part cement and three parts standard sand, by *weight*, shall be equal to or higher than the following:

Age at test, days	Storage of briquetts	Tensile strength pound per sq. in.
7	1 day in moist air, 6 days in water....	200
28	1 day in moist air, 27 days in water...	300

The average tensile strength at standard mortar at 28 days shall be higher than the strength at seven days.

NATURAL CEMENT. — This is the finely pulverized product resulting from the calcination of an argillaceous limestone at a temperautre only sufficient to drive off the carbonic acid gas. Natural cement does not develop its strength as quickly, nor is it as uniform in composition, as Portland cement. Natural cement may be used in massive masonry where weight rather than strength is the essential feature. Where economy is the governing factor, a comparison

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may be made between the use of natural cement and a leaner mixture of Portland cement that will develop the same strength.

Specifications. — The following specifications are taken from the *Am. Soc. Test. Mat. Standards*, 1918 by permission.

Fineness. — The residue on a standard No. 100 sieve shall not exceed [illegible] per cent and on a standard No. 200 sieve shall not exceed 30 per cent by weight.

Soundness. — Pats of neat cement about 3 inches in diameter, ½ inch thick at center, tapering to a thin edge, shall be kept in moist air for a period of 24 hours.

(*a*) A pat shall then be kept in air at normal temperature.

(*b*) Another pat shall be kept in water maintained as near 70° F. as practicable.

These pats shall be observed at intervals for at least 28 days, and, to satisfactorily pass the tests, shall remain firm and hard and show no signs of distortion, checking, cracking, or disintegrating.

Time of Setting. — The cement shall not develop initial set in less than ten minutes, using the Vicat needle. Final set shall be attained in not less than 30 minutes nor more than 3 hours, using the Vicat needle.

Tensile Strength. — The minimum requirements for tensile strength for briquettes 1 sq. in. in cross-section shall be as follows; and the cement shall show no retrogression in strength within the periods specified:

Neat cement	Strength
24 hours in moist air	75 lb.
7 days (1 day in moist air, 6 days in water)	150 lb.
28 days (1 day in moist air, 27 days in water)	250 lb.
One part cement, three parts standard Ottawa sand	
7 days (1 day in moist air, 6 days in water)	50 lb.
28 days (1 day in moist air, 27 days in water)	125 lb.

PUZZOLAN OR SLAG CEMENT. — This is the finely pulverized product resulting from grinding a mechanical mixture of granulated basic blast-furnace slag and hydrated lime. Puzzolan cement is not nearly as strong, uniform or reliable as Portland or natural cement, is not used extensively and never in important work; it should be used only for foundation work underground where it is not exposed to air or running water.

COST OF CEMENT. — As the cost of transportation is an important item in the cost of cement, the market price depends largely upon the place of sale. Quotations are given in the first number each month of *Engineering News-Record*.

BIBLIOGRAPHY. — *U. S. Government Specifications for Portland Cement*, Bur. Stand., Circ. No. 33, 1913. See also *Bibliography* in article on *Concrete*.

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CHAINS AND CHAIN DRIVE. — Chains for hoisting and similar purposes may be made with straight open links, twisted links or with links with transverse studs to prevent the links from collapsing under heavy loads. These types of chains are known as straight-link chains, twisted chains and stud chains, respectively. The twisted chain is usually employed when the chain has to be wrapped around a smooth drum. Crane chains are straight-link chains carefully made to fit the corrugations of the winding drum.

Chains for transmitting power are of various forms. The more common types are block chains, roller chains and various makes of "silent" chains. In all these chains the links are made of several pieces of metal, the longitudinal pieces being riveted, bolted or screwed to the end pieces or studs. In the block chain, an example of which is the ordinary bicycle chain, the end pieces are solid blocks of metal; in the roller chain the end pieces form studs which carry small rollers. With block or roller chains the power is transmitted from or to the sprocket directly by the studs or rollers, whereas in the various types of "silent" chains, e.g., the Morse and Renold chains, the longitudinal pieces of the links are provided with lugs or fingers which mesh with the teeth of the sprocket wheel and thus pull it around.

Link belts are essentially power transmitting chains made by mounting a number of single chains side by side, so that they all move as a unit. Link belts are used both for power transmission and for belt conveyors.

DATA ON ORDINARY CHAINS (Penn. R.R. Specifications, 1920)

Description	Diam. of wire, inches	Width of links, inches	Length of 100 links, inches	Weight per foot, pounds	Breaking load, pounds	Safe working load, pounds
Twisted iron	5/32	....	....	....	1,250	315
Twisted iron	3/16	....	....	....	1,800	450
Straight-link	1/4	1	100	0.70	3,400	850
Straight-link	5/16	1 3/16	114	1.05	5,300	1,325
Straight-link	3/8	1 3/8	125	1.55	7,700	1,925
Straight-link	7/16	1 5/8	137	2.00	10,500	2,625
Straight-link	1/2	1 13/16	150	2.55	13,700	3,425
Straight-link	5/8	2 3/16	187	4.00	21,400	5,350
Straight-link	3/4	2 5/8	217	5.75	30,700	7,675
Straight-link	7/8	3	247	7.75	41,800	10,450
Straight-link	1	3 5/8	280	9.75	54,700	13,675
Crane	5/8	1 1/4	113	1.65	8,200	2,050
Crane	7/16	1 1/2	125	2.10	11,200	2,800
Crane	3/4	1 5/8	144	2.70	14,600	3,650
Crane	5/8	2 1/8	175	4.25	22,800	5,700
Crane	3/4	2 1/2	200	6.00	32,900	8,225
Crane	7/8	3	235	8.00	44,700	11,175
Crane	1	3 5/8	262	10.00	58,400	14,600
Crane	1 1/8	3 7/8	300	13.00	74,000	18,500
Crane	1 1/4	4 1/4	350	16.00	91,400	22,850
Crane	1 1/2	5	412	23.00	131,500	32,875
Crane	1 3/4	5 7/8	475	30.00	177,300	44,325
Crane	2	6 3/4	575	40.00	233,900	58,475

Elongation of all sizes 12 per cent. Proof test one-half of breaking load.

SIZE, PITCH, STRENGTH AND WEIGHT OF CHAINS. — The s of an ordinary chain in which the links are made of wire or rods is specified the diameter of the wire or rod. The pitch of a chain is the distance betwe the centers of successive links, usually expressed in inches. The proof te of a chain is the specified load it must carry without deformation, and is usua taken as one-half the breaking load. The ordinary safe load is usually taken about two-thirds of the proof test, or one-third the breaking load.

The safe working load is dependent on the amount of rivet-bearing surface, speed, size of sprockets, etc., and ranges from 1/8 to 1/40 of the tensile strength.

STRENGTH OF ROLLER AND BLOCK "DIAMOND" CHAINS

Pitch, inches	Tensile strength, pou	
	Roller	Block
½	1,200	.....
5/8	1,200	.....
¾	4,000	.....
1	6,000	1200-2500
1¼	9,000	.....
1½	12,000	5000
1¾	19,000	.....
2	25,000	.....

CHAIN DRIVE. — The advantages of chain drive are positive speed ratio, capability of transmitting large amounts of power at low speeds, not seriously affected by moisture, oil or grease, no stretch, and for short transmissions greater efficiency than leather, rubber or fiber belting. Roller chains should not as a rule be run at speeds of over 1000 feet per minute, and block chains not over 700 feet per minute.

Wherever possible, the distance between centers of shafts should permit of adjustment in order to regulate th sag of the chain. A chain should be adjusted, in proportion to its length, t show slack when running, care being taken to have it neither too tight nor to loose, as either condition is destructive.

The principal cause of trouble within the chain itself is elongation. It r the result of stretch of material or natural wear. Sudden jars or jolts beyon the limit of elasticity of the material will quickly render the chain useless. I for any reason a link elongates unduly it should be replaced at once, as an elongated link will eventually ruin the entire chain.

To minimize wear, chains should be kept well greased and protected fro mud and grit, cleaned often, and when replaced put back so that they run i the same direction and same side up. A new chain should never be applie to a much-worn sprocket.

Sprockets. — Properly proportioned and machined sprockets are essentia to successful chain gearing. For block chain these are obtained as follows:

Sprockets should be gauged to discover thick teeth and inaccurate diameters A poor chain may operate on a good sprocket, but a bad sprocket will ruin good chain. Sprockets of 12 to 60 teeth give best results. Fewer may b used, but cause undue elongation in the chain, wear the sprockets and consum too much power. Eight-tooth sprockets ruin almost every roller chain applie to them, and ten and eleven teeth are fitted only for medium and slow speed with other conditions unusually favorable.

BIBLIOGRAPHY. — Kent's *Mechanical Engineers' Pocket-Book;* Hildage H. T., *Chain Driving*, Mech. Eng. 30, p. 688, 1912 and *Transmission of Powe by Chains*, Engineering, p. 99, 1914. See also circulars of Bradlee & Co., Phila., Link Belt Co., Phila., Yale & Towne Mfg. Co., N. Y., and other manufac turers. See also the works on *Machine Design* listed in the Bibliography at end of article on *Bearings*.

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IMNEYS. — (*See also Draft, Mechanical.*) A chimney serves as a means establishing a sufficient draft through a furnace to produce the combustion the fuel. The amount of air *required* per hour depends upon the quantity fuel burned per hour and the quality of fuel. The amount actually used pends also on the manner of firing, or the judgment and skill of the fireman. he *force required* to produce this draft in turn depends upon the quality of the el, the method of firing, the thickness of the fuel bed, the design of the furnace, e length and cross section of the gas passages, the height and cross section of e chimney, the location of the chimney with respect to neighboring buildings d hills, and the direction and velocity of the wind which may be blowing. he *force available* for producing the draft depends upon the height and cross ction of the chimney and the difference in temperature of the hot gases in the imney and the cold air outside. On account of the number of these variables d their great range of variation from time to time, it is practically impossible deduce a rational formula for the size of the chimney required for the combustion of fuel at a given rate. The following approximate method for determining the height and cross section of a chimney, however, has been found tisfactory in practice. The formula connecting the height, cross section and te of fuel consumption is an empirical one, deduced by the author from merous actual cases, and first published in 1884. It has been extensively ployed with satisfactory results by numerous engineers since that time.

INTENSITY OF DRAFT AND HEIGHT. — The difference in weight tween the hot gases inside the chimney and the weight of an equal column of he external air is the cause of the draft produced by the chimney. The pressure due to this difference is called the "intensity" of the draft and is usually measured in inches of water column required to balance it. The measurement is made by a draft gauge, usually a U-tube partly filled with water, one leg connected by a pipe to the interior of the flue between the boiler and chimney and the other open to the external air. For finer and more accurate readings some form of multiplying gauge is used.

Let t_1 be the average temperature of the chimney gases, t_2 the temperature of the external air, both in degrees Fahrenheit, and let H be the height of the chimney in feet. Then the total intensity of draft produced by the chimney, expressed in inches of water column for normal atmospheric pressure, is

$$F = H\left(\frac{7.64}{460+t_2} - \frac{8.00}{460+t_1}\right).$$

For an atmospheric pressure of P inches of mercury, multiply the left-hand side by $\frac{P}{30}$.

The intensity of the draft and consequently the velocity and the volume of the hot gases will of course be greater the greater the temperature of the hot gases, but as the temperature increases the volume of a given weight increases, that is, their density decreases. When the temperature of the gases exceeds a certain value the increase in the velocity due to a further increase of temperature will be more than offset by the decrease in density. According to Rankine the temperature corresponding to the maximum value of the product of volume and density, that is the maximum weight of gases discharged, is, under ordinary conditions, 600° F., when the external temperature is 60°. Hence the total intensity of draft F_0 corresponding to maximum weight of discharged gases may be found approximately by substituting 600 in the above formula for t_1, and 60 for t_2. The formula then reduces to $F_0 = 0.007\ H$.

The actual intensity of the draft is usually less than that calculated from the

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temperature taken at the bottom of the chimney, on account of the coolin of the gases as they ascend the chimney and from other causes. Taking th reduction at 20 per cent the formula expressing the relation of intensity of draf to height of chimney becomes $F_n = 0.0057\,H$ on the assumption of a temper ture of 600° at the bottom of the chimney.

MINIMUM HEIGHT. — Hence when the intensity of the draft necessar to produce the necessary current of air through the breeching, boiler and furnac is known, the minimum height of chimney which will produce this draft is

$$H = 175\,F_n \text{ feet},$$

where F_n is the net intensity of draft in inches of water required. The followin table gives the intensity of draft required under ordinary conditions.

DRAFT PRESSURE REQUIRED FOR COMBUSTION OF DIFFEREN FUELS

Kind of fuel	Total draft in inches of water	Kind of fuel	Total draft in inches of water
Straw	0.20	Slack, very small	0.7-1.1
Wood	0.30	Coal dust	0.8-1.1
Sawdust	0.35	Semi-anthracite coal	0.9 1.2
Peat, light	0.4	Mixture of breeze and slack	1.0-1.3
Peat, heavy	0.5	Anthracite, round	1.2-1.4
Sawdust mixed with small opal	0.6	Mixture of breeze and coal dust	1.2-1.5
Bituminous, run of mine	0.4-0.7	Anthracite slack	1.3-1.8

Thurston gives the following formulas for the intensity of draft and height chimney in terms of the fuel consumption per square foot of grate per hour.

Let C = pounds of coal burnt per hour per square foot of grate. Then

for anthracite coal

$$F_n = 0.001875\,(C-1)^2 \quad \text{and} \quad H = \frac{(C-1)^2}{4};$$

for best Penn. or Welsh

$$F_n = 0.00148C^2 \quad \text{and} \quad H = \frac{C^2}{5};$$

for Pittsburgh or Illinois

$$F_n = 0.000833C^2 \quad \text{and} \quad H = \frac{C^2}{9}.$$

In any particular case the required draft may differ considerably from the figur given above. The design of a chimney should be left to an engineer of experien in this kind of work.

According to C. L. Hubbard (*Am. Elec., Mar., 1904*), the following heigh have been found to give good results in plants of moderate size (500 horse-pow or less), with sufficient draft to force the boilers 20 to 30 per cent above the rating:

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With free-burning bituminous	75 feet
With anthracite of medium and large size	100 feet
With slow-burning bituminous	120 feet
With anthracite pea	130 feet
Witb anthracite buckwheat	150 feet
With anthracite slack	175 feet

For plants of 700 or 800 horse-power or over, the chimney should not be less than 150 feet high regardless of the kind of coal used. It is evident that the figures in the above table are subject to wide variations with different qualities of coal as regards caking and non-caking, clinkering and non-clinkering, etc., with different proportions of grate to heating surface and with different kinds of grates and furnaces.

On account of the elimination of the grate in oil-burning boilers and the injection of oil under pressure the height of a chimney for an oil-burning boiler is less than for a coal-burning boiler of the same capacity. According to Gebhardt a height of from 80 to 90 feet is sufficient to force oil-burning boilers to 50 per cent above their rating. In large oil-burning plants, however, the chimney is usually designed on the coal-burning basis, in order to permit the use of coal should this subsequently prove desirable.

CROSS-SECTION OF CHIMNEY. — All chimney formulas are based on the hypothesis that the capacity or theoretical coal consumption of a chimney varies directly as the area (effective area) and the square root of the height

Let C = coal consumption in pounds per hour.
A = area of actual cross-section of chimney in square feet.
H = height above the grates in feet.

Then the typical formula may be written:

$$C = KA\sqrt{H}$$

where K = a constant. Kent uses the formula

$$C = K'A'\sqrt{H}$$

where A' is the "effective" area, taken equal to $(A - 0.6\sqrt{A})$, and K' is a constant.

The value of the constant K, as given by different authorities, varies greatly, Toldt gives $K = 5$; Prechtl, $K = 6.4$; Molesworth, $K = 9$; Ser, $K = 9.3$; Hutton, $K = 10$ to 16; Seaton and Rounthwaite, $K = 12$; Henthorn, $K = 16.6$; Brinckerhoff (average), $K = 18.1$. Kent gives for K' the value 16.65. Toldt and Prechtl refer mainly to German metallurgical practice, Ser to general French practice, Molesworth and Hutton to English practice, Seaton and Rounthwaite to marine practice, Henthorn to American mill practice.

An average of 30 stacks of various sizes now doing good work gives $K = 9.4$. An average of three notoriously overworked stacks gives $K = 17.9$.

Ser's figure $K = 9.3$, was obtained theoretically by allowing for twice the amount of air necessary for perfect combustion. By allowing an excess of one-half the amount necessary for perfect combustion, which result can readily be obtained by the use of automatic stokers, the constant $K = 12$ will be obtained. For preliminary calculations the above formula with $K = 12$, gives practical results, but the chimney should be checked by comparison with known stacks of similar diameter and height for the final calculations.

The value of $K = 12$ applies only to brick-lined stacks. In case an unlined iron or steel stack is being considered, the value of K may be increased to 14 or 15 and for small stacks 16 may be used.

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STABILITY — THICKNESS OF WALLS. — All chimneys of any considerable size should consist of an outer stack of sufficient strength to give stability to the structure, and an inner stack or core, independent of the outer one, to protect the latter from the high temperature of the hot gases. The core sometimes extends up to a height of but 50 or 60 feet above the base of the chimney, but better practice is to extend it the full height or to 100 to 120 feet in chimneys over 120 feet high. The core is usually constructed of fire brick; the outer stack may be built of common brick, or radial brick (the Custodis chimney is an example of the latter) or of steel or of reinforced concrete. To determine whether a chimney is stable, treat it as a cantilever loaded throughout its length with a load equal to the total pressure (*see Elasticity and Strength; Wind Pressure*); at no section of the chimney should the stress in the walls exceed the safe working stress for the material of which it is constructed.

Brick Chimneys. — The base of a brick stack should rarely be less than one-tenth of the height. The allowable batter according to different authorities varies from 1 in 192 to 1 in 20 on each side, but the best practice lies between 1 in 30 and 1 in 40 for ordinary brick, with 1 in 60 to 1 in 80 for the Custodis hollow-tile method of construction.

In brick chimneys practice varies as to the thickness of the walls. The linings are not exposed to wind pressure, and consequently can be much thinner than the outside wall. The usual practice is to make the steps about 50 feet high and 4½ inches thick at the top up to a height of 150 feet.

For higher chimneys the lining should be 8 inches thick at the top. The outside walls for chimneys up to 150 feet high may be 8 inches thick at the top, with the steps about 50 feet high or the upper steps may be as high as 60 feet with 50 feet for the lower steps. For stacks built on the Custodis principle the two courses are from 8 to 13 inches thick, depending on the height. The thickness of the moulded brick is increased 2 inches every 5 meters, or about every 16 feet.

All brick stacks should be topped with a waterproof cap, usually of cast iron, although in many cases it is made of stone or monolithic concrete.

Reinforced Concrete Chimneys began to come into extensive use in this country in 1901 and several hundred of them are now in use. Reinforced concrete chimneys built by the Weber Co., of Chicago consist of two parts: the lower double shell and the single shell above. The inside shell is usually 4 inches thick, while the thickness of the outside shell depends upon the height and varies from 6 to 12 inches. The single shell is from 4 to 10 inches thick. The height of the double shell depends upon the height of the chimney, nature and temperature of the gases, etc. The bending forces caused by wind pressure are taken up by vertical steel reinforcement; the resistance of the concrete itself against tension is not considered in calculation.

Steel Chimneys are largely used, especially for tall chimneys of iron-works, from 150 to 300 feet in height. The advantages claimed are: greater strength and safety; smaller space required; smaller cost, by 30 to 50 per cent, as compared with brick chimneys; avoidance of infiltration of air and consequent checking of the draft, common in brick chimneys. The best constructions for steel stacks include a number of vertical stiffeners riveted to the shell which support horizontal cast-iron or steel rings on which the linings are built. The vertical stiffeners are usually spaced about 5 feet apart, and the horizontal rings about 20 feet apart. By this method any section of the lining may be replaced without disturbing the other sections. The thickness of the metal at the top of the stack in such cases is usually ¼ inch, increasing ⅛ inch

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ry 50 feet. Stacks in which the linings are not supported may be ¼ inch k at the top increasing 5/16 inch every 30 feet. They are usually made adrical in shape, with a wide-curved flare for 10 to 25 feet at the bottom. eavy cast-iron base-plate is provided, to which the chimney is riveted, and plate is secured to a massive foundation by holding-down bolts. No guys used.

Sheet Iron Smokestacks. — Guyed stacks of light sheet iron are frequently d for single boilers and even for quite large plants especially where the ected life of the plant is short. The smaller stacks are made up in lengths about 20 feet of ⅛ inch steel connected by angle rings on the outside or the ke stack may be riveted in one piece on the ground and erected with a gin e.

For these stacks the value of K in the general formula may be as high as 20 as y are usually connected directly to the boiler uptake and are exposed to high peratures.

uch stacks deteriorate very rapidly and cannot be considered a desirable truction, but occasionally circumstances will require their use. Galvanized aded wire cables form the best guys and the anchors may be concrete blocks the larger sizes. For the smaller sizes the guys usually lead to the steel build-structure.

WEIGHT OF SHEET-IRON SMOKESTACKS PER FOOT (Porter Mfg. Co.)

...m., ...	Thick-ness, W.G.	Lb. per ft.	Diam. in.	Thick-ness, W.G.	Lb. per ft.	Diam., in.	Thick-ness, W.G.	Lb. per ft.
0	No. 16	7.20	26	No. 16	17.50	20	No. 14	18.33
2	"	8.66	28	"	18.75	22	"	20.00
4	"	9.58	30	"	20.00	24	"	21.66
6	"	11.68	10	No. 14	9.40	26	"	23.33
8	"	13.75	12	"	11.11	28	"	25.00
0	"	15.00	14	"	13.69	30	"	26.66
4	"	16.25	16	"	15.00	..	.....	.....

...ne Stacks. — During the last few years a type of stack has been developed ...urope which offers marked advantages both as to cost and ease with which draft may be controlled. The stack action is based on the injector principle, the theory has not been well worked out as yet. The stack resembles a ...turi meter set up on end, the upper cone or diffuser enclosing an angle of 7°. ...e stacks are rarely over 60 or 70 feet in height and are usually applied to ...e boilers or batteries, in order that the control may be perfect. It is usually ...ble to attain an evaporation of about 2 lb. of water per square foot of boiler ...ce with the stack alone. For the higher ratings air is injected just below ...enturi throat, thereby inducing a higher rate of suction than the height of ...ack would make. It is possible so to proportion the stack and blower ...ities that a suction draft of 3 or 4 inches of water may be obtained, but this ...ally unnecessary, as drafts of from 1 inch to 1½ inch will fulfill most of the ...rements.

...r empirical rules for design of Evasé stacks, see *Engineering of Power Plants*, ...ld and Orrok.

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FOUNDATIONS. — Chimney foundations are as a rule constructed of c crete except where the nature of the soil necessitates the use of piles or a gril of timber or steel. (For the bearing power of various soils see section on *Fou tions* in article on *Power Stations*.) For masonry chimneys the foundatio designed to give the necessary support for the shaft without particular refere to its weight and shape. In steel and reinforced concrete chimneys the wei and shape of the foundation are important factors in securing the proper stabil of the chimney, since the shaft is usually securely fastened to the foundati and the two form practically one mass.

SIZES OF FOUNDATIONS FOR HALF-LINED STEEL CHIMNEYS
(Selected from circular of Phila. Engineering Works.)

Diameter, clear, feet	3	4	5	6	7	9	1
Height, feet	100	100	150	150	150	150	15
Least diam. foundation, ft. and in	15–9	16–4	20–4	21–10	22–7	23–8	2
Least depth foundation, feet	6	6	9	8	9	10	
Height, feet	.....	125	200	200	250	275	3
Least diam. foundation, ft. and in	.....	18–5	23–8	25	29–8	33–6	
Least depth foundation, feet	.....	7	10	10	12	12	

BREECHING. — The area of the flue or breeching leading from the b to the stack is usually made 20 per cent greater than that of the stack. W several boilers discharge into the same flue its section may be tapered proportioned to the number of boilers. When two flues enter the stac opposite sides at the same level a diaphragm is inserted between the openings.

COSTS (Pre-war figures). — The following table gives the cost of l chimneys:

COST OF BRICK CHIMNEYS

Approximate horse-power	Height, feet	Diameter flue, inches	Cost, erected
85	80	25	$598
135	90	30	786
200	100	35	1226
300	110	43	1492
400	120	51	1785
750	130	61	2528
1000	140	74	3060
1650	150	88	3750
2500	160	110	5095

The following approximate cost of radial brick chimneys (adapted Gebhardt, *Steam Power Plant Engineering*) will serve to indicate the variati cost with height and diameter:

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COST OF RADIAL BRICK CHIMNEYS

ameter n feet	Height in feet					
	75	125	150	175	200	250
4	$1400	$3500	.....	.....	.....	.....
6	2000	4300	.....	.....	.....	.....
8	2700	4700	$6200	$7100	$9,300	.....
10	3700	5100	7100	7900	10,500	$16,500
12	.....	.....	7800	9000	11,100	18,300
14	.....	.....	8300	9700	12,500	21,500
16	.....	.....	.....	.....	.....	24,300

The following are approximate costs of sheet-iron stacks:

COST OF GUYED IRON STACKS

Approximate horse-power	Height, feet	Diameter, inches	Cost, erected
25	40	16	$60
...	40	18	70
...	50	18	85
75	50	20	90
...	50	26	105
...	60	22	110
100	60	24	125
...	60	26	135
...	60	28	150
125	60	28	165
...	60	32	190
...	60	34	205
150	60	36	215
200	60	38	230
225	60	42	260
250	60	46	290
300	60	52	340
400	100	60	500

ck and concrete stacks involve little expense for maintenance, 2 per cent a liberal allowance for both maintenance and depreciation. Steel and iron stacks require occasional painting to prevent excessive corrosion.

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CIRCUIT BREAKERS. — (*See also Bus-Bars; Switchboards; Switch*
Switchgear Equipment for Power Stations.) A circuit breaker is a device to ope
an electric circuit which is normally held closed by the action of a latch, togg
or similar mechanism. This tendency to open is the feature that usually di
tinguishes a circuit breaker from a switch, as the latter, although used to ope
electric circuits, is without any latch or similar device and hence will remai
in the closed position. This distinction between switches and circuit breake
is not always followed, as circuit breakers which open in oil are frequentl
spoken of as "oil switches."

TYPES OF CIRCUIT BREAKERS. — When a circuit breaker acts
matically opens the circuit as the result of certain abnormal conditions, such
overload, the circuit breaker is said to be "automatic," but if the breaker do
not open unless tripped by the attendant it is spoken of as "non-automatic.
An automatic breaker usually can be released by hand also. A breaker design
to be closed directly by the operator is spoken of as "direct controlled," wh
a breaker mounted at a distance is "remote controlled." The latter can
"manually operated" if worked through a system of bell cranks, levers or simi
devices; "electrically operated" if worked by motor or solenoid; or "pne
matically operated" if controlled by compressed air.

Small circuit breakers, particularly of low voltage, are usually direct controll
and large-capacity high-voltage breakers are usually remote controlled, su
auxiliary source of power being employed. For such distant-controlled breake
automatic operation is secured through relays (*see Relays*). Relays are a
frequently used with direct-controlled breakers.

Underload, Over-voltage, Under-voltage and Reverse Curr
Breakers. — The principal demand for circuit breakers is to have them op
the circuit when the current reaches a certain predetermined value,
breakers are designed with this end in view. They are also built for und
load conditions to open on minimum current, for over-voltage to open wh
the voltage exceeds a certain amount, for under-voltage to open when the v
age falls below a certain minimum value, for reversal when the current fl
in the opposite direction through the breaker from that which was intended
is, of course, possible to combine these various features of overload, underlo
reversal, etc., in one and the same breaker. (*See Relays.*)

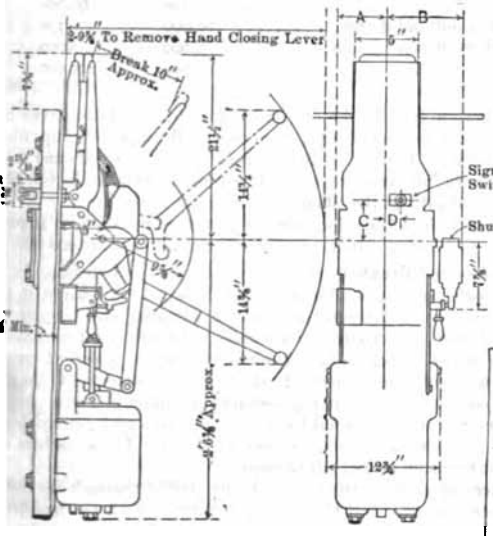
PRINCIPLE OF OPERATION. — The opening of a circuit breake
usually secured by the releasing of a latch or the upsetting of a toggle joint
keeps the breaker closed. Various schemes have been adopted to secure
adjustment or "calibration" of the overload tripping device, so that it may
made to operate within reasonably wide limits, usually 80 to 160 per cent of
normal rating.

Breakers Opening in Air. — Fig. 1 shows the general arrangement of
magnetic circuit of a typical carbon-break circuit breaker, arranged for han
solenoid operation, as used on heavy-capacity d-c. and low-voltage a-c. circ
The current passes in at one stud across the contact brush and back through
other stud, thus forming a loop or turn in the electric circuit. A U-shaped
frame is placed around the lower stud and the movable armature completes
magnetic circuit.

The current passing through the breaker magnetizes the iron circuit and
to lift the movable armature. At a certain predetermined current the attra
overcomes the force of gravity, and the raising of the moving arm opens
latch or upsets the toggle which holds the breaker closed.

Two methods of securing the necessary range or calibration can be emplo
one by varying the air gap between the stationary and moving iron, and

other by giving the electromagnet more work to do by increasing the weight to be lifted. This latter method can employ either additional weights at a fixed



	Amperes	
	6000	8000
A	5 3/16	6 7/16
B	8 1/16	8 13/16
C	5 13/16	5 19/16
D	1 9/16	2 1/16

Fig. 1. Carbon-break Circuit Breaker

istance from the fulcrum, or a fixed weight at a variable distance from the ulcrum.

For small currents the electrical circuit is carried more than once around the on circuit, which results in a solenoid design with a movable plunger. With is scheme the tripping range is secured by adding weights to the solenoid or arying the air gap.

Oil Circuit Breakers (Figs. 2 to 6). — With high-voltage oil circuit breakers e tripping coil is usually a solenoid of a fairly large number of turns, which is nnected in series with the main circuit or serves as the secondary of a current ansformer whose primary is connected in the high-tension circuit. For poly- ase circuits two or more tripping coils are used.

DESIGN. — For different classes of service various types of circuit breakers e used, and the functions of these types overlap more or less. The following ble gives the approximate values of the maximum normal current and voltage which these various types are used at present.

In connection with the carbon-break circuit breaker 24,000 amperes is the rgest size in actual service, but larger breakers could be built if desired. The ximum d-c. voltage at present used for railway service in America, is 5000 t; but carbon breakers can be built for higher d-c. voltages if desired; they e been used up to 22,000 volts for a-c. service.

The fuse type has not been built for more than 100 amperes or 66,000 volts, could be made for higher voltages if desired.

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Type	Max. Current Amperes	Max. Volts
Carbon Break	24,000	5,000
Fuse Type	100	66,000
Magnetic Blowout, old design	10,000	750
Magnetic Blowout, new design	3,000	3,000
Oil Break	6,000	220,000

The magnetic blowout type in the old design for street railway service has been built up to 10.000 amperes but it has been practically superseded by carbon breakers for this service. For d-c. railway service above 750 volts and up to 3000 volts the magnetic blowout breaker has been used owing to the very high speed that can be obtained and the efficient blowing out of the arc.

The oil break type is in service for current capacities up to 6000 amperes and for voltages up to 150,000. It has recently been built for 220,000 volts.

Air-break Carbon-type Breakers are made in a variety of designs; Fig. 1 shows a typical single-pole carbon-break circuit breaker. As shown in the figure, the circuit-breaker mechanism consists of a swinging arm carrying the main and the arcing contacts actuated by a handle and toggle-joint mechanism. The main contacts are of copper and are laminated to insure a perfect contact with the copper blocks which are fastened to the base and connected to the line. Above the copper contacts are the arcing contacts of carbon. These contacts consist of one or more carbons carried by a swinging arm and pressed firmly against stationary contacts when the breaker is closed. These carbons are mounted on a pivot to insure proper adjustment.

When the breaker opens the current is gradually shifted through the copper shunts to the carbon contacts, and thus no arc is formed until the final break takes place between the carbon contacts at the top. This arrangement, combined with the natural tendency of an arc to rise, prevents any injury to the breaker by the arc.

For large capacities strap connections are almost invariably used and to facilitate the employment of these strap connections the studs of large breakers are made of laminated construction.

Heavy capacity carbon-break circuit breakers are also made solenoid or motor-operated. With the solenoid design there is a definite end to the movement of the core that prevents damage to the mechanism from overtravel. The motor mechanism has a device that disconnects the worm gear and shuts down the motor when the breaker has closed and the toggle or latch has locked. This device is also so arranged that if an overload or short-circuit exists when the breaker is closed, the breaker will immediately trip out even though the control switch is held in the "close" position. This feature of being "nonclosable on overload" is one that is embodied in a large number of breakers of all kinds, and is a very valuable and useful one.

Switch and Breaker for Rotary Converters. — A combination motor operated switch and circuit breaker has been supplied for various rotary converters and 600-volt feeder circuits supplying current for third-rail electrifications. One motor is provided for each combined circuit breaker and switch and it has suitable clutches, shafts, operating rods and mechanism, so that in the act of closing the circuit breaker is first thrown in and the closing device is then disconnected before the switch is thrown in, so that in case of trouble the breaker can immediately trip out and open the circuit.

Air-break Fuse-type Breaker. — This type is a modification of the carbon break type and is intended for moderate capacity circuits for voltages of 6000 to 60,000. This breaker consists essentially of a stationary and a movable arm

mounted on suitable insulators supporting the line connections. These arms are hinged together at one end. The free ends are held together against gravity and a strong spring by a piece of aluminum fuse wire that passes through a blow-out tube. When the current exceeds a certain amount, the fuse wire melts and the free end of the movable arm swings away from the stationary arm, the arc being ruptured in a blow-out tube.

Magnetic Blow-out Type Breaker. — This type of breaker is provided with auxiliary contacts that open in a strong magnetic field which blows out the arc formed at these auxiliary contacts. The main contacts are solid copper blocks bridged by a laminated copper brush. These open first when the breaker operates, leaving the final arc to be broken on the auxiliary contacts, which are protected by the magnetic blow-out device and which can be readily renewed at comparatively small expense. Although breakers of this type have been installed on the switchboards of power plants, they have been practically superseded by carbon breakers for this work. For such service as the protection of the circuits on a railway car, requiring a few hundred amperes at 600 volts, the magnetic blow-out principle is used to advantage, as the discharge vent from the blow-out compartment can be so set that the vapors from the arc will do no damage.

Since the advent of the high voltage d-c. railways operating at voltages of 1200-1500 or 2400–3000 the magnetic blowout effect has been utilized to great advantage in connection with the high speed breakers developed for that class of service.

Oil **Circuit Breaker** (Figs. 2 to 6). — The essential feature of this type of breaker is the opening of the circuit under oil and the smothering of the arc in a restricted space. These breakers are used almost to the exclusion of all other designs on d-c circuits of large capacity and high voltage. Oscillograph tests show that the circuit is interrupted at the time of zero point of the alternating-current wave, and, therefore, there is little tendency to set up surges in the circuit. The rapid interruption of a direct current, however, is apt to set up surges, and therefore the oil-break design is not commonly used with d-c. service.

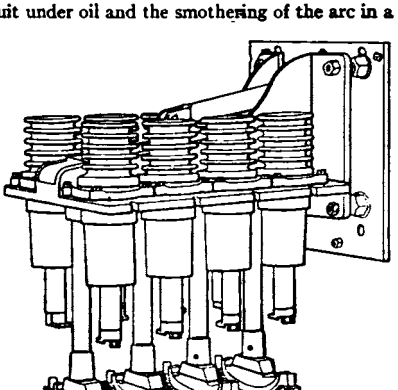


Fig. 2. 300-ampere, 15,000-volt, 4-pole Circuit Breaker

Oil-break circuit breakers are designed to meet various conditions of current, voltage and amount of power that may might be called upon to handle in case of a short-circuit. For moderate amounts of power where the size and cost of the breaker is to be kept to a minimum it is often possible to locate all the poles in one oil tank. For slightly larger amounts of power each pole is in a separate oil tank but all the poles are mounted on the same frame. For still greater amounts of power at moderate voltages each pole is in a separate tank and each tank in a separate compartment. For very high-voltage work each pole is in a

separate steel tank of such substantial construction as to be proof against any explosion due to the effects of a short-circuit.

Fig. 2 shows a 300-ampere, 15,000 volt, 4-pole breaker of a type that is built on various frames for various sizes up to 2000 amperes at 7500 volts, and 600 amperes at 25,000 volts. In this type of breaker each pole with its pair of contacts is in a separate tank with an insulating lining and all poles on the same frame. This breaker is readily arranged for manual operation or electrical operation by a solenoid and it can be mounted on a wall, framework, switchboard panel or on suitable supports of pipe or structural iron for open construction or for masonry compartments.

Fig. 3 shows a solenoid operated breaker of a type built on various frames for wall mounting, pipe mounting, or structure mounting, in capacities up to 2000 amperes at 15,000 volts and 1200 amperes at 25,000 volts. Each pole of this breaker is in a separate tank mounted on an independent frame and arranged

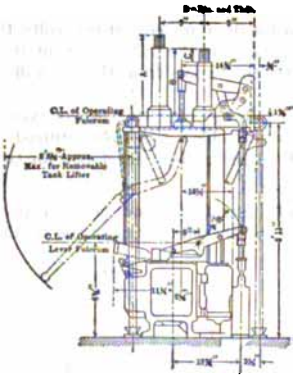


Fig. 3. 2000-ampere, 15,000-volt Solenoid Operated, Oil Circuit Breaker

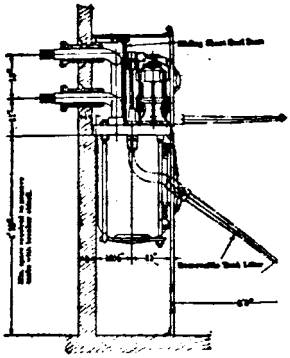


Fig. 4. Solenoid Operated, 15,000-volt, Oil Circuit Breaker

so that it can readily be located in a masonry compartment or on a framewor Two, three, or four pole units are made by connecting the mechanisms of tw three, or four poles to the same soleonid operating device. The mechanism a terminal insulators are mounted on the steel top of the breaker and a simp system of toggles operated by a powerful solenoid is used for closing the break A second solenoid is used to disengage a trigger on the operating mechanism trip the breaker. A two pole, double throw switch is mounted on the breal and operated by the motion of the levers in opening or closing the breaker; t switch being used to control the signals on the switchboard.

Fig. 4 shows a solenoid operated back connected heavy capacity breaker b in capacities of 600 to 3000 amperes at 15,000 volts, guaranteed capable rupturing 23,000 amperes per phase at 15,000 volts. Both terminals of e pole are in a single circular tank pressed out of ¾ inch sheet steel, forming a sea less tank of great strength. An insulated lining is provided and each tank a gauge glass for observing the height and condition of the oil. These breal in service are placed in masonry structures and their design is based on secur the maximum rupturing capacity in a given space. A heavy steel casting car the powerful operating mechanism as well as the contact rods. tanks e

aking the breaker a self-contained unit. A modification of this breaker has he three poles independent, each pole being located in a separate masonry ompartment.

Fig. 5 shows a 400 ampere o,ooo volt indoor frame ounted 3 pole solenoid oper- ted oil circuit breaker. Each ole of the breaker is located i a welded steel tank with icarta lining. All of the perating mechanism is ounted in the tank top and rovision is made for readily ropping any tanks to obtain ress to the mechanism.

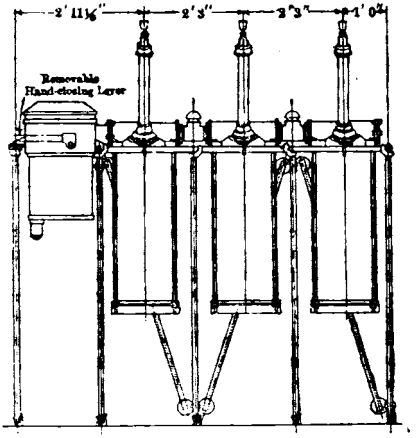


Fig. 5

This type of breaker is built oth for indoor and for out- oor service, frame mounted, nd floor mounted, for voltages om 25,000 to 73,000 frame ounted, and from 37,500 up o 155,000 volts for floor ounting. Designs are avail- ble up to 220,000 volts.

A three pole breaker is made p of three elements entirely dependent of each other, except that they are connected by a single operating d. The spacing of the poles, particularly on the floor mounting breaker, n readily be made to suit the station wiring. For manual operation the perating solenoid is replaced ; a bell crank device. The ndenser bushing leads that m the stationary terminals n readily be unclamped and moved through the cover. he series transformers for the eration of ammeters and re- s are usually arranged to be mped directly around the ndenser bushing leads which m the single turn primary. his permits the use of a sim- , compact and cheap form series transformer.

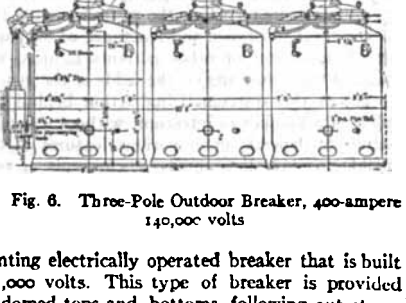


Fig. 6. Three-Pole Outdoor Breaker, 400-ampere 140,000 volts

Fig. 6 shows a 400 ampere, ,000 volt outdoor floor mounting electrically operated breaker that is built izes from 50,000 up to 155,000 volts. This type of breaker is provided h cylindrical tanks having domed tops and bottoms, following out steam ler practice and utilizing tanks that withstand pressures as high as 150 unds per square inch. Designs are available up to 220,000 volts.

The breaker shown on Fig. 6 has main features corresponding closely with se of Fig. 5 previously described.

For outdoor service the condenser bushing leads of the breaker are covered with ries of porcelain insulators, and the space between the bushing and the insula- n is filled with a moisture proof compound.

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The operating mechanism is covered by a metallic hood and the pull rods connecting the poles of the breaker pass through pipes. The various joints are made thoroughly water proof. Access to the interior of the tank is secured by the removal of the mechanism cap or manhole cover which exposes the lever system and presents a sufficiently large opening to withdraw any necessary parts. The mechanism is so disposed that a terminal bushing complete with its contact details can be withdrawn without disturbing any other details, and the moving contact elements can be withdrawn through the mechanism cover.

Where circuit breakers are exposed to temperatures of 0° C. or below, ordinary oil becomes sufficiently viscous to seriously impair the efficiency of the circuit breaker. This is caused by the slowing up of the opening action due to the heavy oil and also to the sluggish action of the oil itself in flowing in and suppressing the arc. Special grade oil having low freezing characteristics is available to overcome this difficulty, but for very large units heating elements may be installed in the tanks and put in service during the continuance of dangerously low temperatures. These heating elements can easily be placed so as not to interfere with the action of the mechanism in any way. The cost of these heating elements and the amount of power consumed by them is less on very large units than the difference in cost between the low freezing oil and the ordinary oil.

High voltage breakers of the outdoor type have been in service for a number of years in various parts of the United States, and have also been supplied to Japan, France, Spain and Italy.

RATING — (*See below for Table of Sizes.*) The rating of a circuit breaker is usually given as the normal current which it will carry continuously with a temperature rise not exceeding 30° C. for carbon breakers and 50° C. for oil breakers, above the surrounding air. This rating has no direct relation to the maximum short-circuit current which the breaker will safely interrupt. (*See below under Ultimate Capacity.*) The tripping range of the breaker is usually from 80 to 160 per cent of this normal rating. The cross-section of the conductors and the area of contact surfaces depend so much upon the character of design, the cooling effect of bodies of oil and masses of metal, that no definite current density can be given as an average value for the various types of breakers.

Ultimate Breaking Capacity. — (*See table below.*) When a short circuit or ground occurs on a line, the rush of current thereby produced depends upon (1) the total resistance and reactance of all parts of the circuit through which flows this current or other currents induced thereby, (2) the demagnetizing action of these currents on the fields of the generators producing them, and (3) the lag of this demagnetizing action behind the current producing it. The ability of a breaker to interrupt, without damage to itself, a current of a given magnitude depends upon various features of design, and it is evidently impossible to state how much synchronous or transforming apparatus may be safely connected directly to a breaker of a given rating, unless the conditions of operation are also fully specified.

In the table below the ultimate capacity of various breakers is given in terms of the amperes that they will actually rupture at the arc at their maximum rated voltage. They will rupture this current twice with a two minute interval between short circuits, and will be in condition to carry their full rated current, but may not be in condition to open up under short circuit without further attention.

For voltages less than the rated voltages the rupturing capacity in amperes can be increased usually more rapidly than the decrease in voltage, but a limit is reached when the short-circuit current amounts to approximately fifty times the normal current rating of the breaker.

Curves were published in the February 1918 Proceedings of the A.I.E.E. giving the short-circuit currents of typical American generators with various percentage

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of reactance after the expiration of various lengths of time and these can be used to advantage in determining the short circuit to be expected in any system.

In determining the short-circuit characteristics of any particular system, the reactance of the generators and other devices has to be considered. On the basis of an average reactance of 8 per cent the momentary short-circuit current is roughly 12½ times normal and this usually dies down to about one-half this amount or 6¼ times normal by the time that any automatic breaker can open. At the expiration of a certain time that may be taken roughly as two seconds, the output of the system will be down to the continuous short-circuit basis of possibly two or three times normal rating.

The larger rupturing capacity breakers for 15,000 volts or less are almost invariably mounted in masonry compartments, usually with each pole in a separate cell and the leads carefully isolated from each other. The very high voltage breakers do not utilize the cellular construction and are very frequently arranged for outdoor installation.

DIMENSIONS, WEIGHTS AND COSTS. — Although the dimensions, weights costs etc. of breakers of various manufacturers naturally differ and are subject to change with the progress of designs, and while the same manufacturer frequently builds various grades for the same capacity the data that follows will give an idea of the range covered by the breakers of a single manufacturer.

CIRCUIT BREAKER DATA

Item	Amperes	Volts	Rupture, Amperes	Height, inches	Width, inches	Depth, ins.	Weight	Prices
1	400	750	.....	24	4¾	14¼	130	$140
2	800	750	.....	24	4¾	14¼	140	149
3	2000	750	.....	24	4¾	14¼	150	227
4	8000	750	.....	32	11⅞	21½	500	785
5	300	4,500	2,800	22⅝	9⅛	16	185	100
6	300	15,000	1,100	31¼	15¾	18	220	235
7	2000	7,500	3,000	34	20½	25¼	660	1,060
8	300	7,500	2,900	26⅝	17¾	38 5/16	635	366
9	600	25,000	1,960	50⅝	20⅛	25¼	500	480
10	600	25,000	2,200	93	46½	30	1,040	1,300
11	600	25,000	5,350	120	54	29	1,760	1,700
12	600	15,000	18,000	87	54	31½	2,500	2,140
13	2400	15,000	23,000	99	74	31½	3,200	4,620
14	400	37,500	2,400	92	94	30	1,575	2,775
15	400	50,000	2,400	108	101	33	1,875	4,375
16	400	73,000	2,400	119	94	42	4,025	6,075
17	400	95,000	2,400	124	149	48	8,200	9,100
18	400	115,000	2,400	139⅝	172	58½	10,700	11,500
19	400	73,000	2,400	124	118	42	5,500	4,975
20	400	115,000	2,400	139⅝	174	58½	12,050	9,660
21	400	135,000	1,600	171	216	69½	26,600	14,875
22	400	115,000	3,750	157	201¾	69½	14,700	14,030
23	400	135,000	5,350	170	272	84¾	26,400	17,660

The information in the above table is based on apparatus manufactured by one of the largest American builders of switchgear and is practically correct at the date of its preparation (October, 1920). Changes are made from time to time in the design of equipment that may slightly modify this information.

The dimensions, height, breadth, and depth for carbon circuit breakers, items 1, 2, 3, and 4, refer to single pole switchboard mounting breakers; and the depth is given from the front of the panel, that is, the length of the studs projecting through the panel is neglected. For the switchboard mounting oil circuit breakers the dimensions are given from the back of the panel, that is, the length of the handle sticking through the board is neglected. All of the oil breakers are three pole, items 5, 6, and 7, being hand operated, the remainder being electrically operated. For the electrically operated breakers the dimensions include the operating solenoids. For cell mounting breakers the dimensions include the cells but the weight and prices are exclusive of cells, oil, current and potential transformers. For the high voltage breakers the dimensions are over the terminals and the width is based on the minimum spacing recommended for any particular voltage. The dimensions are in every case the maximum overall dimensions except as mentioned. The costs given are the approximate selling prices under date of October 1920, and are sufficiently accurate for the preparation of preliminary estimates, but for accurate work should be checked by actual quotations from a reliable builder.

Items 1 to 4 are single pole hand operated carbon circuit breakers, similar to Fig. 1.

Items 5 and 7 are hand operated oil circuit breakers with all contacts in the same tank and barriers between contacts.

Item 6 is an oil breaker with each pole in separate tanks but all tanks on the same frame.

Item 8 is an electrically operated breaker with each pole in a separate tank on a separate frame, and arranged for cell mounting, wall mounting or pipe mounting.

Item 9 is a three pole breaker with all poles in separate tanks, all tanks on a common frame arranged for wall mounting, pipe mounting, or cell mounting.

Items 10 and 11 are essentially cell mounting breakers with each pole in a separate cell, and items 12 and 13 are cell mounting breakers with circular tanks with each pole in a separate tank, all three tanks on the same frame.

Items 14, 15, and 16, are frame mounted solenoid operated indoor breakers.

Items 17 and 18 are solenoid operated floor mounting indoor breakers.

Item 19 is a solenoid operated frame mounting outdoor breaker.

Items 20 and 21 are solenoid operated floor mounting outdoor breakers with oval tanks.

Items 22 and 23 are solenoid operated outdoor breakers with cylindrical tanks.

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LLECTORS, CURRENT. — (*See also Cars, Electric; Locomotives, Elec-; Third-Rail Systems; Trolley Systems, Overhead; Trolley Systems, Under-und.*) Current collectors for electric cars or locomotives are divided into ee classes in accordance with the form of the working conductor from ich they collect current, as follows:

a) Overhead Trolley, which may be of the wheel, scraping bow or roller e.

b) Third-Rail Shoes, which may be of the over-running or under-running e.

c) Underground Conduit Plow.

WHEEL TROLLEY. — The wheel trolley consists of a grooved brass or cop- wheel held in bearings in a prong called a "harp" at the end of a steel pole ich is pressed upward by a system of springs and levers. The trolley wire from 18 to 22 feet above the rails. The pole ses the wheel upward against the wire with a ssure of from 20 to 40 pounds, the higher pres- e being used for the higher speeds. The current ich a wheel trolley can collect is limited at the ious speeds as indicated in the accompanying le. If greater currents are required, resort must ad to the third rail. The trolley wheel is not ry satisfactory on cars in trains as each trolley le requires the attention of a conductor to replace it curves and switches, and moreover, it is difficult to manipulate the trolley e from a platform between two cars.

Miles per hour	Amperes
5	1200
15	600
40	350
60	200

BOW TROLLEY. — This type of trolley is used to collect current from a h-voltage conductor because it is self-adjusting and needs no attention while cars are running. At high voltages its current capacity is sufficient to supply ver for a train of considerable size but it would not have sufficient capacity supply power for heavy trains at 600 volts. In America, bows are usually de of mild steel. In Europe aluminum is preferred but it has been found re that aluminum containing 6 per cent of copper, gives the best results. e bow may be held up either by simple springs in the same manner as the ley pole or it may be mounted upon a pantagraph mechanism which is held by springs and folded down by a compressed-air cylinder. The St. Paul 0 volt locomotives have pantographs with two pans pressing upward with ressure of about 50 pounds per pan and have successfully collected currents 000 amperes at low speeds. The pans are hinged to the pantograph proper order to make better contact with the trolley wire. A special form of overhead struction must be used for the bow trolley as the bow would strike the down- rdly projecting cars and the guy wires of the ordinary trolley construction. e roller trolley may be used in place of the bow on the same form of mech- ism. The roller has a greater current capacity and causes less wear on the rking conductor than the bow. The rollers used by the Butte, Anaconda and ific Ry., are steel tubes 5 inches in diameter and 2 feet long. They are each ured to collect 750 amperes at 2400 volts.

THIRD-RAIL SHOES. — A third-rail shoe will collect currents as high as 0 amperes at low speeds and 600 amperes at 60 miles per hour. As they are l-adjusting two or three may be placed on a locomotive or car just as well one, so that there is practically no limit to the current that can be collected this way. In fact it is always customary to put two on each side of each motive or car in order to prevent a cessation of current when passing

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over breaks in the third rail due to switches or crossings. (See article on *Third Rails*.)

Over-running vs. Under-running Types. — The third rail for top contact or for over-running shoe is cheaper to install, to protect and to maintain and most generally used. The under-contact rail is less liable to trouble from sleet, snow and ice and is therefore warranted where climatic conditions are bad.

UNDERGROUND CONDUIT PLOW. — The underground plow consists of an insulated steel plate hung from a movable structure on the car. On the two sides of this plate and thoroughly insulated from it are two shoes pressed outward from the plate by springs. These shoes press against the two working conductors which are usually steel Tees separated from each other by about 8 inches and supported on some form of ceramic insulator. The current is led from the shoes to the car body by flexible insulated conductors.

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OMPLEX QUANTITIES. — (*See also Vectors.*) The square root of a gative quantity is called an "imaginary" quantity, or a pure imaginary. quantity consisting of the sum or difference of a real quantity and an imagiry quantity is called a "complex" quantity. For example, $\sqrt{-3}$ is a pure aginary, and $2+\sqrt{-3}$ is a complex quantity. All the rules of ordinary ebra apply to pure imaginaries and complex quantities. For example, $\sqrt{-3}$ y be written $\sqrt{-1}\sqrt{3}$, and in general $\sqrt{-a}$, where a is a positive quany, may be written $\sqrt{-1}\sqrt{a}$. The square root of minus one is called the aginary unit and is usually represented by the symbol j (writers on pure thematics use the symbol i), that is,

$$j=\sqrt{-1}.$$

y complex quantity may then be written

$$a+jb,$$

ere a and b are both real quantities.

Geometrical Representation of a Complex Quantity. — A positive real antity may be represented by a line drawn in a given direction; a negative real antity may be represented by a line drawn in the opposite direction. Multiying a quantity by -1 then reverses its direction. Also, since multiplying a al quantity by $\sqrt{-1}$ twice is equivalent to multiplying it by -1, the operaon of multiplying once by $\sqrt{-1}$ may be represented by turning the line repreting the quantity through 90° in the positive direction rotation. The positive direction of rotation is taken as e opposite direction to that in which the hands of a ck move. Hence, a complex quantity $a+jb$ may be presented by the line OP in the figure, where $OA=a$ d $AP=b$. The complex quantity $a+jb$ is then comtely specified by a line of length $\sqrt{a^2+b^2}$ making an gle θ, with the axis of reference OX where $\tan\theta=\frac{b}{a}$.

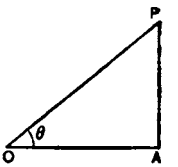


Fig. 1

e length $M=\sqrt{a^2+b^2}$ is called the magnitude of the complex quantity d the angle $\theta=\tan^{-1}\frac{b}{a}$ is called its angle. From the figure it is evident at the complex quantity $a+jb$ may also be written

$$a+jb=M(\cos\theta+j\sin\theta).$$

xpanding $\cos\theta$ and $\sin\theta$ into series (*see Series*) and adding, the resultant ies obtained is the series for $e^{j\theta}$; hence

$$a+jb=Me^{j\theta}. \qquad (1)$$

From the above definitions and equation (1) it is evident that complex numrs possess the following properties:

Addition of Two Complex Quantities. —

$$(a+jb)+(a_1+jb_1)=(a+a_1)+j(b+b_1).$$

Subtraction of Two Complex Quantities. —

$$(a+jb)-(a_1+jb_1)=(a-a_1)+j(b-b_1).$$

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Multiplication of a Complex Quantity by a Complex Number. —

$$(a+jb)(a_1+jb_1) = aa_1 - bb_1 + j(ab_1 + a_1b)$$

or, putting $a+jb = Me^{j\theta}$ and $a_1+jb_1 = M_1e^{j\theta_1}$

where $M = \sqrt{a^2+b^2}$, $M_1 = \sqrt{a_1^2+b_1^2}$,

$$\tan\theta = \frac{b}{a},$$

and

$$\tan\theta_1 = \frac{b_1}{a_1}$$

we have $(a+jb)(a_1+jb_1) = Me^{j\theta}M_1e^{j\theta_1} = MM_1e^{j(\theta+\theta_1)}$.

Hence the product of two complex quantities is in general a complex quant which has a magnitude equal to the product of the magnitudes of the two qu tities and an angle equal to the sum of the angles of the two quantities.

Division of a Complex Quantity by a Complex Number. —

$$\frac{a+jb}{a_1+jb_1} = \frac{(a+jb)(a_1-jb_1)}{(a_1+jb_1)(a_1-jb_1)} = \frac{aa_1+bb_1-j(ab_1-a_1b)}{a_1^2+b_1^2}$$

or

$$\frac{a+jb}{a_1+jb_1} = \frac{Me^{j\theta}}{M_1e^{j\theta_1}} = \frac{M}{M_1}e^{j(\theta-\theta_1)}.$$

Hence the quotient of two complex quantities is in general a complex quant which has a magnitude equal to the quotient of the magnitudes of the t quantities and an angle equal to the difference of the angles of the two qu tities.

Example. — Suppose

$$I = \frac{10+j15}{3+j1};$$

then by the rule for division

$$I = 4.5+j3.5,$$

that is, I contains a real part 4.5 and an imaginary part j 3.5.

Equations Containing Complex Quantities. — Since a real quantity c not be equal to an imaginary quantity it follows that any equation of the fo

$$A+jB = A_1+jB_1,$$

where A, B, A_1 and B_1 are all real quantities (which may, however, consist any number of terms), is equivalent to the two equations

$$A = A_1$$

and

$$B = B_1.$$

Also, if one member of an equation reduces to the form $A+jB$, then the ot member of this equation must likewise contain an equal real and an equal aginary part.

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CONCRETE. — (*See also Cement, Concrete, Reinforced.*) Concrete as used by engineers in construction is generally formed of an artificial mixture of Portland cement (*see Cement*) and an aggregate consisting of sand and gravel or broken stone. These ingredients are mixed with water either by hand or by machine mixers.

Light-weight Concrete. — During the Great War a light-weight concrete was developed for building concrete ships in the U. S. In this concrete the aggregate instead of being ordinary stone is made from calcined clay specially treated. This light-weight concrete weighs about 110 pounds per cubic foot and has a crushing strength of about 4000 pounds per square inch after 28 days ageing. It has to be made richer in cement than ordinary concrete and is consequently more costly. (*W. L. Scott, Engineering, 108*, p. 33, *July, 1919.*)

SPECIFICATIONS. — The quality of the materials can be determined only by careful tests, but for construction of minor importance and magnitude the following simple specifications should give good results.

Cement. — The cement shall be first-class American Portland cement of standard brand, guaranteed to conform to the Standard Specifications of the American Society for Testing Materials. (*See Cement.*) Such cement may be delivered either in bags or barrels but must be kept dry during storage.

Sand. — The sand shall be clean and coarse and free from dust, vegetable, loam or other organic matter, and other impurities, and should pass, when dry, a screen with holes $\frac{1}{4}$ of an inch in diameter.

Gravel. — The gravel shall consist of clean pebbles, and contain no foreign matter. It shall be screened over a ¼-inch mesh; the sand passing through the screen may be remixed in definite proportions with the gravel. If dirty or heavy, the gravel should be washed by a hose before mixing.

Broken Stone. — The broken stone shall consist of hard and durable stone such as trap, granite and limestone. Unless otherwise specified, all stone shall pass through a 2½-inch screen.

Water. — The water used for mixing shall be free from oil, acid and other injurious substances.

PROPORTION OF INGREDIENTS. — The amount of each ingredient is usually measured by volume. The concrete is designated by the proportion by volume of each of the ingredients in the following order: Cement, Sand, Stone or Gravel. For example, a 1 : 2 : 4 mixture is one consisting of one barrel of cement, two barrels of coarse sand, and four barrels of loose gravel or broken stone (standard cement barrels contain 3.8 cu. ft; four bags of packed cement may be considered as equal to one barrel).

The following proportions are somewhat generally adopted for different classes of work.

1 : 1 : 2 or 1 : 1½ : 3 for water tanks and standpipes carrying considerable pressure and required to be water-tight.

1 : 2 : 4 for arches, reinforced floors, beams, columns, engine foundations subject to vibration, sewers, and in general for structures subjected to bending stresses of some magnitude. A mixture as rich as this is also desirable where concrete is to be deposited under water since in such a case some of the cement may be washed away from the mixture.

1 : 2½ : 5 for bridge abutments and piers when laid in air, retaining walls and ordinary machine foundations.

1 : 3 : 6 for heavy walls, ordinary foundations, backing for stone masonry, etc.

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Quantity of Ingredients.— The following rule devised by Wm. B. Fuller may be used for approximate determination of the quantity of the various ingredients.

Let c = number of parts of cement,
s = number of parts of sand,
g = number of parts of gravel or broken stone. Then

$\frac{10.5}{c+s+g} = N$ = number of barrels of Portland cement required per cu. yd. of concrete,

$\frac{1.55}{c+s+g}s$ = number of cu. yd. of sand required for one cu. yd. of concrete,

$\frac{1.55}{c+s+g}g$ = number of cu. yd. of stone or gravel required for one cu. yd. of concrete.

For tables giving more accurate values see Taylor and Thompson, *Concrete, Plain and Reinforced.*

MIXING. — The ingredients consisting of sand and aggregate should be thoroughly mixed while dry until the mass is uniform in color and homogeneous. Mixing should preferably be done by machine. When necessary to mix by hand, the mixing should be done on a water-tight platform and the ingredients should be turned not less than six times. Enough water should be used to produce a mixture which will flow readily into its place in forms or elsewhere.

Concrete Mixing in Freezing Weather. — Reinforced concrete should not be mixed or deposited in freezing weather unless special precautions are taken to keep the materials free from ice, and to protect the concrete from freezing until it has been thoroughly hardened. To accomplish these results the aggregates may be heated, salt water used in mixing, and the concrete carefully covered after it has been deposited. Portland cement concrete which is to be deposited in large masses may be laid in freezing weather provided the surface appearance is not important, and provided that hardened surfaces be thoroughly cleaned from frost as well as dirt before a new surface is laid. Natural cement concrete should never be laid in freezing weather.

Concrete Shrinkage and Temperature Changes. — Cracks in cement may be caused by contraction in setting, or by temperature changes, as well as by excessive stress. To preserve a good appearance it is common to establish artificial cracks in long walls, sidewalks, etc. For spacing of such cracks see reference in *Bibliography*. The insertion of steel reinforcing bars even when not needed to carry stresses due to applied loads is an expedient often adopted to prevent the occurrence of such cracks. The amount of reinforcement to be used for this purpose should generally be not less than one-third of one per cent.

Effect of Sea Water and of Acids on Concrete. — The data available relating to the effect of sea water upon concrete indicate that there may be some chemical action resulting in a softening and disintegration of the surface. To offset this action as far as possible, concrete laid in sea water should be carefully proportioned and well mixed. There is also great danger from disintegration due to frost in cold climates in concrete lying between high water and low water. To protect against this the concrete may be protected by a surface of stone in the zone exposed to such action.

Thoroughly hardened concrete of good quality may be considered as resisting the action of acids and mineral oils as well as other building materials. Oils containing fatty acids may produce injurious effects by combining with the lime in the concrete, resulting in a disintegration of the latter.

Waterproofing Concrete. — Concrete may be made reasonably impervious to water under moderate pressures by using a rich mixture and by careful pl

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portioning and mixing. In the case of building foundations and other structures where leakage is not permissible it is usually advisable to protect the concrete by a separate coating applied either on the outside or inside of the wall or floor. The usual method of waterproofing the exterior is to construct a so-called membranous coating consisting of alternate layers of pitch and tarred felt. The inner surface of concrete basement walls and floors of many of the important buildings in New York City and other large American cities have been waterproofed by the use of a patented compound called "Hydrolithic Cement." Many so-called waterproofing powders, pastes, etc., are manufactured which are claimed to make concrete entirely water-tight if incorporated with it during mixing, but their value is problematical.

COMPRESSIVE STRENGTH AND WORKING STRESSES. — In the Joint Committee Report (*Trans. Am. Soc. C.E.*, 1917) the following table of compressive strength of thoroughly set concrete is given:

COMPRESSIVE STRENGTHS OF DIPPERENT MIXTURES OF CONCRETE

Tested in cylinders 8 inches in diameter and 16 inches long

Set 28 days under favorable conditions

In Pounds per Square Inch

Aggregate	1 : 3	1 : 4½	1 : 6	1 : 9	1 : 7½
Granite, trap rock	3300	2800	2200	1800	1400
Gravel, hard limestone and hard sandstone	3000	2500	2000	1600	1300
Soft limestone and sandstone	2200	1800	1500	1200	1000
Cinders	800	700	600	500	400

The following recommendations are also made:

When compression is applied to a surface of concrete of at least twice the loaded area, a stress of 35 per cent of the compressive strength may be allowed in the area actually under load.

For concentric compression on a plain concrete pier, the length of which does not exceed four diameters, or on a column reinforced with longitudinal bars only, the length of which does not exceed twleve diameters, 22.5 per cent of the compressive strength may be allowed.

The extreme fiber stress of a beam, calculated on the assumption of a constant modulus of elasticity for concrete under working stresses may be allowed to reach 32.5 per cent of the compressive strength.

For reinforced structures see the full report of the Committee in the *Trans. A.S.C.E.*, 1917.

Modulus of Elasticity. — The value of the modulus of elasticity of concrete has a wide range, depending on the materials used, the age, the range of stresses between which it is considered, as well as other conditions. It is recommended that in computations for the position of the neutral axis and for the resisting moment of reinforced concrete beams and for the compression of concrete in columns it be assumed as:

(a) One-fifteenth of that of steel, when the strength of the concrete is taken at 2200 lb. per sq. in. or less.

(*b*) One-twelfth of that of steel, when the strength of the concrete is taken at eater than 2200 lb. per sq. in., or less than 2900 lb. per sq. in., and
(*c*) One-tenth of that of steel, when the strength of the concrete is taken at eater than 2900 lb. per sq. in.

COST OF CONCRETE (Pre-war prices). — The following table * gives pproximate costs of concrete in place not including excavation forms, steel or iscellaneous items. The values include superintendence, overhead charges id general expense but not office expense nor profit.

Item	Cost per cubic yard	
	Range	Average
Mass concrete as in dams, piers, foundations, etc.:		
Labor only	$0.75 to $2.50	$1.25
Material and labor	3.00 to 9.00	5.50
Concrete in tunnels and conduits:		
Labor only	1.00 to 3.00	2.00
Material and labor	4.50 to 8.00	6.25
Concrete reservoirs and standpipes:		
Labor only	0.75 to 3.00	1.50
Material and labor	3.50 to 13.00	7.00
Concrete buildings:		
Labor only	0.75 to 4.00	1.50
Material and labor	4.50 to 9.00	6.50
Concrete bridges:		
Labor only	0.50 to 2.50	1.50
Material and labor	4.00 to 8.00	6.00
Concrete sewers:		
Labor only	0.75 to 1.75	1.50
Material and labor	3.50 to 8.00	6.00
Granolithic sidewalks:		
Labor only	1.00 to 3.00	1.75
Material and labor	6.25 to 9.00	7.00
Granolithic sidewalks:		
Labor only	2¢ to 4¢ per sq. ft.	2¾¢ per sq. ft.
Material and labor	5¢ to 14¢ per sq. ft.	10½¢ per sq. ft.

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* Copied by permission from *Concrete Costs* (1910) by Taylor and Thompson, which ould be consulted for detailed information.

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NCRETE, REINFORCED. — (*See also Cement; Concrete; Structures, ple.*) Reinforced concrete beams, girders and slabs are made of Portland ent concrete with the addition of steel bars or steel mesh to resist tensile ses. They are usually fixed at the ends by being built into columns, walls, ther girders and are continuous over intermediate supports; they are, there- subject to negative bending moments at the ends and at intermediate orts and positive bending moments between supports. It is common to bottom reinforcement throughout the length and top reinforcement across

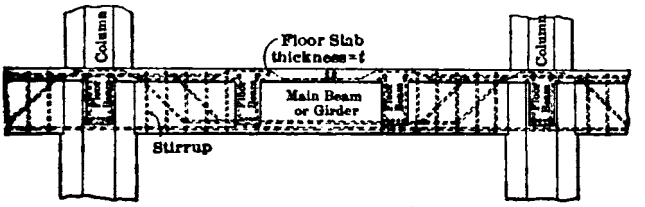


Fig. 1.

supports. Vertical or inclined reinforcement is also usually necessary to ry the diagonal tensile stresses occurring in the web. Fig. 1 shows the general aracter of a reinforced concrete beam and shows methods of making con- ctions to column and floor beams.

Character of Reinforcement. — The steel reinforcement may consist of nd or square bars of which the diameter or side seldom exceeds 1½ inches. The are rods are sometimes twisted when cold, this pe of bar being known as the Ransome bar. There also various forms of corrugated or otherwise formed bars on the market, some of which are wn in Fig. 2. Steel mesh is seldom used for ordi- ry beams, but is frequently employed in floor slabs. e steel reinforcement should preferably be of the me quality as that used for ordinary steel structures, hough the use of a slightly less ductile material may warranted in some cases where the steel is unlikely be subjected to injurious shocks.



Fig. 2.

Proportions of Concrete; Forms. — The propor- ns of concrete for beams and other reinforced con- te structures subjected to flexure is commonly 1:2:4 r *Concrete*). The forms or molds in which reinforced ncrete beams are constructed are usually of wood bolted together, although el forms are sometimes employed. In general, the size of the beam should uch that the forms can be manufactured from standard size boards. Forms uld be watertight, and should be left in place until concrete has set sufficiently carry the load to which it may be subjected at time of removal of forms.

Fireproofing. — In order to make reinforced concrete beams and columns proof the steel reinforcement must be protected by a reasonable amount of ncrete. A common provision is that the metal in girder and columns be pro- ted by a minimum of 2 inches of concrete; that the metal in beams be pro- ted by a minimum of 1½ inches of concrete; and that the metal in floor slabs protected by a minimum of 1 inch of concrete. It is also advisable that all ners shall be beveled or rounded.

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Spacing of Reinforcement. — Lateral spacing should not be less than th diameters center to center, with a clear spacing of not less than one inch. T distance from the side of the beam to the center of the nearest bar should be t less than two diameters. More than two layers should not be used unl securely tied together by metal connections particularly at or near points wh bars are bent.

Electrolysis and Corrosion in Reinforced Concrete. — The best expe mental data available indicate that no danger from electrolysis need be antic pated to the steel reinforcement in carefully mixed and proportioned Portlan cement concrete free from salt or calcium chloride. Portland cement concre may be considered to thoroughly protect embedded steel from corrosion provid the concrete is properly proportioned and mixed. If the concrete is porou corrosion may be expected. See also article on *Electrolysis of Ground Structures*.

Reinforced Concrete Beams. — The table on the following page gives t safe uniformly distributed loads per lineal foot for a series of reinforced co crete beams one (1) inch in width. The constants upon which the table based are as follows: 1:2:4 concrete with ultimate compressive strength 2000 pounds at 28 days. Allowable stress in concrete = 650 and in steel 16,000 lb. per sq. in. Modulus of elasticity of steel 15 times that of concre Area of steel = 0.77 per cent area of beam above center of reinforcement.

FORMULAS FOR REINFORCED CONCRETE STRUCTURES. Detail formulas for design cannot be given here; see references in Bi *ography*.

Reinforced Concrete Slabs. — These resemble beams, are much used f floors of buildings, and usually form an integral part of the floor beams and gi ers as indicated in Fig. 1. They may be computed in the same manner as re forced concrete beams (*see above*) provided the shears and moments due to t outer forces are known. For slabs supported on four sides the distribution of t load may be determined by the application of the following formula recommend by the Joint Committee (*see Concrete*).

$$r = \frac{l}{b} - 0.5,$$

in which r = proportion of load carried by the transverse reinforcement, l length, and b = breadth of slab.

Using values above specified, each set of reinforcements is to be calculated the same manner as slabs having supports on two sides only, but the total amo of reinforcement thus determined may be reduced 25 per cent, by gradu increasing the rod spacing from the third point to the edge of the slab.

If length of the slab exceeds one and five-tenths its width the entire load sho be assumed as carried by transverse reinforcement.

Girderless floors or flat slabs are much used for factories and warehou In this type of construction the flat slab is supported directly on the colu which are constructed with capital of considerable size. For information rega ing the methods of design, reference should be made to the Joint Commit Report, the Building Codes of Chicago and Boston, and the standard text-bo

Columns of Reinforced Concrete. — For such columns it is customary limit to 15 the ratio of unsupported length to least width, and to consider effective area as that within the protective coating (*see section on Fireproof above*), or for hooped columns or columns reinforced with structural shapes the area within the hooping or structural shapes. The reinforcement may c

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t either of longitudinal bars or of longitudinal bars connected by bands, hoops, spirals, or of rigid structural forms. The following formulas may be used design. Let A_c = cross-section of concrete, A_s = cross-section of steel, $A = A_c + A_s$ = total cross-section, n = ratio between modulus of elasticity of steel d concrete, usually 15, P = total safe load, f_c = allowable unit stress in concrete, f_s = allowable unit stress in steel, $p = A_s/A$. Then

$$P = f_c(A_c + n A_s) = f_c A[1 + (n-1)p],$$

$$f_c = \frac{P}{A[1 + (n-1)p]},$$

$$f_s = nf_c.$$

LOWABLE LOAD (POUNDS) ON REINFORCED CONCRETE BEAMS

lowable uniformly distributed load in pounds per lineal foot, in excess of weight f beam, for end-supported rectangular reinforced concrete beams. *Tabular ulues to be multiplied by width of beam in inches to get safe applied load (dead + ive + impact).*

Depth of beam, in.	Distance from top to center of reinforcement, in. = d	Area of steel, sq. in.	Moment of resistance, foot pounds	Span in feet							
				6	8	10	12	16	20	25	35
5	4.0	0.031	144	27	13	7	3	....	....	....	...
6	5.0	0.038	224	44	22	12	6	....	....	....	...
7	6.0	0.046	323	64	32	18	10	....	....	....	...
8	7.0	0.054	440	89	46	26	15	5	....	....	...
9	7.75	0.060	539	110	57	33	20	7	....	....	...
10	8.75	0.067	687	142	75	44	27	10	....	....	...
11	9.75	0.075	853	177	95	56	35	15	....	....	...
12	10.75	0.083	1,037	217	117	70	45	19	8	....	...
13	11.5	0.089	1,186	249	134	81	52	23	10	....	...
14	12.5	0.096	1,401	296	160	97	63	29	13	3	..
15	13.5	0.104	1,635	347	188	115	75	35	17	5	...
16	14.5	0.112	1,886	402	219	134	88	42	21	7	...
17	15.5	0.119	2,155	460	251	154	102	49	25	10	...
18	16.5	0.127	2,442	523	286	176	117	57	30	12	...
19	17.0	0.131	2,592	555	304	187	124	61	32	13	..
20	18.0	0.139	2,906	624	342	211	141	70	37	16	...
22	20.0	0.154	3,588	773	425	263	175	88	48	22	...
24	22.0	0.169	4,341	938	517	321	215	109	61	30	...
26	24.0	0.185	5,166	1119	618	385	259	133	75	38	6
28	26.0	0.200	6,063	....	728	455	307	159	91	48	10
30	28.0	0.216	7,032	....	847	531	359	187	109	58	14
36	33.5	0.258	10,070	....	1220	767	521	275	162	90	27
42	39.5	0.304	13,990	....	1704	1074	733	392	235	134	47
48	45.5	0.350	18,570	....	....	1435	981	528	320	187	70

COST. — See section on *Costs* in article on *Concrete*.

BIBLIOGRAPHY. — See *Bibliography* in article on *Concrete*.

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CONDENSERS, ELECTRIC. — (*See also Capacity and Charging Current.*) Any two conductors separated from each other by a dielectric form an electric condenser. The capacity C of such a condenser is the quotient of the numerical value of charge Q on either conductor by the difference of potential V between the two conductors *when equal and opposite charges are given the two conductors*, i.e., $C = Q/V$. The usual way of giving the conductors equal and opposite charges is to connect them respectively to the two terminals of a battery or other source of electromotive force. Unless the conductors are close to each other relative to the linear dimensions of their surfaces the capacity is small. Large capacities are usually obtained by using flat plates separated from each other by a thin sheet of dielectric. Unless the two conductors are close to each other relative to their distances from other conductors their capacity is influenced by the presence of the other conductors.

Formulas for Capacity. — See the article on *Capacity and Charging Current*.

Condensers in Series and in Multiple. — See *Electricity and Magnetism, Principles of*.

Energy Stored in a Condenser. — See *Electricity and Magnetism, Principles of*.

Electric Absorption and Dielectric Hysteresis in Condensers. — When an ordinary condenser is charged by connecting it to the terminals of a source of constant e.m.f. the amount of charge which it takes depends upon the time during which the e.m.f. is applied, i.e., there is an apparent absorption of charge by the dielectric. Time is also required for the dielectric to give up this charge when the plates are short-circuited. Absorption is particularly pronounced in such heterogeneous substances as glass, paper, ordinary mica, etc. On account of this absorption both the capacity and apparent resistance of a condenser in general depend upon the time of application of the e.m.f., i.e., upon the time of electrification.

Dielectrics, when submitted to an alternating electric field, absorb a certain amount of energy over and above that corresponding to the direct current "ohmic" loss. This loss is made up of two elements, one due to the conversion of displacement current into the leakage current at the boundaries of electrically dissimilar elements of the insulation, and the other due to a property similar to magnetic hysteresis. The former depends upon the frequency but is not proportional thereto; the latter is directly proportional to the frequency.

TYPES OF CONDENSERS AND THEIR APPLICATION. — Condensers may be classified according to the nature of the dielectric used as (1) air condensers; (2) mica condensers; (3) glass condensers; (4) paper condensers; and (5) electrolytic condensers.

Air Condensers. — Due to the low specific inductive capacity and relatively low dielectric strength of air, air condensers have very low capacity and are therefore seldom used except for standards of small capacity. For the latter purpose they are well suited, since their capacity is not appreciably affected by temperature, time of electrification, or frequency.

Mica Condensers. — These are built of alternate sheets of mica and metal foil, impregnated with paraffine. They are much used for standards of capacity and for telephone, radio and other work requiring condensers which have a small power factor, high insulation resistance and which remain constant. A good working thickness of mica is from [illegible] to [illegible] inch. A single sheet of this

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ph (product of megohms by microfarads not less than 1000) and the absorption
, only sheets of the finest clear "ruby" mica should be used.

Fig. 1 shows the plan view and connection
a subdivided mica condenser. Since this ar-
gement permits of series, parallel, or series-
allel connection of the condensers a very
ge number of values of capacity may be ob-
ned.



Fig. 1. Subdivided Standard Condenser

The power factor of well-made standard mica
ndensers ranges from about 0.1 per cent to
out 1.75 per cent; see Grover, F. W., *Bulletin of the Bureau of Standards*,
l. 3, No. 3.

Glass Condensers. — On account of its high dielectric strength and specific
luctive capacity glass is particularly well suited for high-tension condensers,
ch as required for wireless telegraphy and the like. The Leyden jar is a
mmon form of glass condenser. Moscicki's modification of the Leyden jar,
wn in Fig. 2, consists of specially formed glass tubes closed at one end and
ted inside with silver deposited chemically, the outer coating being sometimes
plied in the same way and sometimes dispensed with altо-
her, the outer electrode in the latter case consisting of
ixture of glycerine and water in which the tubes are
mersed.


Fig. 2. Moscicki Condenser

Mordey (*Jour. Inst. Elec. Eng., 1909, Vol. 43, p. 621*) re-
rts a test on a Moscicki condenser consisting of 8 tubes
ving a total capacity of 0.03 microfarad, designed for 10,000-
lt a-c. working. Each tube is 2 inches in diameter and 2 feet
inches long, or with connections 3 feet 2 inches long. The
wer factor of this condenser was approximately constant
d equal to 1.0 per cent for frequencies from 40 to 60 cycles
r second and for voltages from 5000 to 10,000 volts.

Condensers of this type are used to a considerable extent in Europe as a
otective device on high-tension overhead transmission lines, as well as for
reless telegraphy. It has also been suggested by Mordey that they could be
ed economically for improving the power factor of highly-inductive loads,
ch as induction motors.

Paper Condensers. — Paper condensers for telephone and telegraph work are
de either (1) by building up a stack of alternate sheets of tinfoil (0.0003
h thick) and tissue paper, two sheets to the layer, each sheet about 0.001 inch
ck, or (2) by rolling up alternate strips of foil or "foiled" paper and tissue
per, the roll after being dried and impregnated with paraffin or other wax
ing pressed into a cubical shape, and suitably mounted in airtight metal boxes.
e "foiled" paper is made by depositing very fine flakes of tin on suitable tissue
per which is then run through a press which forces the flakes into contact with
ch other, resulting in a paper resembling the so-called silver paper used for
apping tea but having a fairly high conductivity. According to G. F. Mans-
dge (*see reference below*) this paper possesses two decided advantages over the
inary metal foil, (1) it is much lighter, and (2) when punctured it is self-
aling, the spark vaporizing the tin in the immediate vicinity of the puncture
thout destroying the paper itself. For a complete description of the method
making the paper and the condensers see Mansbridge, G. F., *Jour. Inst.*
r. *Eng.*, 1908, Vol. 41, p. 535.

Paper condensers for telephone and telegraph work are usually built to with-
nd about 400 volts. The following weights and dimensions are taken from
British Post Office specifications for metal-cased telephone condensers

One-microfarad paper condensers designed for a working pressure of 1000 and having the dimensions 8¾ by 6¼ by ½ inches and weighing 8 ounces are made by the Western Electric Co.

DIMENSIONS AND WEIGHT OF PAPER CONDENSERS

British Post Office Specifications

Capacity, microfarads	Length, inches	Width, inches	Thickness, inches	Weight, ounces
0.5	4¾	2⅝	5/16	4
1.0	4¾	4¾	5/16	8
2.0	4¾	4¾	9/16	12
4.0	4¾	4¾	1⅛	20
10.0	4¾	4¾	2 1/16	46

The power factor of well-made paper condensers ranges from about 0.5 to 2 per cent, but unless care is taken in their manufacture the power factor may be considerably larger; values as high as 30 per cent have been obtained.

Paper condensers similar in construction to those used for telephone work are also used for power factor correction on distribution circuits up to 2300 volts. These condensers are usually made up of a number of units in parallel, each unit having a capacity of 5 kv-a. at 60 cycles. See *G. E. Bulletin, No. 4071A, Feb, 1920.* Up to about 300 kv-a. the cost of a static condenser is less than that of a synchronous condenser (*see Motors, Synchronous*).

Electrolytic Condensers. — Electrolytic cells of the three following types have been used to a limited extent in Germany as condensers for telephone work: (1) acid cells, consisting of two small electrodes of platinum dipping in an acid solution, (2) sodium cells, in which the electrolyte is a solution of common salt, and (3) aluminum cells, in which the electrodes consist of aluminum and the electrolyte is some kind of basic solution. The capacity action of these cells arises from the formation of an extremely thin insulating layer at the anode of the cell which apparently has an enormously high specific inductive capacity. The anode and electrolyte therefore form two plates of a condenser having this thin layer of dielectric between them, forming a condenser of exceptionally large capacity per unit volume. The power factor of this condenser, however, is very high, due to the leakage current from anode to electrolyte, and consequently these cells are little used strictly as condensers, either in telephone or in power work. However, the aluminum cell is very extensively used as a lightning arrester, on power circuits, its capacity action combined with the self-healing property of the film making it an excellent device for this purpose (*see Lightning Protectors*).

TESTING OF CONDENSERS. — The three important properties of a condenser are its capacity, its insulation resistance and its power factor. The insulation resistance is determined by the use of direct current (*see Resistance and Conductance*). The power factor is measured by employing a source of alternating e.m.f. and a Wheatstone bridge and may be looked upon as a measure of the effective a-c. resistance. The power factor of a good mica condenser is practically constant over a wide range of frequency.

A great many arrangements of circuits have been devised for measuring the capacity of condensers, cables, etc. Only one or two of the simple methods

l in engineering practice can be described here. For a description and com-son of the various methods which have been used see Grover, F. W. *Bulletin* e *Bureau of Standards*, Vol. 3, No. 3.

-C. Versus A-C. Capacity Tests. — Due to the effect of electric absorp- above described, the charge taken by a condenser depends upon the time lectrification; the discharge also depends on the time. Consequently, when capacity is measured by any direct-current scheme a standard time of elec-ication and a standard method of determining the discharge must be chosen. British Post Office call for the capacity to be measured by taking the instan-eous discharge (by ballistic galvanometer) after the condenser has been rged for a period of 10 seconds. As a rule the capacity measured by a-c. thods is less than that measured by d-c. methods, since the charge does not e time to soak in; for the same reason the a-c. capacity also decreases htly with increase of frequency. Hence a-c. tests should be made at a stand-frequency, preferably that of the circuit on which the condenser or cable is e used. It is also desirable, when possible, to make the capacity test at the e voltage, both in value and wave form, as is to be used on the condenser.

Voltmeter-ammeter Test of Capacity. — Connect the condenser in series h an a-c. ammeter and impress on this circuit the selected a-c. voltage. asure the voltage drop across the condenser by means of a high-resistance voltmeter. Let the current read by the ammeter (voltmeter circuit open) d, the voltmeter reading V, the frequency f, then the capacity is

$$C = \frac{I}{2\pi f V},$$

ided the voltage is a pure sine wave and the power factor of the condenser ligible. As neither of these conditions are usually fulfilled, such a test rule gives only a rough approximation to the true capacity.

Ballistic Galvanometer Method. — Fig. 3 shows the arrangement of cir-ts for testing the capacity of a cable. B is a battery ing the desired constant e.m.f., K a highly insulated , G a ballistic galvanometer properly shunted (*see Gal-nometers and Shunts*). The sheath of the cable is ally earthed. It is best to charge the core of the le positively as shown. If a condenser is to be tested rial of a cable, the plate corresponding to the sheath y or may not be earthed, as desired. Care should be re that there is no leakage of current directly from the battery into the lvanometer or into the cable.

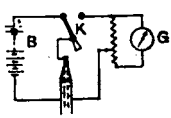


Fig. 3.

The procedure is as follows: Throw the key to the left for the desired length of e, note the position of the galvanometer needle (or spot of light), then throw key to the right and note the first swing or maximum deflection of the spot ght. Call this D_x. Next, keeping the same battery, substitute for the cable ndard condenser of known capacity C and make a similar observation. Let deflection in this case be D. Then the unknown capacity is

$$C_x = \frac{D_x}{D} C,$$

ided the damping of the galvanometer is the same in both cases.

While this method is satisfactory when applied to perfect condensers, it fails a greater or less extent when applied to cables, especially if they are very long, to any condenser having high absorption. With such condensers the dis-rge consists of two portions: a sudden rush when the key is first closed,

followed by a current gradually diminishing toward zero, due to the re of the "absorbed" charge. Both portions of the discharge are active in ducing the deflection, hence the apparent capacity depends to a certain e on the period of the galvanometer employed, as well as upon the ti electrification.

Wheatstone Bridge Method. — The following method gives a mea measuring both the capacity and power factor of a condenser, provided the available a standard condenser whose capacity and power factor is known. The bridge is arranged as shown in Fig. 4. C is the standard condenser and C_x the condenser to be tested. All resistances must be non-inductive and adjustable. A is a source of alternating e.m.f. of pure sine-wave form and of frequency f. T is the detector; it may be either a telephone or, if the frequency be kept perfectly constant, a vibration galvanometer. For ordinary tests the telephone is the more convenient instrument; for good work with it the frequency should be high.

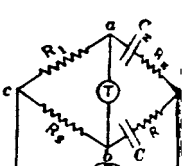


Fig. 4.

The balancing is effected as follows: with R_x and R both zero, adjust R_1 R_2 until a minimum of sound is obtained; then adjust either R_x or R as t case may require, until the minimum is the best possible; then readjust R_1 R_2, and so on, thus obtaining the perfect balance by successive adjustments.

$$C_x = \frac{R_2}{R_1} C,$$

$$\tan \phi_x = \tan \phi + 2\pi f (RC - R_x C_x),$$

where f is the frequency, ϕ_x is the angle whose *sine* is equal to the power fact of the condenser under test and ϕ is the angle whose *sine* is equal to the pow factor of the standard condenser. The effective alternating-current conductan of the condenser under test is then

$$G_e = 2\pi f C_x \tan \phi_x,$$

which as a rule is many times the reciprocal of its insulation resistance as measu by direct-current methods (*see Resistance and Conductance*).

The value of the power factor for the standard is best determined at t Bureau of Standards in Washington; it is done by indirect reference to an condenser.

Sources of Error. — The sources of error when the most refined measu ments are to be made are the inductance or capacity of the various resistanc error in the ratio of R_1 and R_2, and electrostatic induction between the brid and its surroundings. These sources of error are fully discussed by Grov above referred to.

COSTS OF CONDENSERS (Pre-war prices). — A good standard mi condenser of ½ microfarad, guaranteed to stand 300 volts maximum across terminals costs about $25. An adjustable mica condenser, such as shown in F 1, having a maximum capacity of 1 microfarad and suitable for voltages up 300 volts costs about $60. Paper condensers, such as used on telephone circu cost about 70 cents per microfarad. A standard 1000 volt, 1 microfarad pap condenser can be had for about $3.75.

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CONDENSERS, STEAM.— (*See also Cooling Systems for Power Stations; Power Stations; Pumps; Steam Engines; Turbines, Steam.*) The primary object of a condenser is to reduce the back pressure in the exhaust of a steam-engine or steam turbine, although in cases where the supply of suitable feed-water is limited the recovery of the condensed steam is of equal importance. Theoretically the gain in the output of a given engine for the same steam-output is proportional to the reduction in back pressure, but practically the gain is usually much less than this, depending upon the type of engine and conditions of operation.

CLASSIFICATION OF CONDENSERS. — Condensers are of two general types, jet condensers and surface condensers.

Jet Condensers. — In a jet condenser cooling water and the exhaust steam mingle together in a closed chamber, the water condensing the steam by direct contact. The cooling or injection water on entering the condenser is broken up into a fine spray or is spread out into a thin sheet. Jet condensers may be classified as follows:

Standard or Ordinary Jet Condensers, in which the cooling water, condensed steam and air are exhausted by a pump.

Barometric Condensers (Siphon Condensers), in which the cooling water and condensed steam are exhausted by a barometric column, the air being exhausted with the water and condensed steam or by means of pump. In certain types of barometric condensers the condensing water is forced into the condenser by atmospheric pressure (if the lift of the condensing water is not over 15 feet), and the condenser is then called a "siphon" condenser.

Ejector Condensers, in which the condensed steam and air are exhausted directly to the atmosphere by the momentum acquired by the cooling water and condensed steam as they pass through the condenser.

Rotary Condenser. — The best known form of this type of condenser is the Leblanc Condenser (made by the Westinghouse Machine Co.), which accomplishes the separate removal of water and air by means of a pair of relatively small turbine-type rotors on a common shaft in a single casing, which is integral with or attached directly to the lower portion of the condensing chamber. The condensing chamber itself is but little more than an enlargement of the exhaust pipe. The injection water is projected downwards through a spray nozzle, and the combined injection water and condensed steam flow downward to a centrifugal discharge pump under a head of 2 or 3 feet, which insures the filling of the pump. The space above the water level in the condensing chamber is occupied by water vapor plus the air which entered with the injection water and with the exhaust steam. This space communicates with the air-pump through a relatively small pipe.

The air-pump differs from pumps of the ejector type in that the vanes in traversing the discharge nozzle at high speed constitute a series of pistons, each one of which forces ahead of it a small pocket of air, the high velocity of which effectually prevents its return to the condenser. A small quantity of water is supplied to the suction side of the air-pump to assist in the performance of its functions. The power required for the pumps is said to approximate 2 to 3 per cent of the power generated by the main engine.

Surface Condensers. — Ordinary surface condensers consist of nests of small brass or copper tubes usually ⅝ inch or 1 inch in diameter through which cooling water is forced and which are surrounded by an air-tight shell to which the exhaust steam is admitted. There may be one, two or more sets of tubes through which the steam passes in succession, the condenser being referred to

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"single-flow," "double-flow" or "multi-flow" respectively. Steam is
tted at the top of the shell and the condensed steam drawn off at the bottom.
r enters the lower tubes and is discharged at the top, securing thus the
ntages of the counter-flow principle. The rate of heat transmission depends
y upon the state of the tubes. Transmission is much retarded by a water
ating the exterior of the tubes and by interior coatings of scale, dirt or
sion. In the so-called "dry-tube" type baffles are arranged to catch the
from each set of pipes, drain it off at the side and so prevent it from falling
e pipes below.

Evaporative and Air-cooled Surface Condensers are sometimes
oyed when condensing water is scarce. Brief descriptions and references
e found in Gebhardt's *Steam Power Plant Engineering*.

LASSIFICATION OF CONDENSER PUMPS. — (*See also Pumps Pumping Engines.*) The following names are usually applied to the pumps in connection with a condenser.

njection or Circulating Pump, the pump used for injecting the cooling r into a condenser.

Vet-air Pump, the pump used for exhausting the air, condensed steam hot water from a condenser when these are all exhausted together.

Dry-air Pump, the pump used for exhausting the air and water vapor ly. A dry-air pump must be used when high vacua are required.

Hot-well Pump. — This name is applied to the wet-air pump when this mp exhausts to a hot-well. The hot-well is a well provided to hold the con-nsed steam, which is approximately at the same temperature as that of the aust steam in the condenser. If this hot water is to be used over again for ler feed it is pumped from the hot-well to the boiler by the boiler feed pump (*Boilers, Steam*).

CHOICE OF TYPE OF CONDENSER. — The chief advantage of the face condenser over the jet condenser is that the condensed steam does t mingle with the cooling water and therefore the condensed steam may be ed over again for boiler feed water, provided any oil which may be carried the exhaust steam from the cylinders is eliminated before the steam reaches t condenser (*see Separators, Steam*). When there is plenty of cooling water ldily handled a higher vacuum is usually obtained by means of a surface ndenser than by means of a jet condenser. To offset these advantages, how-r, the surface condenser is much more expensive than a jet condenser, and quires as a rule a greater amount of cooling water.

Consequently the use of a surface condenser is in general justified only when e cost of obtaining suitable feed water is relatively high (*see also Feed-water aters and Purifiers*), and cooling water, unsuitable for feed water however, lively cheap (*see also Cooling Towers, Ponds, etc*). Before finally selecting her type of condenser an estimate of the total annual cost, including interest, preciation, maintenance and all operating charges should be made for each e.

According to Prof. Wickenden the following vacua, based on a 30-inch barom-r, have been found most economical in general practice.

Piston engines	26 to 26.5 inches
Turbines at 20 per cent load-factor or less	27 to 27.5 inches
Reaction turbines at high load-factors	28 to 29.5 inches
Impulse turbines at high load-factors	28.5 to 29 inches

summer months warm cooling water often renders these vacua impracticable. hen cooling towers are required to conserve the water supply the economic

limits of vacuum are lower, due to the extra investment and the relati warm state of the water. Jet condensers are cheaper to install and ope for vacua up to 27 inches. They require less water and give somewhat h hot-well temperatures if closely regulated. For higher vacua the load o dry-air pump becomes excessive, due to the air entrained with the co water. Surface condensers are then preferable and for extreme vacua they indispensable.

DEGREE OF VACUUM AND BACK PRESSURE. — Let

V = degree of vacuum, i.e., the reading of vacuum gauge, in inches of mer column,

B = reading of barometer.

Then the back pressure in pounds is

$$p = 0.491\,(B - V).$$

The degree of vacuum is usually referred to a barometric pressure of 30 inch Calling V_0 the vacuum in inches of mercury corresponding to a barom pressure of 30 inches, and B and V the observed barometric pressure and ga reading respectively, then

$$V_0 = V + (30 - B).$$

(If V_0 is the vacuum in inches referred to 760 millimeters or 29.91 inches mercury, substitute for 30 the number 29.91.)

Vacua from 20 to 29 inches are used in practice, corresponding to back pr sures of from 4.5 to 0.5 pounds. The higher the vacuum the more cooling w required and the greater the cost of the air and circulating pumps.

CONDENSING WATER REQUIRED. — Let

T = temperature, in ° F., of dry saturated steam at the pressure corresponding to the desired degree of vacuum,

T_i = temperature, in ° F., of the injection water,

T_s = temperature, in ° F., of the condensed steam at bottom of condenser,

T_w = temperature, in ° F., of the discharge water (for a jet condenser $T_w = T_s$),

H = total heat (above 32° F.) of the exhaust steam, in B.t.u. per pound.

Then the weight of condensing water required per pound of steam is

$$W = \frac{H - T_s + 32}{T_w - T_i}.$$

In applying this formula the values of T_s and T_w must be determined and an allowance must be made for the regulation of the supply of condensing water

	Jet condensers		Surface condensers	
	Parallel-current	Counter-current	Single and double flow	Multi-flow*
	Deg. F.	Deg. F.	Deg. F.	Deg. F.
T_s less than T by.....	10 to 15	5 to 10	5 to 10	0 to 5
T_w less than T by.....	10 to 15	5 to 10	10 to 20	0 to 10

* Cases have been reported where T_s and T_w are both *higher* than T by a few degrees. (*Proc. Inst. Nav. Arch., March., 1906.*) [Probably due to errors of gauges.]

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ituse of T_s and T_w. — Air is always present in exhaust steam and in the of jet condensers a certain amount of air also enters the condenser with ooling water. The effect of the air is to reduce the temperature of the n (T_s) below that corresponding to saturated dry steam (T) at the same ure. The amount of air present depends upon the type of condenser and upon the amount of air in the cooling water in the case of a jet conden-

he relations between T_s, T_w and T, as shown in the table on page 256, found to hold in practice.

lowance for Regulation of Injection Water. — It is usual to take for the above formula the value corresponding to dry saturated steam at the n pressure in the condenser (*see tables in article on Steam*), and then to ease the value of W so obtained by from 5 to 15 per cent to allow for im-ect regulation of the injection water and for the more or less unknown state he steam as it enters the condenser.

ample. — A vacuum of 25.85 inches, referred to 29.92-inch barometer, be maintained in a surface condenser, with injection water at 60° F. The e of T from the steam tables is 126° F. and H = 1115 B.t.u. Take T_s = °, T_w = 115°, T_i = 70°; then

$$W = \frac{H - T_s + 32}{T_w - T_i} = \frac{1115 - 120 + 32}{115 - 70} = 22.8.$$

IMENSIONS OF CONDENSERS. — There is so great a difference he design of the various forms of jet condensers that it is impossible to give average dimensions. See the catalogues of the makers; representative es of the various types are listed above.

n the case of surface condensers the tube surface exposed to the steam varies ectly as the coefficient of heat transfer (i.e., the number of B.t.u. per hour ° F. difference in temperature between the steam and water per square foot ooling surface) and directly as the mean temperature difference between the ter and the steam. Let

T_i = temperature, in ° F., of the injection water,
T_s = temperature, in ° F., of the exhaust steam at condenser pressure,
T_w = temperature, in ° F., of the discharge water,
Q = pounds of cooling water required per hour,
U = coefficient of heat transfer.

en, according to Josse (*Power, Feb. 2, 1909*), the required cooling surface square feet is

$$S = \frac{2.3\,Q}{U} \log_{10} \frac{T_s - T_i}{T_s - T_w}.$$

e value of U depends upon the metal used for the tubes, the condition of the ernal surface of the tubes and especially upon the condition of the internal face of the tubes (scale and corrosion decreasing the value of U very markedly), d upon the velocity of the water, being greater the higher this velocity. may be taken as 250 for water velocities of from 25 to 50 feet per minute d 375 for velocities of from 50 to 75 feet per minute. There is, however, siderable difference of opinion regarding the proper formula for S and proper value to assign to U. (*See Hoefer, K., A.S.M.E., J. 41, p 962, 1919*).

In reciprocating engine plants an allowance of 2 square feet of tube sur-e per indicated horse-power is customary. In early steam-turbine instal-ons an area of from 2 to 4 square feet per kilowatt was commonly ployed, but subsequent improvements in condensers and the water rates turbines have tended to reduce these areas. In the most modern plants

of large capacity condenser surfaces range from 1.2 to 2.5 square feet kilowatt.

From the relations implied in the above formulas it is seen that the surf may be reduced by forcing large quantities of water at high velocities to pass tubes; or, with a given surface, the vacuum may be heightened by increas the flow of cooling water. However, the gain may be more than offset by t cost of pumping this water.

SIZE OF CONDENSER PUMPS. — (*See also articles on Blowers a Compressors; Pumps and Pumping Engines.*) The size of the injection or c culating pump required can be calculated directly from the quantity of injecti water to be handled and the head against which it is to be pumped, includ of course the friction head. Separate injection pumps for jet condensers a not usually required, as the head does not as a rule exceed that correspondi to the difference between atmospheric and condenser pressure. In the case surface condensers the intake and discharge tunnels are usually at about t same level, and consequently the head is largely friction head. The fricti head of a condenser is not readily calculated, but may be obtained from t manufacturer.

Wet-air Pumps. — The predetermination of the size of wet-air pumps difficult, owing to the uncertainty in estimating the quantity of water vapor air which they must handle. In the case of jet condensers the total weight water (including the vapor) and air is equal to the combined weight of exhaust steam and cooling water, whereas for a surface condenser only the t densed steam and air in it is handled by the wet-air pump. Hence the wet- pump for a surface condenser is usually much smaller than for a jet conden

Formulas, partly analytical and partly empirical, for calculating the pis displacement of wet-air pumps will be found in Gebhardt's *Steam Power Pl Engineering*. For average practice the volume capacity or piston displacem is equal to the volume of *cooling water* multiplied by the following factors.

For jet condensers, single-acting pump	3
For jet condensers, double-acting pump	3.5

Piston speeds are usually about 50 feet per minute at full load.

For surface condensers the volume capacity is equal to the volume of *condensed steam* multiplied by the following factors.

For reciprocating engines	10
For steam turbines	20

These figures are based on a study of some 200 installations (Gebhardt, 1910 e

Dry-air Pump. — The required volume capacity is found in practice be equal to the volume of the *condensed steam* multiplied by the follow factors:

For vacua under 27 inches	20 to 30
For vacua 28 inches or over	50

In both cases the barometer is assumed as 30 inches. These figures are gi by Gebhardt and are based on an investigation of some 50 installations.

POWER REQUIRED FOR CONDENSER PUMPS. — The power quired for the circulating pump is calculated in the ordinary way from weight of the water delivered and the head, including the friction head *article on Pumps and Pumping Engines*).

The power required for the wet-air and dry-air pumps can be accura determined only when the proportion of air in the exhaust steam and als the cooling water, in the case of a surface condenser, is known. Surface w under atmospheric pressure contains from 2 to 12 per cent, by volume, of To allow for leakage, a liberal factor of 20 per cent may be taken.

ower Required to Exhaust the Air.—Let
p_a = atmospheric pressure, pounds per square inch,
p_c = pressure in condenser, pounds per square inch,
T_i = initial temperature of injection water, in ° F.,
T_f = initial temperature of feed water, in ° F.,
T_c = temperature in condenser in ° F. (approximately the temperature of the exhaust steam),
W_w = weight of cooling water in pounds per *minute*,
W_s = weight of condensed steam in pounds per *minute*.
n for a jet condenser the volume of air in cubic feet per minute at condenser sure to be handled by the pump is

$$V_1 = \frac{(W_w + W_s)\, p_a\, (T_c + 460)}{310\, p_c\, (T_i + 460)},$$

for a surface condenser

$$V_1 = \frac{W_s p_a\, (T_c + 460)}{310\, p_c\, (T_f + 460)},$$

suming in both cases that there is 20 per cent air by volume in the water at nospheric pressure. This percentage is probably high when the feed water aken from a hot-well, since the heating of the water drives out the air. Also, e temperature T_c for a counter-current jet condenser and separate air pump ower nearly the temperature of the injection water than that of the steam. The horse-power required to exhaust the air is then

$$P_a = \frac{p_c V_1}{66.2\, e} \left\{ \left(\frac{p_a}{p_c} \right)^{0.29} - 1 \right\},$$

re e is the mechanical efficiency of the pump, which may range from 30 to er cent. (*See article on Blowers and Compressors.*)

ower Required to Exhaust the Condensed Steam and Water.—The er required to exhaust the water and condensed steam from a jet condenser r be calculated in the same manner as for an ordinary pump (*see article on ps and Pumping Engines*), using the proper value of the head under which pump operates. This will depend upon the arrangement of the condenser, tion of the pumps and hot-well, etc.
f a wet-air pump only is used, then the total horse-power of this pump will $P_a + P_w$, where P_w is the horse-power required to remove the condensed m and water. If a dry-air pump is used in connection with the wet-air p (which then exhausts the water only) the horse-power of the dry-air p is P_a, and the horse-power of the wet-air pump P_w.

er Cent of Total Available Energy Used by Condenser Pumps.—n steam-driven pumps are employed and the exhaust from these pumps t utilized the steam consumption of the pumps is properly taken as a measure he energy required for their operation: this may range from 5 to 20 per cent he total steam generated by the plant. When the exhaust from the steam aders of the pumps is utilized for heating the feed water (*see Feed-water ters*), the *heat consumption* of the pumps is properly taken as a measure of energy required for their operation; this may range from about 1 to 5 per . of the total B.t.u. utilized by the main engines, for a large part of the : in the steam used in the pumps is returned to the boiler via the feed water. n electrically-driven pumps are employed, the kilowatt-hour input to the ors driving the pumps is properly taken as a measure of the energy required operating the pumps; this may range from about 2 to 8 per cent of the put of the main generators.

LOCATION AND ARRANGEMENT OF CONDENSERS. — Wh there is only one engine installed the condenser is usually placed close to it just below the engine, so that all condensation may gravitate into it. In sm large vertical steam turbine outfits the condenser (surface type) is at the ba of the turbine and forms an integral part of the structure. When seve engines or turbines are installed in a power house a separate condensing outf may be used for each engine, or the so-called "central system" may be employ in which one condensing outfit serves several engines. This arrangement particularly well adapted to plants in which the individual units are subject to extreme variations in load, as in rolling mills.

Additional data on the location and arrangement of condensers will be fou in the article on *Power Stations*.

COST OF CONDENSING EQUIPMENT (Pre-war figures). — approximate formula that is sometimes used for determining the cost of condensers is,

$$\text{Cost in dollars} = 500 + 1.0 \times \text{h.p.},$$

Potter (*Power*, Dec. 30, 1913) gives:

Type	Capacity	Cost, dollars
Barometric (28-in. vac.)....	Up to 30,000 lb. steam per hour	1055 +0.112 X lb. steam cond. per hr.
Jet (28-in. vac.).....	Up to 30,000 lb. steam per hour	1176 + 0.1138 X lb. steam cond. per hr.
Surface (28-in. vac.).....	Up to 35,000 lb. steam per hour	1630 + 0.2038 X lb. steam cond. per hr.
Surface (26-in. vac.).....	Up to 30,000 lb. steam per hour	413 + 0.1015 X lb. steam cond. per hr.

Twenty-eight inch vacuum surface condensers with pumps cost from $1 $1.80 per square foot of surface, depending on price of copper, or from $150 $250 per 1,000 pounds of steam condensed per hour.

J. R. Bibbins (*Power, Jan, 1905*) gives a curve showing the relative c of high-vacuum surface condensers compared with 26-inch-vacuum surfa condensers. The following figures are taken from this curve.

Degree of vacuum, inches.....	26	26.5	27	27.5	28	28
Relative cost, per cent.....	100	111	123	137	158	1

Maintenance of Condensers. — The cost of maintenance of a surfa condenser is subject to wide variations, depending upon the corrosion and e terioration of the condenser tubes, the exact cause of which is not often und stood. With clean, fresh water, free from acid, the tubes of a condenser l indefinitely, but where the cooling water contains sulphur, as in drainage fr coal mines, or sea water contaminated by sewage, such as harbor water, t deterioration is exceedingly rapid.

The maintenance of a jet condenser is much less affected by impurities the water.

BIBLIOGRAPHY. — Gebhardt, *Steam Power Plant Engineering*, contai 62 pages on condensers and a full bibliography of the subject.

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CONDUITS AND CONDUIT LINES, UNDERGRO

also Distribution Lines; Transmission Lines; Wires and Ca Wiring of Buildings.) The following is a brief table of content

Terminology.....
Use of Conduit Lines.....
Types of Conduits.....
Splicing Chambers.....
Rodding and Wiring of Conduit Lines.....
Specifications.....
Installation.....
Maintenance.....
Repairs.....
Costs.....
Bibliography.....

Underground cables are now almost universally installed in either of glazed tile, wood or paper fiber. The pipes or condu as to form a series of continuous ducts for a length of not and are terminated in brick or concrete chambers, from which pulled into the ducts.

TERMINOLOGY. — While there is some confusion in t of conduit lines, the best recent literature, except the specif American Electric Railway Engineering Association, sanction definitions.

Conduit, a pipe or tube designed or used for containing e cables.

Duct, a passage or opening, designed or used for accomm wires or cables.

Conduit Line, a group of installed conduits. (The expre largely used for conduit line, but will not be used herein, as it is such expressions as "the subway subway," meaning the cond underground railway.)

Splicing Chamber, a chamber built to give access to the duc line; frequently called a manhole. Properly, a manhole is the access to the splicing chamber.

Manhole, an opening giving access to an underground spl from the surface of the ground; frequently, but improperly, us the entire splicing chamber.

Service Box, a part of a splicing chamber with facilities distributing conductors to the mains. Service boxes are usuall iron and set on the roof of the splicing chamber like a manhole c

USE OF CONDUIT LINES. — Conduit lines are used f tion of electrical energy wherever the unsightliness, danger o pole lines prohibits the use of the latter. It is therefore in large have found their principal application. They are used for tl and distribution cables of lighting systems, power plants and ra telephone and telegraph lines.

Since the invention of the Pupin loading-coil, the use of c telephones has received considerable impetus. Underground now extend from Boston to Washington, a distance of nearly 500 pump-log being used for the conduit the greater part of the w notable installation of conduit for trunk-line railroad electrific

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the New York Central which comprises over 1,600,000 duct feet, partly in tile conduit and partly in iron pipe.

Advisability of Double-conduit Line. — A conduit line of a large number of ducts should be avoided wherever possible. While a large line may be permissible for telephone work, it certainly is not desirable for light or power work. The entire output of a station or substation of considerable size should not be carried out through one conduit line, but should be divided between two or more lines kept well separated.

TYPES OF CONDUITS. — While tile conduit is used far more than any other kind, there are four other kinds in fairly extensive use; namely, fiber conduit, wrought-iron pipe, cement-lined iron and pump-log.

Tile Conduit. — Fig. 1 shows the tile conduits used in the Electric Zone of the N. Y. C. & H. R. R. R. near New York and Fig. 2, the standard of the

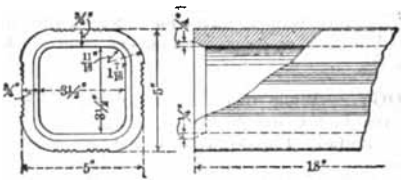


Fig. 1.

A.E.R.E.A. They represent what is probably the best practice up to date. The conduit shown in Fig. 1 weighs 16½ pounds per length of 18 inches. Four-

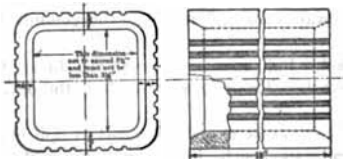


Fig. 2.

duct conduit is now comparatively little used; it weighs about 100 pounds per length of 3 feet.

Fiber Conduit consists of tubes, made by rolling paper saturated with asphalt or bituminous compound around a mandrel. Like iron pipe, which it resembles in appearance, lengths of fiber conduit are usually joined by screw and coupling although it is also made for socket, sleeve and drive joints. It is lighter and easier to handle than iron pipe with which it compares favorably in cost, but is more expensive than tile conduit. It is mechanically inferior to other types of conduit, and difficulty is often experienced in drawing heavy cable around bends without breaking the conduit. For some classes of work this disadvantage is entirely compensated for by superior gas and water tightness.

The dimensions of fiber conduits are given as follows by the Johns-Manville Company and substantially the same by the Fiber Conduit Company.

Socket joint				Sleeve joint			
Inside diameter, inches	Thickness of walls, inches	Approximate average weight per foot, pounds	Length of section, inches	Inside diameter, inches	Thickness of walls, inches	Approximate average weight per foot, pounds	Length of section, inches
1	¼	0.45	30	1	¼	0.45	30
1½	¼	0.75	60	1½	¼	0.75	60
2	¼	0.90	60	2	¼	0.90	60
2½	¼	1.05	60	2½	¼	1.05	60
3	¼	1.30	60	3	¼	1.30	60
3½	¼	1.60	60	3½	7/16	2.50	60
4	¼	1.85	60	4	½	3.20	60
Screw joint				**Drive joint**			
1½	5/16	0.85	60	2	¼	0.90	60
2	5/16	1.35	60	2½	¼	1.05	60
2½	5/16	1.70	60	3	¼	1.30	60
3	7/16	2.20	60	3½	¼	1.60	60
3½	7/16	2.50	60	4	¼	1.85	60
4	½	3.20	60				

Wrought-iron Pipe is used in city streets where the conduit line has to twist about sub-surface obstructions. It is more expensive than tile conduit and does not last as long on account of rusting. The usual sizes are 3-inch and 3½-inch pipe, 20 feet long, provided with threaded ends and couplings. (For weights and dimensions see article on *Pipes*.)

Cement-lined Iron Pipe consists of thin sheet-iron cylinders, like stovepipe, with a lining of hydraulic cement. When the conduit is old the iron usually rusts away without detriment to the construction.

Pump-log Conduit is used only on telephone lines, as its inflammability renders it dangerous for power work. It consists of wooden blocks with the

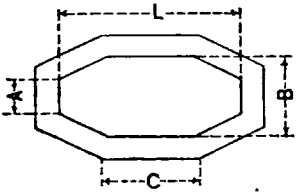


Fig. 3.

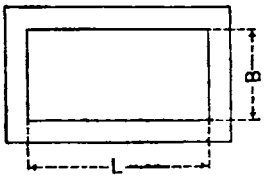


Fig. 4.

duct hole drilled out. A description of a typical pump-log installation is given below under Installation.

SPLICING CHAMBERS. — Splicing chambers, for straight runs, are usually built in the shapes shown in Figs. 3, 4, 5 and 6. That shown in Fig. 3 is usually regarded as ideal, as the excavation is a minimum, and the cables can

follow the walls very closely without being bent to a dangerously small radius, a frequent occurrence in chambers with square corners. The rectangular form shown in Fig. 4 is somewhat more common, but requires more excavation and more wall material than the first form, and is conducive to sharp bends in the

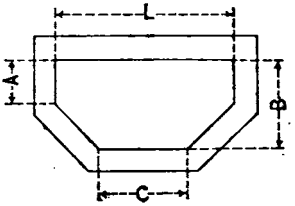


Fig. 5.

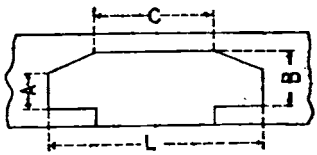


Fig. 6.

cable. The type shown in Fig. 5 is convenient where it is desired to have a wide chamber without occupying much space on one particular side of the duct line as, for example, where two duct lines run parallel and a short distance apart. In this case, economy may be obtained by the use of a common wall on the long side of the chamber.

Fig. 6 shows the side-wall type of chamber, which is entered from the side instead of the top. This form is used in the side walls of tunnels or in retaining walls, and usually takes the form of a long niche in the wall. When built in tunnel walls not far from the surface of the ground, it is desirable to have them open from the street above as well as from the side, in order to avoid the necessity of having the use of a tunnel track when work is to be done in the chambers.

Material of Splicing Chambers. — Monolithic concrete is the cheapest and best material to use where a large number of identical chambers have to be built, as the same form can be used over and over again. Where such uniformity cannot be attained, as in streets congested with sub-surface construction, brick or concrete hollow tile are better and cheaper materials.

Dimensions of Splicing Chambers. — The height of large splicing chambers is usually determined by the height in which a man can stand upright and is seldom less than 6½ feet. The width is similarly influenced by the space required to work in, which is about 4 feet. The length depends upon the length of splice and the space required to curve the cable from the ducts to the supporting shelves or racks, considerations which make a length of 8 feet the practical minimum where there are large cables.

Special chambers, such as those for bare grounded cables, for a small number of telephone or other small cables, may be made of smaller dimensions than stated above, because a man can work on his knees in a chamber 4 feet high and 3½ feet wide, and the length may be reduced to about 4 feet if the cables are small and flexible.

Table I gives the dimensions of standard splicing chambers used by several large traction and lighting companies. The letters refer to the dimensions on Figs. 3, 4, 5 and 6. The average volume of a splicing chamber is about 16 cubic feet per splice, although a maximum of 40 and a minimum of 6 are sometimes found.

Spacing of Splicing Chambers. — It is found that the greatest length of cable that can be pulled through a glazed tile conduit without injuring the cable or requiring special apparatus is about 400 or 500 feet on a straight or slightly curved run. Hence at distances of 400 or 500 feet along a conduit line it is necessary to provide splicing chambers, where the separate lengths of cable may

TABLE I. — DIMENSIONS OF SPLICING CHAMBERS

Name of company	Fig. No.	A	B	C	Height inside	L	No. of splices
		Feet and inches					
Chicago Edison Co.	3	2′ 3″	6′ 0″	3′ 3″	6′ 6″	7′ 6″	16
District Ry., London	5	2 4	5 0	5 6	7 6	14 3	32
I. R. T. Subway, N. Y.	6	1 3	3 0	4 4	14 0	11 4	64
Long Island R.R.	5	1 6	4 0	2 3	6 6	10 0	18
Long Island R.R.	4	.....	4 0	....	6 6	9 0	18
Long Island R.R.	3	1 8	4 0	3 8	6 6	9 0	18
Manhattan Ry., N. Y.	4	.....	6 0	....	6 6	8 0	16–48
New York Cent. R.R.	3	2 4	5 0	3 6	6 6	11 0	20
New York Cent. R.R.	5	2 6	5 0	3 6	6 6	11 0	20
New York Cent. R.R.	5	1 10	4 0	3 6	6 0	10 0	5
New York Cent. R.R.	6	1 10	3 0	3 6	6′ 6″–8′ 0″	8 6	20–32
Pennsylvania R.R.	4	.....	4 0	....	6 4	8 0	24
Philadelphia R.T.	5	1 8	3 6	curved	6 3	7 10	20
P. R.R. Tunnels	(Special shape)				4 9	6 0	

be pulled in and spliced. Local conditions and curves may prevent the full length being attained in all cases, but it is desirable to have no lengths greater than the standard, in order to avoid the necessity of keeping special long pieces of cable in stock.

Service Boxes. — Service boxes are usually iron castings similar in shape and size to an ordinary manhole casting, but provided with a completely waterproof inner cover which screws down on a gasket. The outer cover resembles that of a manhole. Inside the inner cover is a distribution board with copper bus bars, to which the main and feeder cables in the chamber connect through the bottom of the board.

Waterproofing and Drainage. — There is some diversity of opinion with regard to the value of waterproofing splicing chambers, although the modern tendency is to omit waterproofing and provide efficient drainage. Waterproofing is futile unless the duct lines leading to it are waterproofed. This is a very difficult and expensive process which seldom shows good results. Water will also enter chambers from the top and will be retained if the chamber is waterproof.

Every chamber should be provided with a sump into which the water can drain, Fig. 7. It is desirable to connect the sump to the sewer through a syphon and back-water valve. If this is not practicable the sump may be drained through the manhole by a hand pump.

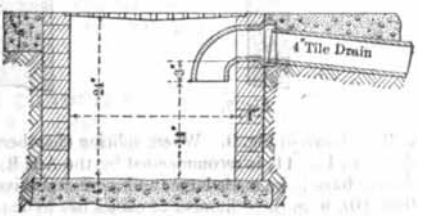


Fig. 7.

Where natural drainage cannot be secured, as, for example, where the chamber is below the sewer level, it is good practice to provide a special drain pipe to which all the chambers are connected, the drainage being towards a general sump pit, which is kept

dry by an automatic sump pump. The cost of such a system often compares favorably with that of waterproofing, besides yielding superior results.

The sump of a splicing chamber should be covered with an easily removable grating; wooden ones are often used on account of their property of floating when the chamber is flooded, thereby leaving the sump open for the pipe of a hand pump.

Manhole Castings. — Manhole castings are usually made with two covers (Fig. 8), the outer of which should be made strong enough to stand the weight of the heaviest vehicle, and the inner should be as light as consistent with the rough usage they receive in handling. Both covers should be provided with means to grip them with a hook-bar. Where power cables are used it is essential to provide ventilating holes. It is usual to lock the inner cover with a substantial brass padlock with protected keyhole.

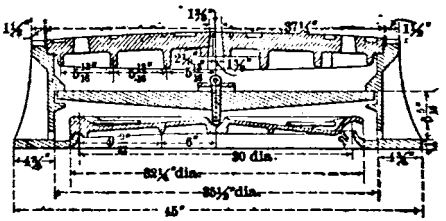
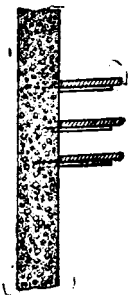
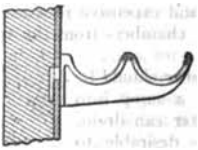


Fig. 8.

Cable Supports. — (*See also article on Wires and Cables, Insulated.*) Cables in splicing chambers are usually supported on iron brackets attached to the chamber walls. This construction is very satisfactory, especially if the power cables are properly wrapped with asbestos, but some engineers consider a shelf to be preferable, as it affords insulation and provides more protection between cables.

Concrete reinforced with expanded metal or wire cloth has proved satisfactory for shelves one inch thick, and is inexpensive. A good support for shelves in concrete splicing chambers is a pair of iron pins set in iron pipes, which are sunk in the chamber wall at a slight angle, so as to tilt the shelves toward the chamber


Fig. 9.


Fig. 10.

wall as shown in Fig. 9. Where splicing chambers are made of brick, the design shown in Fig. 11, is recommended by the A.E.R.E.A. Splicing chambers with shelves have to be made larger and more expensive than those with duplex racks (Fig. 10), if an equal number of cables has to be carried.

RODDING AND WIRING OF CONDUIT LINES. — The only test which it is usual to apply to conduit lines is rodding with a mandrel in order to ascertain whether the ducts are continuous and unobstructed.

The rods used for this purpose are of hickory about one inch in diameter

and three or four feet long and are fitted at the ends with steel couplings such as that shown in Fig. 12. The first rod is attached to a mandrel and pushed into the duct. Another rod is coupled to the first and the pair pushed further

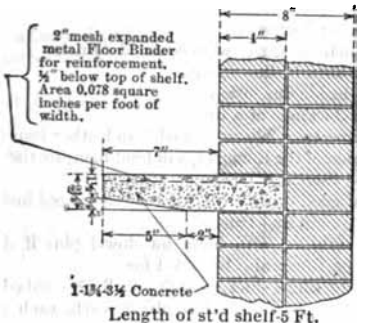


Fig. 11.

into the duct. By successively coupling other rods and pushing them into the duct, the mandrel is made to travel from one chamber to another. As soon as the mandrel emerges into the receiving chamber, the rods are pulled through and uncoupled. If an obstruction stops the mandrel an attempt is made to force it through by repeated blows, failing which, it becomes necessary to cut into the conduit line from the side.

Mandrels for Rodding. — Various types of mandrels are used for testing ducts, some hollow and smooth with sharp cutting edges, others fitted with numerous sharp projections and known as hedgehogs (Fig. 13).



Fig. 12.

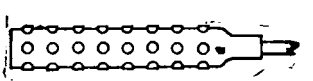


Fig. 13.

"Wiring" the Ducts. — It is usual to attach a galvanized steel wire (No. 10 or 12) to the last rod and leave the wire in the duct after the removal of the rods. The ducts may also be "wired" by the use of a conduit machine. This consists of a reel of steel tape and means for winding and unwinding the tape into the duct at the rate of about ten feet per second. This tape or "snake" having been pushed through the duct is pulled out again with the wire attached to its end.

SPECIFICATIONS FOR CONDUIT LINES. — (*See also article on Specifications.*) By far the greatest number of cable breakdowns occur from injury to the lead sheaths either by electrolysis or by abrasions during installation. Sharp projections in the ducts should therefore be carefully guarded against, as a cable pulled over such a projection will have a groove cut along its entire length and the effective thickness of the sheath will be thereby materially reduced. The specifications for inspection and rodding given below are typical of the best modern practice, but unfortunately duct inspection is usually so lax that often in a large installation scarcely a single duct conforms in every particular with the specifications. Engineers are now beginning to realize the practical importance of giving each duct a rigid inspection, and rejecting those which have any

roughness or irregularity. Scarcely less important is rigid inspection during installation, in order to assure the most perfect alignment.

Details of Construction. — The following items should be covered:

Conduits. —

Single-way, or four-way.
Holes circular or square with rounded corners.
Maximum outside dimensions.
Minimum inside dimensions.
Minimum thickness of walls.
Shall be free from blisters, cracks and other imperfections which, in the opinion of the Engineer, will tend to injure the cables to be accommodated therein.
Shall be of good quality tile, thoroughly glazed inside and outside.
Shall be straight and true.
Shall be provided with holes for dowel pins if ducts are four-way. Dowell pins may also be called for.
The sides of single duct conduits shall be combed with two (2) sets of three (3) longitudinal combings each, each combing to have a width of one-quarter (¼) inch and a depth of one-sixteenth (1/16) inch. Multiple-duct conduits shall be scored transversely near the ends.
Conduits shall be of stated length. It is usual to call for a certain percentage of shorter lengths (generally 1 per cent), in order to finish runs or stagger joints. The permissible variation from the specified length should be stated.
(If fiber conduit is to be used, substitute the corresponding requirements.)

Cement. —

Shall be of approved brand.
Briquettes made of neat cement and kept one day in air and six days in water shall show a stated tensile strength. A corresponding strength may be similarly required of briquettes made of one part cement and two and one-half parts sand.
Shall be protected from moisture during work.

Sand. —

Shall be clean and free from loam or salt.
Shall be sharp and of stated coarseness.

Stone. —

Shall be of crushed granite, lime stone, trap rock or other approved variety.
Shall pass through a sieve of stated mesh.

Brick. —

Shall be of good commercial hard-burned sewer brick, or other stated variety.

Concrete. —

Stated proportions of cement, sand and stone. (Usually 1 part of cement, 2 parts of sand and 4 parts of stone.)
Maximum size of aggregate. (Usually ¾ inch.)
Sand and cement shall be mixed dry and wetted with only sufficient water to make a stiff paste. The stone having been previously wetted shall be added while wet and thoroughly mixed until all the stones are covered with mortar. It shall then be deposited as rapidly as possible. Machine-mixed concrete will be accepted if made in a manner approved by the Engineer.

Cement Mortar. —

Stated proportions of cement and sand. (Usually 2½ to 1 of cement.)

Concrete mortar shall not be laid in freezing weather, and shall not be used after initial set has taken place.

Excavation. —

Shall always be of such depth as to leave a stated minimum distance between the top of the concrete over the conduits and the surface of the ground.

Ground on which conduits are laid shall be rammed solid before any concrete is laid.

Refilling Excavations. —

The best part of the material excavated shall be used.

Surplus material shall be carted away by the contractor (or will be carted away by the company).

Filling shall be thoroughly tamped and rolled, or flushed, as seems necessary to the Engineer, and shall be done in a manner to prevent, as far as possible, a settling of the earth after completion.

Obstructions. —

Obstructions encountered in the course of the work shall be overcome in a manner to be approved by the Engineer.

Laying Conduits. —

Shall be laid with ends square so as to leave a tight, well-fitting butt joint.

Joints shall be staggered horizontally and vertically.

Conduits shall be laid in a bed of cement mortar of about ¼-inch thickness.

Each joint shall be wrapped with two strips of burlap 6 inches wide and coated with neat cement mortar, the ends of the wrap to lap 4 inches. (It will insure more careful work if it be specified that the contractor shall supply rubber gloves to the men who lay the burlap.) Where conduits are laid on curves, the wraps shall be doubled if required to protect the openings between the ends of the conduits on the outside of the curve, and to exclude mortar from said openings. (This method of wrapping is not universal. If another method is to be used, corresponding details should be given.)

Conduits shall be laid with a mandrel of specified length and width and provided at the end with a rubber washer for wiping the joints.

Conduits shall be laid on a bed of concrete of stated depth, shall be covered at the top with a stated depth of concrete, and shall have a stated thickness of concrete on each side. Where the conduit line goes under railroad tracks, the concrete shall be suitably thickened and reinforced.

If conduits are four-way, they shall be laid with dowell pins at joints.

The alignment horizontally and vertically shall be satisfactory to the Engineer.

Drainage of Conduit Lines.— The grade of all conduit lines shall be such that water cannot stand in the ducts but shall drain into one or both splicing chambers.

Repairing. — All repairing shall be done in a manner satisfactory to the Engineer and the municipal authorities.

Extras. — No extras will be allowed the contractor for irregular work except

Rock blasting, if necessary.

Removal of pipes or other obstructions, if necessary.

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Such work shall not be done without the consent of the Engineer. T
tractor shall specify the cost of such work before it is begun.

Details of Terminals of Conduit Lines. — (Whether they
power stations, etc.)

Splicing Chambers. — Shall be built according to plans supplied
local conditions interfere, in which case the suggested modifications s
approved by the Engineer.

Chambers to be not more than a stated distance apart.

State any details pertaining to the design of the chamber as
supports which may not be clear from the plans.

Tests. — The contractor shall notify the Engineer sufficiently in a
of the completion of the conduits to enable inspection at the factory
arranged for.

Rodding, Cleaning and Wiring. — After the conduits are la
the cement is sufficiently set, they shall be rodded and the contractor shal
after such rods, wire brushes and a mandrel of specified dimensions. All r
and other foreign matter shall be removed. If obstructions are found
cannot be removed by cleaners so as to pass the specified mandrel, the
shall be removed and relaid. Any expense incurred by such work sh
borne by the contractor. A galvanized wire of stated size shall be left i
conduit from splicing chamber to splicing chamber, and sufficient length
be left at each end to permit it to be bent in order to prevent it from sli
into the duct.

Inspection. — During the process of construction, the Engineer re
the right to inspect and the right to reject any and all parts which are not st
in accordance with this specification.

INSTALLATION OF CONDUIT LINES. — The problems conn
with the installation of conduits vary greatly with the local conditions.
involve the choice of trench excavation, drainage, removing or avoidin
structions, concrete mixing and so on. The following details are gleaned
first-class examples of the various kinds of work described but should i
sense be regarded as standard.

Cross-country Conduit Lines. — The excavation for the conduit lin
the American Telegraph and Telephone Company, between New York
Washington, was made partly by a trenching machine and partly by a tr
plow. The trenching machine was of the Austin "caterpillar" type and
a trench 18 inches wide and 3 feet deep at the rate of 3 feet of clean trench
each minute of actual working time. An engineer and two assistants
required to operate the machine, replacing, it is estimated, 50 laborers. O
sections were excavated by a trench plow drawn by two mules or horses.
furrow being made a few inches deeper at each pass, and the loose earth remo
by shovelers. The conduit used in this installation was "pump-log" m
of southern yellow pine 4½ inches square and 7 feet long with a circular
3 inches in diameter. These conduits were creosoted by the pressure pro
with 15 pounds dead oil of coal tar per cubic foot of wood. Splicing cham
having concrete-block walls were built every 500 feet.

A wheel type trenching machine made by Pawling & Hornischfeger Co.
been successfully used by the Wisconsin Telephone Co. This machine h
cutting wheel 7½ feet in diameter, digging a trench 15, 18 or 21 inches wide
with a maximum depth of 5½ feet. The machine weighs 9 tons and is oper
at a speed of 3½ feet per minute, by an operator and one helper.

Conduit Lines for Railroads are usually difficult to construct and op
for the following reasons:

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Owing to the right-of-way being usually on made ground, excessive tities of concrete and reinforcement are required to make a reasonably g duct construction.

Owing to the width of the right-of-way being usually very restricted it essary to shore-up tracks in order to excavate close to them.

) Owing to the vibration caused by heavy trains, it is necessary to bury onduits at a greater depth, first to avoid undue stress on the conduit, and id to avoid crystallization of the cable sheaths.

order to have the conduits below the frost level, the depth of ballast must eglected, as it has been found that with stone ballast on top of the ground, frost penetrates the ground about as far as if the ballast were not there, as the ballast is very dirty.

) There is considerable difficulty in obtaining best results from labor where e are continual interruptions from trains. On a busy section a duct conction gang engaged for ten hours can possibly work two full hours.

;) Owing to the right-of-way being often quite low, in many cases along- of rivers, duct construction is likely to be seriously impeded by the flooding reaches.

5) Where the right-of-way shows signs of settlement, as, for example, on shy ground, continuous piling is necessary to support the ducts. This olves the use of the track for construction purposes for long periods, and reby not only impedes, but also endangers traffic.

(7) Duct-line construction generally involves interference with signal and erlocking apparatus, thereby introducing danger and expense.

8) Bridge abutments, bridges, culverts, and in fact all special right-of-way conoction, present complicated problems which can be solved only at great expense.

Conduit Lines in Cities. — The obstructions due to sewer, water and gas es, car tracks and foreign conduit lines, also render conduit construction in cities a complicated problem. Plans made in the office can seldom be folred in the field, as the municipal pipe plans are seldom reliable, and the ervision of an experienced civil engineer is needed to solve the numerous oblems which constantly arise. Excavation is almost invariably performed hand labor, and when the conduits have been laid and covered with concrete, is usual to lay a plank over them in order that future excavators may not ve picks into them. Obstructions are often avoided by changing the group- ; of the conduits.

Laying Conduits. — Conduits must be laid so that joints are mechanically ong and the ducts unobstructed. With this in view joints should be staggered rizontally and vertically, and each joint covered with a wrapping impervious mortar in bulk. Formerly the wrapping was omitted and the conduits ined with stiff mortar, but this became too expensive when the labor unions sisted upon the employment of masons for this work.

Single-duct Conduits are laid with their joints wrapped in a light- eight fabric saturated with thin cement mortar. In the Pennsylvania Tunnels, anvas weighing 10 ounces per yard was used, and cut into six-inch strips. heese cloth doubled has also et with favor. When laying nduits it is necessary to ve a long mandrel (Fig. 14) remove loose cement from e ducts. This mandrel is sually provided with a rubber asher at the rear, and a hook- ye at the front end. The conduit layer is provided with a hook rod by means f which he draws the mandrel after him as he lays the conduit.

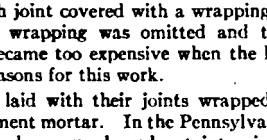
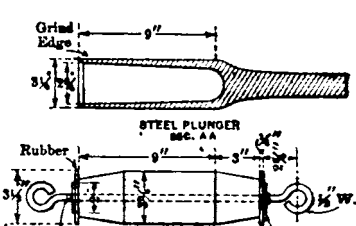


Fig. 14.

Four-duct Conduits are usually provided with holes for dow by means of which the ducts are aligned. The joints are wrapped in soaked in asphalt and afterwards painted with asphalt. No mandrel in this type of construction.

Concrete Covering. — However the conduits may be laid, the group is always inclosed in concrete to secure rigidity and protection finished ducts are cleared of rubbish and obstructions by pushing a steel through them by means of the rods described above. A steel plunger purpose is shown in Fig. 15, in which is also shown a wooden plunger with rubber washers, which should be drawn through the ducts to collect the loose particles left behind the steel plunger.



Steel Plunger, Steel Wire Flue Brush and Wooden Plunger to be passed through ducts in order named.

Fig. 15.

MAINTENANCE OF CONDUIT LINES. — The principal items of conduit-line maintenance are those relating to keeping the line clean and safe, namely, pumping out water, blowing out gas, rem mud, opening and closing manholes for the benefit of cable workers an specting the line to guard against theft and injury. Large systems have u one or more wagons equipped with apparatus required for these purposes, have men ready to go out with it upon emergency calls.

Removal of Water is usually the most important of operating tro especially where no drainage system is installed. When cable accidents o it is important to have the chambers accessible without delay and a por pump is required. For this purpose a small gasoline or electric pump is u having a capacity of about 50 gallons per minute. Such a pump which has good service is of the horizontal centrifugal type with horizontal discharg costs about $200 complete with electric motor, hand priming pump and st rheostat.

Ventilation does not occur naturally in conduit lines, because the cold contained in them has no tendency to rise. Noxious gases therefore tend accumulate in splicing chambers, endangering workers and making explos possible. No permanent system of ventilation has proved successful, as it found that pressure is maintained only at or near the blowing points. Wh it is necessary to blow out the chambers, it is therefore usual to employ a por able blower in conjunction with an air-tight false manhole cover.

Cooling duct lines is sometimes desirable in order to increase the carrying c pacity of the cables in them. L. E. Imlay has accomplished this at Niagara keeping the surrounding soil moist. The Duquesne Light Co. of Pittsbu installed several blowers each of 600 cubic feet per min. capacity and forced into alternate splicing chambers. A reduction of temperature from 125° F 96° F. was obtained.

Protection from theft of cable is secured (1) by locking the inner manh cover and having the lock combination periodically changed; (2) by patrol's

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the line and (3) by using cable differing in some way from that used by neighboring companies, so that it can be easily identified if stolen.

Electrolysis is more fully treated in the article on *Electrolysis*. It should be noted that the prevention of electrolytic corrosion of cable sheaths depends more upon efficient drainage than anything else.

Maintenance of Conduit Lines Along Railroads present the following peculiar operating difficulties.

(1) Owing to the right-of-way being often on made ground, duct lines settle and crack, injuring the cables in them and preventing the removal and replacement of injured cables.

(2) Owing to the great depth of splicing chambers necessitated by railroad conditions, they are often full of water and cannot be cleared for repairs without pumping water out of as much of the system as is at the same level, a process which may take many hours to complete, possibly interfering with traffic during that time. Drainage is usually out of the question, owing to the absence of any kind of a drainage system below the surface system.

(3) The great depth of chambers requires the use of narrow chimneys connecting the chambers to the surface of the ground. This makes it almost impossible for employees to escape from chambers in case of trouble.

(4) Where improvements are made involving the raising of the right-of-way, as, for example, in eliminating grade crossings, ducts laid previous to the improvements become so deep that they are practically inaccessible for repairs and splicing chambers are correspondingly dangerous on account of their distance from the surface.

(5) The existence of water in low splicing chambers renders the cables particularly liable to electrolytic corrosion. This is a very serious matter where the grounded return is only a few feet away, as is almost invariably the case on a railroad. Electrolytic trouble cannot always be reduced by grounding the cable sheaths to the track rails, as such connections are seldom permissible where electric signals are used.

REPAIRS. — The principal repairs to conduit lines are those due to settlement and to damage done by adjacent building operations, such as the construction of sewers or railway tracks. It is sometimes desirable to replace the conduit line without disturbing the cables they contain. In such cases, the conduits are broken, the utmost care being taken to avoid injuring the cables. New conduits are then relaid on a firm foundation, after having been split longitudinally so as to fit over the cables. The whole construction is then rendered rigid by being inclosed in concrete.

COSTS. — The costs of conduit lines published from time to time are of merely local value, the labor of preparing a dry trench free from obstructions being an item whose variations are so great as to render insignificant the items of constant cost. Costs as low as 20c, and as high as $3.00 per duct foot, are recorded.

The items to be considered in making an estimate of the cost of a conduit line are the following, the quantities all being per foot of trench.

Labor: excavating trench; excavating for splicing chambers; boxing and bracing; removing obstacles, such as gas and water pipes; mixing and placing concrete; placing conduit; carting and dumping; repaving; superintendence, outside; office expense.

Material: conduit; manhole and service boxes; covers, shelves, etc.; sand, stone and cement; brick for splicing chambers (unless made of concrete); lumber for protecting top of ducts; lumber for bracing; incidentals.

Depreciation. — (*See also article on Depreciation.*) Conduit lines depreciate

very slowly from the effects of deterioration or obsolescence. There are few conduit lines in existence which have lost much of their value from age unless unforeseen circumstances have deprived them of some useful association upon which their value depended. The value of conduit lines often increases with age especially where they have been laid in growing districts, where the demand for duct space increases more rapidly than the supply.

BIBLIOGRAPHY. — American Electric Railway Engineering Association. *Specification for Electrical Conduit Construction* A.E.R.E.A. Handbook, 1919; Meyer E. B., *Underground Transmission and Distribution for Electric Light and Power*, N. Y. 1916. Reports of Underground Systems Committee of N.E.L.A.

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CONTROL SYSTEMS FOR RAILWAY MOTORS. — (*See also Controllers; Motors; Railways, Electric Traction Systems for.*) The function of the control equipment is to regulate the speed and direction of the motors by certain definite systematic changes in connections. The speed of direct-current railway motors is controlled in two ways: (1) by connecting suitable resistances in series with the motors, which will reduce the voltage across the motors and thereby the current which they will take; (2) by changing the connection of the motors so that they will be connected at first in series, thereby applying half of the line voltage to each motor, and then in parallel across full line voltage. In most control equipments a combination of both methods is used. For the speed control of alternating-current railway motors an auto-transformer, or compensator, is used instead of the resistances.

The direction of rotation of the motors, d-c. or a-c., is changed by changing the direction of the current in either the fields or the armatures; it is customary to connect the terminals of each field coil to a reversing switch in order to accomplish this effect.

TERMINOLOGY. — The following terms are in general use.

Cylinder or Drum Control or Direct Control are names commonly applied to an equipment in which all the connections are made by contacts on a cylinder or drum which is manually operated by the motorman and located on the platform. This may, therefore, be called direct control.

Multiple-unit, Indirect, Remote Control or Train Control are names applied to an equipment in which the changes in connection of the main power circuit are made by switches called "contactors," usually located underneath the floor of the car, and controlled by electric circuits coming from a small master controller on the platform. There are two systems of multiple-unit control in use in this country, viz.,

Sprague-General Electric System. — In this system the contactors are closed by electromagnets which force a plunger against a spring, the latter normally holding the switch open.

Westinghouse "Unit Switch" System. — In this system the contactors are closed by compressed air, from the air-brake cylinders, the air valves at the switches being controlled electrically from the master controller.

Hand Control is a term applied to that method of control in which the motorman has it in his power to regulate the current to any value he pleases by moving the controller handle, the change in connections depending only upon the motion of the latter.

Automatic Control, as distinguished from hand control, is a type of control in which certain automatic devices prevent the motorman from causing the motors to take a current greater than a predetermined value. With this method of control the motors start with a definite current and as soon as the current has decreased to a specified value a change in the connections is automatically made. Thus the rate of acceleration and the current are kept practically uniform throughout the period of control. It is nearly always used in connection with multiple-unit control.

Rheostatic Control consists in connecting a resistance in series with the motor and short-circuiting consecutively parts of this resistance. It is seldom used at present, except on mining locomotives and for single motor operation.

Series-parallel Control, which is used on practically all railway equipments, includes the feature of connecting two motors and their resistances in series on the first step, then short-circuiting portions of the resistance consecu-

tively until all resistance is cut out, under which condition the motors will operate efficiently at approximately half speed. On the next step of the controller the two motors with resistance in series are connected in parallel and subjected to full line voltage. There are three methods of accomplishing the change from series to parallel.

Transition with Power Off. — In the so-called type L controller power is entirely cut off from both motors while the change in connection is being made. This was formerly used for large-size motors and locomotives but is not at present much used.

Transition with Series Resistance. — During the transition from series to parallel a resistance is placed in series with one motor and the other motor is first short-circuited, then disconnected from the main circuit, and finally, placed in parallel with the other motor. This method is in general use in equipments of small motors with the so-called type K controller.

Bridge Transition. — The so-called "bridge" method consists in grouping the motors and their resistances like the arms of a Wheatstone bridge, so that after the two motors are in full-series position the resistances may be placed in circuit again in parallel with the motors, without opening the circuit; the two motors are then connected in parallel with each other and each in series with its own resistance. This method is preferable to either of the other two in that both motors are in operation throughout the whole control period. There is no noticeable jerk and it is not necessary to open the circuit, which would cause flashing at the switches. It is used in certain forms of the K control and in most of the multiple-unit control equipments, particularly for motors of large capacities and for locomotives.

Series-parallel Control with Four-motor Equipment. — Whereas the three methods just described apply particularly to two-motor equipments, they are equally applicable to four-motor equipments by connecting two motors permanently in parallel and treating them as a unit.

TYPE K CONTROL. — The type of control as well as the construction of the controllers for ordinary single-car equipments has been practically standardized in this country, the large manufacturers supplying control equipments which are practically identical. This type of control is known as the type K. The various sizes of type K controllers are listed in the table below.

Where type K controllers are used for motors of large capacity they are sometimes adapted with a modification of the remote control by the addition of two electrically-operated main switches placed underneath the floor of the car, the function of which is to open the main power circuit every time it is necessary that it should be opened and thus remove all flashing and arcing from the controller. This expedient makes it possible to use a smaller controller for a given capacity of motors and obviates all danger to the passengers from fire and fright. The scheme is accomplished by substituting for the main power circuit on the controller an auxiliary circuit carrying only one or two amperes and every time this auxiliary circuit is opened in the main controller the main switches underneath the car open the power circuit. When the auxiliary circuit is closed the main switches close the main circuit. By means of an overload trip operated by a coil in the main circuit these switches are also used as circuit breakers and if the current taken by the car exceeds a certain value a relay opens the auxiliary circuit which in turn causes the main switch to open.

Capacity and Weight of Type K Controllers. — The more usual forms of type K controllers and the capacity in motors for which they are adapted are as follows:

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TYPE K CONTROLLERS

Designation	Number of motors	Total h.p.	Number of points	Weight, pounds*
K-10-A	2	80	5 series 4 parallel	940
K-10-H	2	80	5 series 4 parallel	
K-11-A	2	120	5 series 4 parallel	1020
K-11-H	2	120	5 series 4 parallel	
K-12-A	4	120	5 series 4 parallel	1175
K-12-D	4	120	5 series 4 parallel	
K-28-B	4	160	5 series 5 parallel	1350
K-28-F	4	160	5 series 5 parallel	
K-34-D	2 or 4	360	6 series 4 parallel	2250
K-34-F	2 or 4	360	6 series 4 parallel	
K-35-G	2 or 4	240	5 series 3 parallel	1800
K-35-M	2 or 4	240	5 series 3 parallel	

* Weight includes cables, etc., but not motors.

The 10 H, 11 H, 12 D, 28 F, 34 F and 35 M have auxiliary contactors for opening the main circuit.

The K 34 and K 35 have "bridge" transition. All others short-circuit one motor during transition.

The letter "B" in the designation of a controller indicates that it has contacts added to it to make it possible to operate electric brakes by causing the motors to act as generators to energize electric brake shoes, either of the axle or rim type.

Method of Operation of Type K Control. — The principle of the type K control for small and moderate-size motors is shown in Fig. 1. The controller has an operating handle which moves the main cylinder and thereby changes the connections, and also a reversing handle which moves the reversing cylinder. The latter merely changes the direction of the current through the fields of all the motors with respect to the armature. These two handles or cylinders are interlocked so that the reversing handle can only be moved when the operating handle is in the off-position, thus preventing reversal with voltage on the motors.

One terminal of one of the motors is grounded throughout. The first three points are known as accelerating steps. As resistance is in circuit for each of these points the controller should not be left on any of them for a considerable

length of time, for there is a considerable power loss in the rheostats and t are not designed for continuous operation. The fourth step, full series, is efficient "running point," giving about half normal speed. The next two steps are transition steps and are not marked as points on the controller as they must be passed over rapidly. During this period one terminal of the second motor is grounded, thus short-circuiting the motor which has one terminal grounded initially; the connection between the two motors is then opened; finally the two motors are connected in parallel but in series with a part of the rheostat. Points 5, 6, and 7 are accelerating steps with motors in parallel and resistance in series and are therefore not to be used continuously. At the last point the motors are in parallel, and all resistance is cut out; it is therefore an efficient high-speed running point. The two terminals of the armatures of each motor are led to fingers on the reversing cylinder as are also one terminal of each field and the two points of the main circuit to which the motors are connected. Thus, in reversing, the current is reversed in the armatures, but in the fields.

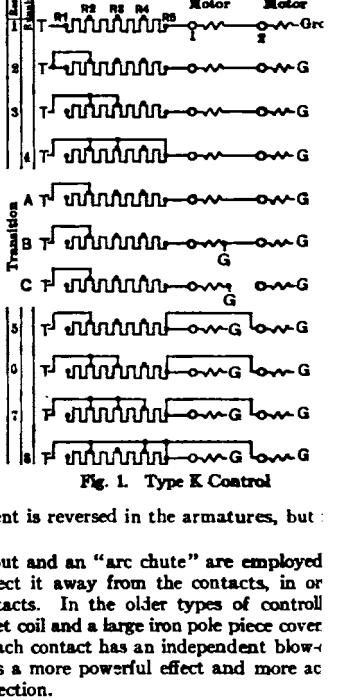


Fig. 1. Type K Control

In all controllers a magnetic blow-out and an "arc chute" are employed interrupt the current quickly and direct it away from the contacts, in or to prevent short-circuiting other contacts. In the older types of controll this was obtained from one large magnet coil and a large iron pole piece cover all the contacts. In the later forms each contact has an independent blow-coil and small pole pieces. This gives a more powerful effect and more ac rately directs the arc in the proper direction.

EFFICIENCY OF TWO- AND FOUR-MOTOR CONTROLLERS. See *Railways, Energy Requirements for*.

REASONS FOR MULTIPLE-UNIT CONTROL. — When the to capacity of the motors on a car or locomotive exceeds 300 horse-power i advisable, and when the capacity exceeds 400 horse-power it is necessary use the indirect or multiple-unit control, for the cylinder type of control required to handle the large currents become too bulky and dangerous to pl on the platforms of passenger cars. The cylinder control is also inadequ when it is desired to control simultaneously the motors on the several cars i train, which is necessary in order to obtain the high tractive effort necessary high-speed service on elevated and underground railways.

For these two reasons the system of multiple-unit or train control was de oped. As originally proposed by Sprague this consisted of a large cyli controller on each car and each controller was actuated by a small motor inst of by hand. These small motors were controlled synchronously from a si point by means of auxiliary control circuits. With the growth in the capa

the motors this system became inadequate and was replaced by the systems w in use.

SPRAGUE-GENERAL ELECTRIC CONTROL. — There are two types use, the type MK and the type MA. The chief difference in these two pes is that the type MK is non-automatic whereas the type MA is provided

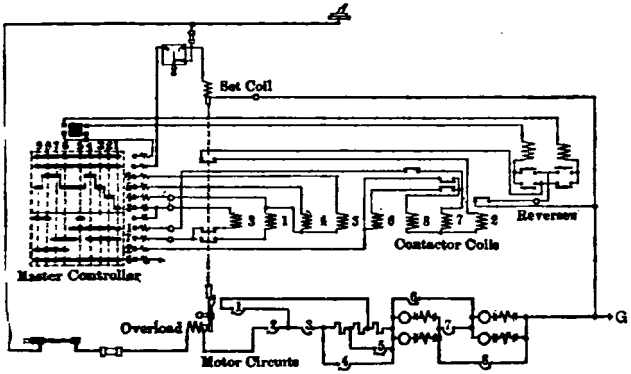


Fig. 2. Sprague-General Electric Type MK Control

with a current-limiting relay. Fig. 2 is a diagram of the type MK, showing the control circuits in light lines and the motor circuits in heavy lines.

The material included in the control equipment of a motor car consists of:

2 master controllers;
1 motor controller containing 8 or 10 contactors and a reverser;
3 master control switches;
1 main switch;
1 main fuse box;
1 set of rheostats;
Cables, Train Couplers.

Master Controller. — This is very similar to an ordinary railway drum-type controller but is much smaller, as the current carried by it is small. Each master controller is equipped with an operating handle, reversing handle, individual magnetic blow-outs and (optionally) a "deadman's handle," which automatically interrupts the current and applies the brakes when the motorman's hand is removed from the button located in the top of the handle.

Motor Controller. — This consists of an iron box lined with asbestos in which the several contactors and the reverser are placed, and is mounted under the car.

Contactors. — Each contactor consists of a powerful magnet operating an arm by means of a toggle joint against a spring pressure. This arm closes and opens the circuit in a strong magnetic field which acts as a blow-out. As one contactor can carry and break currents of several thousand amperes no extra circuit breakers are required. Each contactor is provided with interlocks in the form of relays so that contactor No. 2 cannot be operated until after No. 1 is closed, thus providing the proper sequence of operation under all conditions.

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Reverser. — This is a switch with several circuits and contacts and comparable to the reverser cylinder in an ordinary controller. These contac are mounted on a rocker-arm actuated by two electromagnets, one for movin the switch to the forward and the other to the reverse position. The electr magnets receive their current from the master controller and are interlocke so that only one can be operated at a time.

Switches and Fuses in Control Circuit. — Motor cut-out switches ar located on the reverser to permit cutting out a disabled motor. In the contro circuit there is one main control switch and fuse to protect the control circuits and near each master controller is located a "control and reset" switch, whic in one position closes the circuit to the resetting coil of the overload relay i the main controller and in the other position closes the supply circuit for th master controller.

Main Switch. — A knife-blade switch is placed in the power circuit and i intended to disconnect the motor circuits from the trolley when it is desired t test the motor controller.

Train Couplers are provided where cars are to be operated in trains. Thes couplers or jumpers provide a means of connecting together similar contr circuits of the different cars. They contain from 8 to 12 wires and are s designed that it is impossible to couple the cars together improperly.

Current-limiting Relay. — For automatic control, or acceleration at predetermined current, a current-limit relay is provided on each car and thi prevents each successive contactor from operating until the current in th motors has decreased to a predetermined value. On roads having a fairly lev profile and operating with frequent stops this refinement is desirable, as i makes it possible for the motorman to accelerate the train every time at th maximum allowable rate and yet never exceed that rate except on a dow grade. When this relay is provided the control equipment is known comme cially as the type MA control.

WESTINGHOUSE "UNIT SWITCH" SYSTEM. — The Westinghous multiple-unit control is known as "Unit Switch Control" and is designed eithe for the operation of several motor cars in a train or of single cars or locomotive using either large currents or high voltage. There are four types of unit-swit control classified as follows:

Type H. L. — Hand-operated (non-automatic), using line voltage fo the control circuits and having as many points on the controller dial as ther are steps in the operation; also has a seperate reverser handle. One motor o group is short-circuited during transition from series to parallel.

Type A. L. — Automatically operated, using line voltage for the con trol circuits. The controller dial shows three points forward and three reverse corresponding to switching, series running and parallel running, although ther are more steps in the operation. Uses bridge transition from series to par allel.

Type H. B. — Hand-operated, using current from a storage battery fo the control circuits. Otherwise similar to the H. L.

Type A. B. — Automatically operated, using current from a storag battery for the control circuits. Otherwise similar to the A. L.

Operation of Type H. L. Control. — As typical of all of these classes th diagram in Fig. 3 shows the connections of the H. L. type for a four-moto equipment for either a car or a locomotive (*Cole, Electric Journal, Oct. 1912*)

s many as five motor cars per train may be operated by one man with this ntrol system.

The main-circuit connections are made by means of a number of independent eumatically-operated switches, known as unit switches, each provided with strong magnetic blow-out and normally held open by a powerful spring. he overload trip that controls the opening of all switches in case of overload

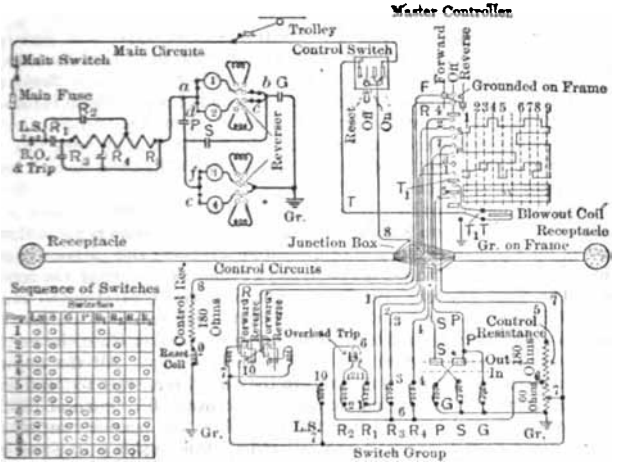


Fig. 3. Westinghouse, Type H. L. Unit Switch Control

r short-circuit is actuated by the magnetic pull produced by one of the blow-nt coils, which is in the main circuit. When a predetermined current value is ceeded, a plunger carrying two contact discs breaks the control circuit, which uses certain switches to open in the line and switch group. This trip can nly be reset when the controller is in the off-position.

A pneumatically-operated reverser controls the direction of operation of the ar. This reverser consists of two pistons similar to those attached to the unit witches, which serve to move the reverser drum to forward or reverse position. The air-brake system furnishes compressed air for operating the reverser and witches.

A multi-conductor train line extends the length of each car and is tapped off at the master controllers and at the unit switch group to form the circuits needed. This train line is made continuous throughout a number of cars by multi-conductor jumpers between cars fitted into receptacles on each car. The current for the electromagnets which operate the valves of the unit switches is taken from low-voltage taps on a resistance connected across line potential.

Operation of Type A. L. Control. — The A. L. control differs from the hand-operated control in that the acceleration of the train is automatic. The master controller has only three positions, switching, series running and parallel running. The "off" position is in the center. The unit switches are provided with interlocks which are electrically connected with the valve magnet in such a manner that the closing of one switch energizes the magnet of the next, thus producing automatic progression of the switches, under the direction of the limit switch. This limit switch controls the rate at which the resistance

is cut out of circuit so as to give uniform accelerating current. The limit swi consists of a solenoid operated by the current of one motor or a pair of mote When this current exceeds a specified limit for which the switch is adjusted, t circuit is opened through a pair of contacts in the operating circuit. The circ remains open so that no more unit switches can close until the accelerati current falls below the predetermined limit, when the control circuit is ag closed and allows the unit switches to continue their progression.

Operation of Type PK and PC Control. — This type was first int duced in 1914 and is a simplification of the older Multiple Unit Systems. uses air from the air brake system to operate the switches in groups thus requ ing only two or three air cylinders and valves instead of many which is the ca of its simplicity and improved reliability. The two forms PK and PC are ma by different manufacturers but are sufficiently similar so that cars with bo forms may be operated in the same train. On account of its cheapness, it is qu generally used for single cars as well as trains.

The PK (manufactured by the Westinghouse Co.) is the simpler as it mer consists of a standard form K controller (which see) whose drum is rotated, not by notch, by a pair of electrically controlled air cylinders and pistons to whi is added an air operated main-line switch and a cylinder for rotating the reversi drum. The small Master Controllers on the platforms control small curre at low voltage in 7 or 9 control wires which admit or exhaust air at definite int vals to the cylinders which move the reversing drum, open or close the main-li switches and advance or return the main control cylinder. All the apparat except the master controllers is underneath the car. From start to "full serie the change is gradual and automatic under the control of a "current-limiting device, and similarly from series to "full parallel." The master controller h three positions "Off," "Series" and "Parallel" thus making it possible f equipments with different numbers of steps to be operated in the same tra It is possible to adapt old "K" controllers by merely adding the "PK Hea and main line switch to one of the old controllers and placing it underneat the car.

The "PC" Control (manufactured by the General Electric Co.) uses a simil combination of electrically controlled pneumatic cylinders to rotate, notch notch, a main cam shaft and the cams on this shaft open and close spring actuat switches or "Contactors." These cam operated switches cut out the starti resistance and change the motor connections from series to parallel. Cams al operate the main line switch while other cylinders actuate the reversing dru The main line switches have suitable magnetic blow-out coils and serve as a c cuit-breaker by means of a series trip coil.

The advantages claimed for both forms of this type of control are:

1. All power circuits and the weight of the main control apparatus are remov from the car platforms, i.e. the system is operated by remote control.

2. The main line current is always broken by large, suitably design switches.

3. Multiple unit operation may be secured with less apparatus and therefo adapted to smaller equipments.

4. The operation of the switches being mechanical it is more positive a therefore the time element is definite.

5. Automatic or selective acceleration may be provided with less complexit

6. A greater number of motor cars may be operated in multiple in one trai (16 motor cars in one train is claimed).

7. The current from the control circuits is so small that storage batteries ma be used, thus making this control easily adaptable for operation on a-c. or hig voltage d-c. systems.

SPECIFICATION FOR MULTIPLE UNIT CONTROL EQUIPMENT.

The following memoranda are intended to assist in writing specifications for complete equipment for the electrical control for a multiple unit car or locomotive exclusive of motors and collecting shoes. See also article on *Specifications*.

Give a complete description of the service in which the equipment is to be used, including the maximum number and weight of cars or locomotives per train.

Similar motion of the master-controller handle shall always produce similar train motions.

A device shall be provided (this is optional) which will limit the rate at which the controller increases the motor voltage, and will assure even acceleration without surging, at the changes from series to series-parallel, and series-parallel to parallel, etc.

A relay shall be provided (this is optional) limiting the current to a specified maximum. (The use of such a relay is more usual on heavy, than on light, equipments.)

Provision shall be made so that acceleration can be arrested at any position of the master controller and so that the motor-circuit combinations shall never be beyond the position indicated by the master controller.

The controller shall automatically return to initial or open-circuit position when the general current supply fails, and when current is restored the control shall progress, as specified, to its former advanced position.

The reverser shall be interlocked so that it cannot be thrown when the motors are taking current.

The control apparatus shall operate satisfactory with a maximum line voltage of . . . . and a minimum line voltage of . . . . and shall never take current exceeding . . . . amperes per car.

In the event of a train breaking in two, provision shall be made so that power shall be cut off from the detached rear portion without affecting the control of the front portion.

The master-controller handle shall be designed (this is optional) so that if the motorman releases it while operating a train, the power will be automatically cut off.

State whether controller is to be interlocked with air brakes.

Main circuit switch (for street cars only) shall be within easy reach of motorman at each end of car.

Each car or locomotive shall be provided with a control-circuit cut-out switch, which will enable the contactors on any car or locomotive to be disconnected from the control circuits.

Each car shall be provided with an automatic circuit breaker and devices for tripping it from any car of the train.

Number of motors	H.P. of each motor	Type of control	Weight of control equipment, pounds	Weight of each motor, pounds	Total weight of equipment, pounds	Cost of equipment, dollars
4	25	*K*	1200	1900	8,800	2400
4	50	*K*	2200	2450	12,000	3600
4	75	*K*	2200	3200	15,000	4800
4	75	Multi-unit	2800	3200	15,600	5100
2	125	Multi-unit	2700	4150	11,000	4000
2	200	Multi-unit	3200	6400	16,000	5600

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CAPACITY, WEIGHT AND COST OF CONTROL EQUIPMENT. — The preceding table gives the capacity and weight and the approximate costs of some typical control equipments.

CONTROL OF HIGH-VOLTAGE D-C. MOTORS. — The motors operating on systems of from 1200 to 1500 volts are usually designed to operate two in series, thus each receives normally 600 or 750 volts. However, the insulation of each motor must be designed to withstand the whole line potential and each motor must be able to withstand momentarily the line voltage across its commutator, for if one motor slips the voltage will be unevenly divided between them. For operation on high voltage two motors in series are normally treated as a unit and the series and parallel connection made with the double units. The multiple-unit control is preferable with these high voltages and contactors or unit switches similar to those for 600 volts are used. To operate the control it is customary to supply a self-starting dynamotor (q. v.) which provides 600 volts for this purpose as well as for the lights and other auxiliary apparatus.

Provision for 600-volt Operation. — Since these equipments usually operate also over 600-volt sections of road, provision has to be made to change the connection of the dynamotor when the transfer is made. If the cars are to operate at reduced speed on the lower voltages, as is usually the case on entering the city districts, no change need be made in the motor connections. But if the cars must operate at 600 volts at high speed over an interurban section then provision must be made to separate the pairs of motors so that all motors will be in parallel for full-speed operation on 600 volts. This requires a commutating switch with automatic protection in order to provide that it is always changed when the car passes from one section to another.

2400-volt Systems. — For locomotive work 1200-volt motors are constructed to operate two in series on 2400 volts. The control for such a locomotive is similar to the control for a 1200-volt equipment.

CONTROL OF A-C. COMMUTATOR MOTORS. — A transformer or compensator is always used to transform the line voltage (3000, 6000 or 11,000 volts) to a voltage suitable for the motors, which is usually from 400 to 500 volts for two motors in series. Taps on the low-voltage side of the compensator (or auto-transformer) provide the various voltages necessary to start and control the motors and thus there is no need of series-parallel control or rheostats, and the energy lost in the rheostats is obviated. A compensator or auto-transformer is usually preferred to a transformer as it is lighter for a given capacity. It is usually placed in oil in a tank suspended from the bottom of the car body. Fewer steps (5 or 6 in all) are required for the control of a-c. motors on account of the reactance of the circuits. To avoid open circuiting the connection to the motors in changing from tap to tap or short-circuiting the portion of the transformer between the taps a "preventive resistance" is connected in the circuit momentarily during the transition. A reverser is provided to reverse the connection of the series fields or exciting windings.

The control may be either of the cylinder or multiple-unit type. In the former type a standard controller may be adapted for the work. If the multiple-unit control is used the cores of all the magnets and contactors must be laminated iron and a special design of magnet used on account of the differences in characteristics of a-c. and d-c. magnets. In some a-c. multiple-unit equipments a storage battery is used to supply current for the control circuit, in which case d-c. electromagnets may be used in the contactors.

Provision for D-C. Operation. — For operation on direct current as well as alternating current provision must be made to perform the following operations:

(1) cut the transformer out of circuit, (2) connect the motors for series-parallel control, (3) connect rheostats in circuit, (4) change the field connection of the motors, (5) change the connections of the compressor motors, (6) change the connections of the lighting circuits. All this is done by a "commutating switch" which is thrown over at the instant the change is made. This is so arranged that it can only be moved when the controller is at the off-position. The commutating switch is frequently operated automatically, so that when the car reaches a dead section of the trolley between the a-c. and d-c. sections, a no-voltage release throws everything to off-position and when the car reaches the new live section a "selector" coil moves the commutating switch to the proper position.

CONTROL OF THREE-PHASE INDUCTION MOTORS. — Three-phase induction motors for railway work may be controlled by three methods, viz: (1) Changeable pole windings, (2) concatenation of two motors, (3) variable resistance in secondary.

The first two methods were given a considerable trial by German manufacturers some years ago, and have been practically abandoned on account of their complications. In addition to their complications the variable resistance method must also be used with them to provide the smaller gradations of speed.

Variable-resistance Methods. — The secondaries of the motors have a definite winding and the terminals are brought to collector rings by means of which a three-phase starting resistance is connected into the circuit. The speed of the motors is controlled by varying this resistance. Under these conditions the operating characteristics of the motors are similar to those of a d-c. shunt motor. At all fractional speeds a considerable amount of energy is wasted in the rheostats and there is only one efficient running speed. For prolonged running at fractional speed the rheostats must have considerable heat-dissipating capacity. To reverse the direction of the motors a reverser is employed which reverses the connections of two of the three primary leads on each motor. Either the cylinder or multiple-unit control may be used. With induction motors it is desirable to provide a separate set of resistances for each motor to avoid the tendency of the motors to exchange current and "buck," which would occur if the driving wheels were not of exactly the same diameter and one set of resistances were used for all motors. With several induction motors on one car it is desirable to accurately maintain the same diameter of driving wheels on all axles in order to divide the load equally between the motors.

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CONTROLLERS. — (*See also Control Systems for Railway Motors; Regulators; Rheostats; Switchgear Equipment for Power Stations.*) Any device for regulating the current or voltage of an electric circuit may be called a controller. Various kinds of controllers have been given different names by users and manufacturers.

DEFINITIONS. — To avoid confusion the various names are used throughout this book as defined below.

Compensator or Induction Starter, an auto-transformer for supplying reduced voltage to the terminals of an induction motor during acceleration; see *Starters, Motor.*

Controller, a device which controls, in some predetermined manner, the operation of the apparatus to which it is connected; generally it controls the running speed of a motor. This article deals only with the latter type A controller frequently combines starting with running features; see *Starters, Motor.*

Regulator, any device for adjusting the voltage of a circuit. A compensator is a special form of regulator. The term regulator is sometimes reserved for devices which utilize inductive action for their control properti s; such a device will be designated specially as a potential regulator; see *Regulators.*

Resistor, the resistance portion of a controller or starter, through which flows the main current of the circuit whose voltage is controlled. A field rheostat is any device employing a variable resistance to control the voltage across the field windings of a generator or motor. The field rheostat of a d-c. motor indirectly controls the speed, because it controls the voltage and current of the field winding; see *Rheostats; Starters, Motor.*

Motorstarter, a controller designed for accelerating a motor to normal speed in one direction of rotation.

FUNCTIONS OF CONTROLLERS. — Controllers are designed to be used with motors of different kinds and to take care of the functions not incorporated in the motor design in order to enable the latter to operate under the specified conditions of load. The functions usually supplied by the controller are the following:

To limit the current during the acceleration of the motor.
To limit the torque during acceleration.
To change the direction of rotation of the motor.
To limit the load on the motor.
To disconnect the motor on failure of voltage.
To regulate the speed of rotation.
To start and stop the motor at fixed points on the cycle of operation, or at the limit of travel of the load.
To stop the motor.
To protect the operator from injury.

Not every controller has to embody all of these features in the same degree but these are the underlying points of controller design and they must be procurable when they are needed.

TYPES OF CONTROLLERS. — Controllers may be divided into the following classes: Face-plate, drum, drum-contactor, and magnetic contactor, controllers.

Face-plate Controller. — The simplest form of controller for starting and regulating the speed of d-c. motors is the face plate type shown diagrammati-

cally in Fig. 1, and intended for use with a variable speed motor connecting resistors in the armature and field circuit. With this type of controller the contacts are mounted on the face of a suitable base and a moving arm makes the connections to the armature and field circuits, the speed of the motor being changed by varying the field strength. The rheostat arm is made in two parts, the under part making contact with the segments R–1 to R–12 and with the contact ring E, while the top arm engages the upper row of round contacts. When starting the two arms are held together by a spring. The bottom arm is provided with a notched segment engaging the plunger forming part of the low voltage release magnet. The notched segment and pawl hold the arm in any operating position after the low voltage magnet is energized. To start the motor

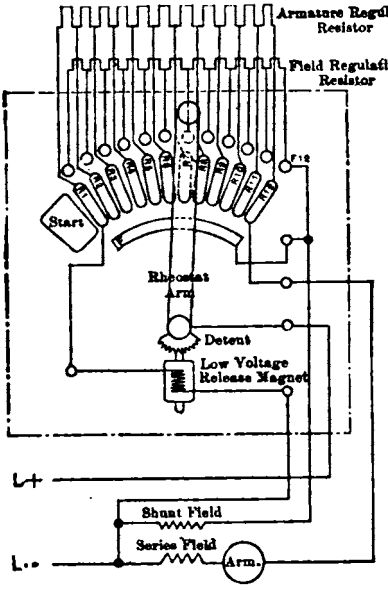


Fig. 1.

the contact arms are moved from the off position to contact R–1, and the connections can readily be traced from that point. The arms are gradually moved to the right eliminating successively each section of the armature resistor until the bottom arm makes contact with R–12. In this position the armature is connected directly across the lines and the segment E is disconnected from the rheostat arm. The shunt field circuit now is from the positive side of the line to the upper rheostat arm to the right-hand field contact F–12, thence to the field winding. This gives a motor speed due to full field strength. If it is desired to increase the speed of the motor the upper arm can be moved to the left across the field contacts to insert resistance gradually in the shunt field circuit, and thus within its range, give the increased speed desired, while the low voltage release magnet holds the lower arm on contact R–12. If the circuit is interrupted the low voltage release magnet will allow the lower arm to be carried to the off posi-

tion by means of a spring. This in turn picks up the upper arm and the two are moved quickly to the off position.

Drum Controller. — Another type of controller in common use is the drum controller. This is used with machine tools for varying the speed and reversing the direction of rotation of adjustable speed d-c. motors by means of armature and field resistance. On the larger sizes magnetic blowouts are used. The drum controller usually has two rows of contact fingers attached to the framework of the controller but insulated from it so as to be electrically separated from each other. Between these rows of fingers is mounted an insulated cylinder or drum which is revolved by the handle. On this drum are mounted copper segments of different lengths which engage the contact fingers. The length and location of these segments are such as to make different connections for each position of the controller handle.

Drum-Contactor Controllers. — A type of controller which, due to its wide application has found very extensive use, is the drum-contactor controller. It is used with series and compound wound motors for adjusting the motor speed by regulating the resistance in series and shunt with the motor armature or for crane hoist service requiring graduated dynamic braking while lowering. This controller consists of a series of spring closed contactors mounted on steel rods and a cam shaft for operating these contactors. In outward appearance it resembles an ordinary drum controller and in internal appearance and operation it is very similar to the magnetic contactor controllers, except that the contactors are operated by a cam shaft instead of by magnetic coils. The line contactors are provided with magnetic blowouts and the same type of rolling contact is used as has been so successful on magnetic contactor controllers. It has relatively quick make and break in operation, is small in size and is easy to operate and inspect. Repairs can be easily and cheaply made. Contacts have exceptionally long life.

Magnetic Contactor Controllers. — These controllers have many advantages which, notwithstanding their increased initial cost, recommend their use wherever rapid and frequent operation is required or where continuity of service is essential. These controllers consist of a series of magnetically operated contactors and accelerating relays which first connect the motor to the line with all resistance in circuit and gradually cut out resistance in series with the motor armature. The rate of acceleration is always dependent on the load of the motor. They are absolutely positive in operation. The motor may be completely controlled by a small master switch, field rheostat, or push button station, any one of which may be placed at a distance from the controller proper. The motor is always accelerated at the proper rate and can be provided with protection against overload and voltage failure. All safety features can easily be incorporated.

CONTROLLERS FOR INDUCTION MOTORS. — Controllers with squirrel cage secondaries usually operate by supplying the motors with various voltages obtained from transformer taps. If the motors are provided with wound secondaries the controllers frequently operate by varying the resistance in the secondary circuit. The resistors must then be designed to carry the running current of the motor continuously without overheating (*see Motors, Polyphase Induction; Starters, Motor*).

With a reversing motor, as in crane or rolling mill service, a similar method of control is used except that the controller is provided with two drums which are operated by a single handle. Primary reversing contacts are located on one drum so that the motor will run in one direction when the handle is turned to the right, say, and in the reverse direction when it is turned to the left. In going from the off position the first step connects the primary circuit of the motor

e line and subsequent steps cut out the secondary resistance. In passing full speed in one direction to full speed in the other the resistance is all cut circuit before reversing. In the off-position the motor is entirely disconnd from the line.

e of Contactors with A-C. Controllers. — For reversing mill or hoistork using induction motors with wound secondaries many very ingenious ighly satisfactory installations have been put in service which use solenoidted magnet switches, or contactors, for the secondary and occasionally e primary circuits. These are worked from a master controller or similar e, or are operated automatically by the positions of the rolls, hoist, etc. matic acceleration can be obtained in the same manner as with directst motors and various safeguards, such as dynamic breaking, can also be oyed.

Automatic Control of Input to Flywheel Motor-generator Set. — her application for contactor control with automatic features is with eel motor-generator sets which use a very heavy flywheel in connection a d-c. generator and an a-c. motor with wound secondary. The power nto the flywheel or delivered up by it depends upon the variation in speed e motor generator. By varying the resistance in the motor secondary peed regulation can be secured. By the use of suitable relays the input e motor and consequently the load on the a-c. system can be kept practiconstant, while the output of the d-c. generator supplying power to a d-c. or rolling-mill motor is undergoing wide fluctuations, the energy in the eel taking care of the difference between the constant input and the variable t. See also article on *Flywheels for Load Equalization*.

OST OF CONTROLLERS. — The following figures will serve as a rough ation of the cost of various sizes and types of controllers. Costs of conrs vary through wide limits depending upon the design, the amount of l variation desired, etc.

COST OF CONTROLLERS FOR 220-VOLT MOTORS *

H.P. of Motor (approximate)	5	25	50	100
e plate type speed adjusting	$38	$70	$100	$220
m type	64	100	158	...
m contractor	85	155	125	...
gnetic contactor L.V.–O.L. Reversing	318	377	545	887
ersing controllers for wound rotor induction motors	80	100	200	400

*ntrollers for 110 and 550 volts cost relatively the same as for 220-volt motors.

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CONVERTERS, SYNCHRONOUS OR ROTARY. — (*See also* i *erators, Alternating-current; Generators, Direct-current; Motor Generators; Ma Synchronous; Transformers; Substations, Railway.*) Since in general it is n economical to transmit electrical energy in the form of alternating curr and more convenient to utilize it in the form of direct currents, some m of converting from one form of electrical energy to the other is desirable. this purpose synchronous converters and motor-generator sets (q.v.) are a able. Synchronous converters are also called "rotary converters."

A synchronous converter is a machine very similar to a d-c. generato which certain commutator segments, or the conductors connected to them, connected to 2, 3, 4 or 6 collector rings as the case may be. When the mov member is caused to rotate, the voltage between any two collector rin alternating. Such a machine, when driven by an engine or motor, ma operated as an a-c. generator or as a "double-current" generator giving a nating current from its collector rings and direct current from its commut If the collector rings are connected to a source of alternating currents machine will run as a synchronous motor and direct current may be obta from the brushes on the commutator; i.e., the machine, with but one s windings acts simultaneously as an alternating-current motor and a di current generator. It has therefore the friction, core-loss and excitation of one machine instead of two, and since the motor and generator currents in the same winding and during at least the major part of each cycle a opposite directions, they more or less balance each other and the arm RI^2 loss is much less than in either a motor or generator alone.

Synchronous Converter versus Motor Generator. — A convert much more efficient and weighs and costs less than a motor-generator s the same capacity. It also occupies less space. However, since only winding is used, there is a definite relation between the e.m.f's. of the a-c. d-c. terminals. The maximum value of the alternating wave bears a de relation to the direct e.m.f. (*see below*). It is therefore necessary to su the converter with a voltage of the same order as the direct voltage and involves the use of transformers, if a high-voltage transmission line is us supply the converter. Motors operating at voltages as high as 13,000 can be used in motor-generator sets.

Relative Efficiencies. — The efficiency of a converter is in the n borhood of 93 per cent and of the transformers 97 per cent, thus the effic of the combination is about 90 per cent. The efficiency of a synchronous m is in the neighborhood of 93 per cent and of a d-c. generator 92 per cent, the combination motor-generator set has an efficiency of 85.5 per cent the supply voltage is greater than 13,000 volts, transformers will also be n for the motor-generator set and the net efficiency would then be 83 per ce

Synchronous Converter versus Rectifiers. — A converter differs fr rectifier (q.v.), since the former gives a direct e.m.f. of constant and uni value and the latter gives a pulsating unidirectional voltage and current the former the energy is stored in the form of magnetism for an instant wh in the latter there is no magnetic field and no storage of energy. A re will not work satisfactorily on an inductive d-c. circuit but a converter will

APPLICATION OF CONVERTERS. — The most common applic of synchronous converters is in electric railway work. The great majori motors for electric traction are direct-current series type, operating at 500 to 600 volts. The energy for these motors must be transmitted over distances, which requires a high voltage a-c. transmission line and conv to link the d-c. distribution with the a-c. transmission. Converters hav

developed for high voltage d-c. traction systems, these converters giving volts d-c. Two such converters may be connected in series for 3000 volt distribution (*Elect. J. 12, p. 154, Apr. 1915*). Synchronous converters are used for lighting and power service and for electrolytic work.

TERMINOLOGY. — The following terms are used to describe certain characteristic features of the various kinds of synchronous converters.

Phases and Rings. — A single-phase converter has two collector rings and ring is connected to the windings by as many equally spaced taps as there pairs of poles. The taps for the two rings alternate at equal spaces. A single-phase converter is therefore a two-ring converter.

A three-phase converter has three rings and three equally spaced taps (one each ring) for every pair of poles. A four-phase or quarter-phase converter four rings and four taps for every pair of poles. A six-phase converter has rings and six taps per pair of poles.

Shunt and Compound-wound Converters. — A converter may be shunt compound wound, depending upon the service for which it is intended. series winding is intended to make the converter take leading current when load increases and thus increase the voltage at the a-c. terminals, but the of the a-c. *terminal* voltage to the d-c. voltage remains unaltered.

Inverted Converter. — Sometimes a converter is operated to convert from to a-c. It is then called an "inverted converter." The machine will rate satisfactorily in this manner, but its speed depends upon the nature of -c. load. An inductive load in the a-c. circuit causes the armature to magnetize the fields, with a resultant increase in speed. It is therefore dangerous to operate an inverted converter on an inductive load unless it is provided with a speed-limit device. This effect does not occur when the machine operating as an a-c. motor, since its speed is fixed by the frequency of the supply circuit.

Cascade Converter or Motor Converter. — This is a combination of an induction motor and converter connected in series or concatenation (*see Motors*, Sections). The converter receives half the power in mechanical form from the shaft and half the power inductively, in the form of alternating current at half frequency, from the secondary of the induction motor. By this means the steady load of a 30-cycle converter is obtained in a 60-cycle unit.

Split-pole Converter. — The "split-pole" or "regulating-pole" converter is used to give a variable ratio of alternating e.m.f. to direct e.m.f., for operation in parallel with storage batteries and similar purposes. The field poles are divided into sections the excitation of which may be controlled independently. The effect of the split pole is primarily to produce a third harmonic in the flux distribution curve, which increases or decreases the *total* flux per pole and thereby the d-c. voltage, but does not change the a-c. counter e.m.f. between slip rings, since these rings are connected to the armature winding at points 120 electrical degrees apart. Split pole converters give a voltage variation of about per cent.

Converter with Series Booster. — A synchronous converter with series booster is sometimes used for purposes similar to those of the regulating pole converter. It is merely a converter with a separately excited a-c. generator on the same shaft as the converter, and the armature of this generator is connected in series with the converter armature and the line. This generator acts as a-c. booster and raises the line voltage.

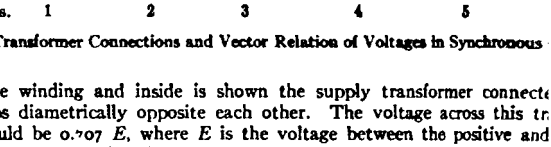
RATING AND PERFORMANCE. — The standards of the A.I.E.E. specify a maximum rise of 50 degrees C. on any part of the windings and

70 degrees on the commutator for continuous operation. Son are more conservative in their continuous rating and give the temperature rise after operation for two hours at 25 pe occurring immediately after a continuous run. Twenty-five will give momentarily an output of three times their normal rati age or injurious sparking at the commutator, but sixty cycle con sensitive to overloads.

PRINCIPLES OF CONVERTER ACTION. — In this se treated those features of a synchronous converter, in whic differs in action from an a-c. or d-c. generator; see table on summary of the voltage, current and capacity relations.

Connections and Voltage Ratios. — The ratio of voltage c to that on the d-c. side depends upon the number of rings an nection employed.

Two-ring Converter. — The two collector rings are taps to the same winding as the commutator; hence the alternat the same value as the direct e.m.f. at the instant that the taps pas As this is also the maximum value of the alternating e.m.f., the e (i.e., the value to be indicated by a voltmeter) will be 0.707 times or 0.707 times the direct e.m.f. Fig. 1 shows in a simple manner t of a single-phase converter. The external circle represents a tw



Figs. 1 2 3 4 5

Transformer Connections and Vector Relation of Voltages in Synchronous

ture winding and inside is shown the supply transformer connect taps diametrically opposite each other. The voltage across this tr would be 0.707 E, where E is the voltage between the positive and brushes on the d-c. side.

Four-ring Converter. — If two additional collector rings are c to conductors spaced half way between the former taps, there results the phase converter shown in Fig. 2. The voltage across each supply c transformer is the same as before, but the two voltages will differ in 90 degrees.

Three-ring Converter. — If three collector rings are conne taps spaced 120 degrees apart the e.m.f. between adjacent collector ri be the vector sum of AO and OB in Fig. 3. Since AO and OB eac $0.5 \times 0.707\ E$ the voltage AB will be $\sqrt{3} \times 0.5 \times 0.707\ E = 0.612\ E$. in a three-ring or three-phase converter the voltage between adjacent 0.612 times the direct voltage and the connections of transformer an Figs. 3 and 4.

Six-ring Converter — Diametrical and Double Delta Connec — A six-ring converter may be connected diametrical as in Fig. 5 in whic the voltage of each transformer will be $0.707 \times E$ and the result will be li combination of three single-phase groups. A six-ring or six-phase con

may also be connected "double delta" as shown in Fig. 6, which is similar to the combination of two groups of three-phase delta transformers. In both cases the voltage between adjacent taps of a six-phase converter is 0.355 E.

n-Ring Converter. — In general the voltage between taps of any converter having n equally spaced taps per pair of poles is

$$E_{ac} = \frac{E \sin \frac{\pi}{n}}{\sqrt{2}}.$$

Current Ratios. — To determine the ratio of the continuous current I to the alternating current I_3 per collector ring in a three-phase converter, for example, assume the d-c. output equal to the a-c. input with unity power factor; then

$$\sqrt{3}\, E_3 I_3 = EI,$$

and, from preceding paragraph,

$$E_3 = 0.612\, E,$$

where E_3 = a-c. voltage between lines; I_3 = alternating current per line; E = direct voltage; I = direct current. From these two relations

$$I_3 = 0.94\, I.$$

The ratios of currents for other converters are obtained similarly, and are given in the table on page 296.

In actual practice the current on the input side must be greater than that given by these relations, in order to supply the losses in the converter, and the alternating current will also vary inversely as the power factor, which is taken as unity in the table.

Resultant Coil-Current. — In any machine acting simultaneously as a motor and a generator the two currents must flow in opposite directions, and the current in any particular conductor will be the difference between the two. In any particular coil the direct current is constant in amount and direction from the instant the commutator segment connected to this coil passes the positive brush to the instant it passes the negative brush, and conversely from negative to positive brush. In any coil midway between the a-c. taps the alternating current is a maximum when this coil is half way between brushes (at unity power factor), and the current falls to zero as the coil reaches the interpolar position. Therefore, for the period of time that the direct current in a coil remains constant in amount and direction there is also in it a variable current changing from zero to a maximum and back to zero again. The net or resultant current will therefore have a wave shape and frequency somewhat as shown at R in Fig. 7. The heating in this particular coil will therefore be proportional to the product of the resistance of the coil by the square of this current, and it is readily seen that the power lost is less than that due to either the direct or alternating current alone.

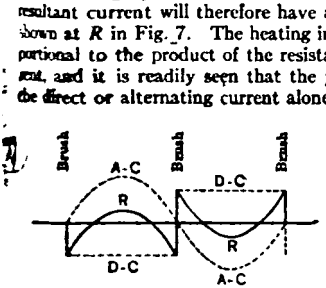


Fig. 7. Current in Coil Midway

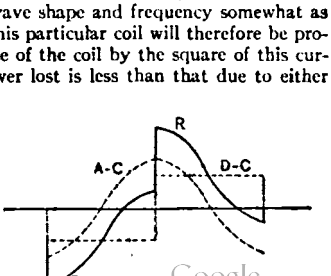
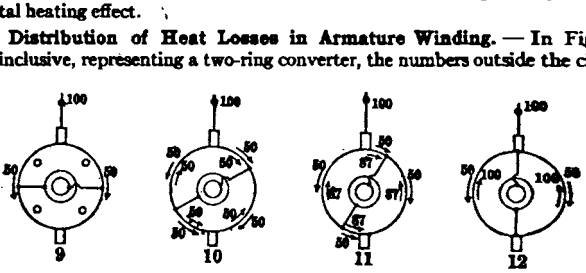


Fig. 8. Current in Coil at Tap in

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A coil situated very near one of the a-c. taps will carry a direct current sub ject to the same law as before mentioned, but the alternating current in th coil is the same as that in the middle coil and has its maximum value when th middle coil is at the middle of the poles and not when this particular end co is at the middle of the pole. The alternating current in this coil may there fore reach its maximum value soon after the coil has passed a brush, as show in Fig. 8, and the resultant of the two currents is greater than that in the midd coil. The further a coil is situated from the middle coil of a group, the greate is the phase displacement of its alternating current, the greater is the value o the resultant current and the greater is the heating effect. Thus although th heating effect in a rotary converter winding is less than that of a direct-curren machine having the same output it is different in each and every coil, is min mum in the central coil (when the power factor is unity) and is maximum i the coil nearest the tap, and the greater the angle between taps the greater the total heating effect.

Distribution of Heat Losses in Armature Winding. — In Figs. to 12 inclusive, representing a two-ring converter, the numbers outside the circl



Component Currents in a Two-ring Converter

represent the direct current in the winding (corresponding to 100 amperes the external d-c. circuit and unity power factor on a-c. side) and the numbe inside the circles the instantaneous alternating current in the winding. It w be seen that the resultant current in a coil midway between taps, Figs. 9 and 1 never exceeds 50 amperes. A coil 30 degrees from the middle, Fig. 10, has maximum current of 100 amperes. A coil 60 degrees from the middle, Fig. 1 has a maximum current of 50+87=137 amperes, and a coil 90 degrees from t middle (tap coil) may have a current of 100+50=150 amperes. The heating the armature winding is therefore not uniformly distributed, though the co duction of heat from one part of the winding to another tends to equalize t temperature rise.

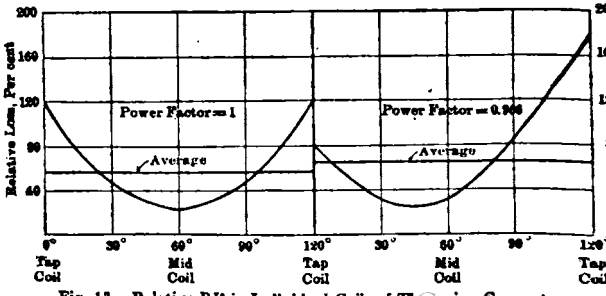


Fig. 13. Relative RI^2 in Individual Coils of Three-ring Converter

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If the converter operates at a power factor different from unity, the position f minimum resultant current is no longer at the middle coil, but is moved ne way with leading current and the opposite way with lagging current. Thus ne end coil has improved heating conditions, and the middle coil and the other id coil have much worse heating conditions, the result being that the heating i a whole has increased and is more non-uniformly distributed than with unity ower factor.

The power lost in each individual coil of a converter and the effect of the ower factor on this loss is very well shown in Figs. 13 and 14, taken from a aper by J. E. Woodbridge (*A.I.E.E., 1908*). In Fig. 13 the curved line shows ne relative RI^2 loss in a coil having any position throughout 120 degrees of ne phase of a three-phase converter when the power factor is unity. The

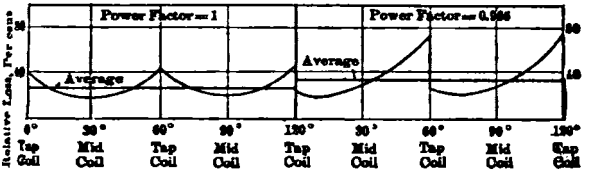


Fig. 14. Relative RI^2 in Individual Coils of Six-ring Converter

ure shows the ratio of the loss compared to the loss in the same machine ning as a d-c. generator of the same capacity. It will be noted that the middle il has a loss of 22 per cent of that of the generator and the end coils 120 per nt., and that the average loss is 57 per cent. For a power factor of 0.966, presenting a phase displacement of current of 15 degrees, the loss in individual ils ranges from a maximum value of 180 per cent at one tap to a minimum ue of 22 per cent in the coil shifted 15 degrees to one side of the middle coil. he other end coil has a loss of a little over 80 per cent of the generator loss. he average value has been increased to 65 per cent.

In Fig. 14 the same ratios are shown for a six-phase converter, in which the nding of one phase is distributed over only 60 degrees. Consequently the nditions are better and the maximum loss due to low power factor is less.

Dependence of Output upon Number of Phases. — As a result of these nditions we have the following relations of the capacity of a given armature th various numbers and connections of taps, the capacity being based on an al total amount of RI^2 loss.

It should be remembered that there are other losses besides coil losses in the nverter, and that therefore practical figures are slightly different from those en in the table on page 296.

Field Excitation. — The variation of the field excitation of a synchronous nverter has much the same effect as in the case of a synchronous motor (*see tors, Synchronous*); that is, if its field is under-excited the armature will aw a lagging current which assists the field and sets up the necessary flux, hereas if the field is over-excited, the armature will draw a leading current hich opposes the field and reduces the flux. By this means the converter ay be made to take either a leading or lagging current. A leading current using over a line having inductance tends to raise the voltage at the receiv- g end of the line.

Line Compounding. — If there is sufficient leading current and suffi- nt inductance in the line, the voltage at the receiving end may be greater an at the sending end in spite of the resistance of the line. This is some-

VOLTAGE, CURRENT AND OUTPUT RATIOS

	D-C. generator	Converters					
		2-ring	3-ring	4-ring	6-ring diametrical	6-ring double delta	12-ring
D-C. volts	100	100	100	100	100	100	10
A-C. volts between lines	...	71	61.2	71	71	61.2	7
A-C. volts between rings	...	71	61.2	50	35	35	3
D-C. amperes	100	100	100	100	100	100	10
A-C. amperes in line	...	141	94	71	47	47	2
A-C. amperes in winding	...	71	55	50	47	47	4
Relative RI^2 loss	100	137	55	37	26	26	2
Relative output:							
Unity power factor	100	85	134	165	197	197	22
87 per cent power factor	...	...	99	115	129	129	13

times called "line compounding." The relation between the voltages at two ends of the line may be expressed as follows:

Let

E = voltage to neutral at sending end;

V = voltage to neutral at receiving end;

I_1 = component of line current in phase with V, i.e., the power compon of the line current;

I_2 = component of line current at 90 degrees to V, i.e., the *leading* reactive c ponent of the line current;

r = resistance of one line;*

x = inductive reactance of one line;*

then, noting that I_2 is to be taken positive when leading,

$$E^2 = (V + rI_1 - xI_2)^2 + (xI_1 + rI_2)^2.$$

Use of Series Field. — In practice a series field is added to the c verter and the shunt excitation is adjusted so that the armature current lagging at no load. As the load increases the series field increases, the adj ment being such that at about ¾ load the proper excitation for unity po factor is given. Hence at all loads over ¾ the field will be over-excited, current will be leading and the voltage will be raised or compounded.

DESIGN. — The design of a synchronous converter is very similar to design of a d-c. generator (q.v.), except for certain special conditions due the fact that the frequency is fixed by the frequency of the supply system, that greater latitude is allowed in the choice of the nominal value of the armature reaction and copper density, because the real value of th quantities is the difference between their nominal d-c. values and th a-c. values.

* r and x should include respectively the resistance and reactance not only of line wire, but also the transformers and reactance coils through which the line cur passes.

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Speed and Number of Poles. — The revolutions per min
mber of poles are definitely related to the frequency of the s
cycles per second, in accordance with the formula:

$$120 \times (\text{frequency}) = (\text{number of poles}) \times (\text{rev. per mi}$$

he choice of the number of poles usually depends upon the com

Commutator. — The design of the commutator is usually the lin
l therefore the first to be considered. This is particulary true o
equency (60 cycle) machines or when the d-c. voltage is 600 or
ctors must be considered in the design of the commutator to sec
mmutation and life of the commutator, namely, peripheral spee
een bars, thickness of bars. If the peripheral speed or the volt
rs is too high commutation will be bad. If the commutator
m the commutator will not retain its shape and commutation
hese three limiting factors are very closely related and in a high
ive give very little choice. The diameter of the commutator d
e voltage and frequency, and its minimum value is given by t
wing relations. Let

s = pitch of commutator bars in inches. This ranges from c
machines to 0.20 in high-voltage or high-frequency mach
in liberally designed machines. These values include t
bar and about 0.03 inch insulation between bars.

V = peripheral speed of commutator in feet per minute. This
3500 in liberally designed low-voltage, 25-cycle machine
60-cycle machines, and is extended to 6000 under compul

e = average volts per bar = machine voltage divided by the nu
between brush studs. Normal values are from 8 to 14. T
voltage between bars is about 1.57 times this.

f = frequency in cycles per second;

E = voltage between d-c. terminals;

p = number of poles;

n = total number of commutator bars;

d = diameter of commutator in inches.

hen

$$s = \frac{Ve}{10Ef}, \qquad n = \frac{pE}{e}, \qquad d = \frac{sn}{\pi}.$$

Armature Ampere Turns and Current Density. — Since the
rmature reactions are opposed to each other the nominal valu
rmature reaction ampere turns may be chosen much higher th
ues and values of from 4000 to 8000 ampere turns per pole ar
ractice. The nominal or apparent value of the ampere conduct
f periphery varies from 500 to 900, and the apparent current den
armature copper from 2500 to 5000 amperes per square inch.

Diameter of Armature. — The diameter of the armature pe
om 3.5 inches to 6 inches, and the diameter is usually from 6 inch
reater than the diameter of the commutator, the difference depend
ossibility of making a good mechanical construction of the end
he number of slots in the armature and the number of segments
mutator must be a multiple of both the number of phases and t
oles.

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Armature Winding. — The winding of the armature is usually of the multi drum type, although the series winding may be used The turns per pair poles are divided by equally spaced taps (to the slip rings) into as many grou as there are phases. The number of turns in series between brushes is a justed for the proper direct e.m.f. and a reasonable value of flux per pole. T alternating e.m.f. bears a definite relation to the direct e.m.f. depending upon t type of connection (*see above*), and also to some extent upon the shape a length of pole arc.

Flux Density in Air Gap. — The air gap or pole-face flux density usual has a value ranging from 40 to 60 kilolines per square inch as in generators.

Damping Copper in Pole Face. — In the pole face of every converter squirrel-cage winding should be provided to assist in starting and to preve hunting. The total cross-section of copper per pole ranges approximate from 1/10 to 1/8 of the armature copper per pole and the end rings must be reasonable cross-section compared to the bars. The joints between bars a end rings must be carefully made.

Shunt and Series Fields. — The determination of the length of armatu length of commutator and the design of the field follow the same laws as t design of these parts for a d-c. generator. The proportioning of the seri field results from the considerations given above under *Field Excitation*, t problem being that a certain amount of leading current is required at a giv load and to make the armature take this leading current the field excitati must be increased by a certain number of ampere turns, from which the nu ber of turns in the series field can be determined.

Equalizer Connection. — In large multi-polar machines it is customary connect to a common ring all commutator bars which are at the same potenti these "equalizer connections" avoid local cross-currents in the armature fr flowing through the brushes and causing bad commutation. These cross-c rents are caused by unequal or uneven air gap.

Shaft, Bearings, Etc. — Since the transfer of energy is in the conducto themselves, there is no mechanical torque other than that to overcome fricti and core-loss. Therefore the shaft, bearings and mechanical housing of a rotary converter are quite light and present no particular mechanical difficulties in mechanical design. For the same reason converters do not require very elaborate foundations. Machines of less than 1000 kilowatt capacity are usually supplied with a base and are complete in a piece, while larger sizes are supplied with foundation plates.

Kw. rating	500	300
Frequency	25	60
Core-loss	1.00	1.75
Armature RI^2	0.55	0 60
Shunt field RI^2	0.70	0.60
Brush RI^2	0.40	0.40
Bearing friction	0.55	1.50
Brush friction	0.30	0.65
Efficiency	96.50	94.50

Efficiency and Losses. — The efficiency and distribution of losses of typical 25-cycle and 60-cycle converter are shown in the accompanying tab All values are in per cent of input at full load.

EXAMPLES OF DESIGN. — In the table on the next page are giv design data on four representative converters of different capacities.

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TESTING OF CONVERTERS. — The following are the usual tests made on converters to determine the efficiency, regulation, heating and to show any defects in construction.

1. **Resistance of Armature, Shunt Field and Series Field.** — The armature resistance is usually measured between points on the commutator diametrically opposite and the equivalent resistance calculated from this value by the equation

$$\text{Equiv. Res.} = \frac{4 \times (\text{diametrical resistance})}{(\text{number of poles})^2}.$$

SYNCHRONOUS CONVERTERS

Design Data

Item	Unit	1	2	3	4
Poles		4	6	6	6
Rating	kw.	500	500	100	300
Speed	rev. per min.	750	500	1000	1200
D-C. volts	volts	600	600	440	600
Frequency	cyc. per sec.	25	25	50	60
Number of phases		6	6	3	3
Armature reaction	amp. turns	15,000	6720	7400	3500
Nominal σ*	amp. cond.	1500	710	675	475
Flux density in gap	kilolines	58	52	23	53
Armature diameter	inches	25.6	36	21	28
Slots per pole		24	24	85%	21
Armature length	inches	11	17.25	7.1	10.5
Commutator diameter	inches	19.7	28	16.5	20
Number of segments		288	288	194	252
Periph. speed of commutator	feet per minute	3800	3650	4300	6280
Volts per bar	volts	8.3	12.5	13.6	14.3
Pitch segments	inches	0.17	0.306	0.266	0.25
Armature diameter per pole	inches	6.4	6	3.5	4.75
Nominal U†	amperes	6000	3600	2630	3400

* σ = ampere conductors (d-c.) per inch periphery.

† U = amperes (d-c.) per square inch.

To obtain the true RI^2 in a converter armature this equivalent resistance is multiplied by the square of the external direct current and by a constant as given in the accompanying table:

	Theoretical	Commercial
Single phase	1.39	1.47
Three phase	0.56	0.59
Quarter phase	0.37	0.39
Six phase	0.26	0.27

These values only hold if the converter is operating at unity power factor. For any other power factor the reactive component of the alternating current per phase must be found and the square of this component times the resistance per phase of the armature gives the additional RI^2 loss due to the lesser power factor.

2. **No-load Saturation Curve.** — The no-load saturation curve, as in a-c. generators and d-c. generators (q.v.) is usually plotted between commutator voltage and ampere turns of shunt field.

3. **Core-loss** as in a-c. and d-c. generators (q.v.).

4. **Phase Characteristic** at no load and at full load as in synchronous motors (q.v.).

5. **Synchronous Impedance** as in a-c. generators (q.v.).

6. **Starting Tests** to determine current and voltage necessary to start the converter on a-c., time to reach full speed, and voltage induced in field windings as in synchronous motors (q.v.).

7. **Heat Run.** — This may be made either with a resistance for load or two similar converters may be tested in parallel by the Hopkinson or "pump back" method; see *Transformers*. In addition to a source of d-c. power of the rated voltage of the converter to supply the losses, either a d-c. booster or an a-c. potential regulator is needed to adjust the load.

8. **Insulation Tests.** — See *Generators, Alternating-current*, and *Standardization Rules of the A.I.E.E.*

9. **Pulsation Test.** — A synchronous converter is very sensitive to any change in impressed voltage or frequency. A sudden change in either of these factors will cause a pulsation which will start the machine hunting, as discussed in the article on *Motors, Synchronous*. This hunting may increase until the machine falls out of step or flashes over. To determine whether a converter has a dangerous tendency of this kind, a test is made in which two similar machines are supplied with power from a common generator. Between each converter and the common connection a resistance is placed in each a-c. line, having a value that will give with full-load current a drop in voltage of 15 per cent of the rated voltage of the machine. Thus there is 15 per cent *RI* drop between each converter and the generator and 30 per cent between the two converters. The two machines are operated at no load and at rated voltage with the shunt fields adjusted for minimum input. The voltage across the commutators is observed for any periodic variation. Then the field of one machine at a time is varied from half normal to twice the normal value and any indications of periodic variations of the direct voltage noted. If the machines have a proper damper winding in the pole faces, they should not develop any dangerous hunting, even under the above unfavorable conditions.

SPECIFICATIONS FOR SYNCHRONOUS CONVERTER. — The following memoranda are intended to assist in writing specifications. See also article on *Specifications*.

Principal Characteristics and Conditions of Service. — Use to which converter is to be put, such as railway, lighting, motor driving or battery charging. Whether it is to convert from a-c. to d-c. or vice versa. Voltages and number of phases. Nominal rating in kilowatts or Institute rating in kilowatts. Frequency and speed.

Style and Description; Details of Construction. — Whether interpole; whether shunt or compound wound, or whether there is a split-pole field winding; whether rheostat is to be supplied for shunt field; if so, its characteristics. Proposed method of starting and whether starting apparatus is to be supplied. Whether a speed-limit device is required; if so, the shunt field rheostat shall have sufficient resistance to speed the machine for testing the speed-limit device, the latter being set at 15 per cent over rated speed. Whether an end play device (or oscillator) is desired and if so, what type or types are acceptable.

Work to be Done by Other Contractors. — Whether the synchronous converter contractor is to furnish and install the following: Main wiring, field

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ring, field-rheostat grids, dial plate and chains, starting panels, starting ostat or motor generator, foundations.

Performance and Tests. — Temperature rises upon which nominal and stitute ratings are to be based. Overload capacity (*see Standardization Rules the A.I.E.E.*). Commutation limits. Efficiency at 25, 50, 75, 100, 125 and o per cent nominal load. High-potential tests of insulation. Requirements garding effect of moisture upon insulation. Converters shall operate in par- el without "hunting" from no load to stated (say 200 per cent) overload, ovided drop in high-tension lines due to resistance between any converter and y other synchronous apparatus in the system does not exceed a stated value ay 20 per cent), and provided that the phase variation does not exceed a stated lue (say 2.5°). What voltage regulation is required, how it is to be obtained d whether it is to be hand or automatic. If the converter is shunt wound, ne voltage-regulation requirements. What per cent reactance between a-c. s and converter is required?

OPERATION OF CONVERTERS. — In the operation of synchronous nverters the points mentioned below should receive special attention.

Transformer Connections. — The usual methods of connecting transformers supply converters are shown diagrammatically in Figs. 1 to 6 and are dis- sed above in the section on *Voltage Ratios* and also in the article on *Trans- mer Connections*. Of the three-phase to six-phase connections the choice ist be made with some care, as all connections are not equally good for each ecific use of the converter.

Methods of Starting. — The several methods of starting converters are as llows:

Alternating-current Starting, which is the same as the starting of otors; *see Motors, Synchronous.*

Direct-current Starting. — The machine is started as a direct-current unt motor and synchronized on the a-c. side after it is up to speed. This quires less power, but takes more time and more skill in order to synchronize. o secure maximum starting torque, the a-c. side should be disconnected from e transformers, which otherwise act as a shunt to a part of the starting current *Veinberg and Smith, Elec. J., 15, p. 24, Jan. 1918*).

Starting with Auxiliary Motor. — This involves the extra cost and tra continuous loss of the auxiliary induction motor. It is no more efficient an starting by direct current and requires the same amount of time. By the se of suitable relays the starting and synchronizing may be made entirely tomatic (*Wensley, R. J., El. Ry. J. 53, p. 948, May 17, 1919*).

Combination Alternating- and Direct-current Starting. — The ma- hine is started up with direct current, then disconnected from the d-c. mains nd connected to a low-voltage tap of the a-c. supply and brought up to full peed. This method is more economical of power and time but requires more tarting apparatus than either the a-c. or d-c. methods.

Field Break-up Switch. — All converters are supplied with a switch to ren the field in several places to avoid the strain of the high potential induced the field during starting and to reverse the direction of current in the field fter the machine is up to speed in order to reverse the polarity in case it should ot be right. This is usually a double-throw switch with several poles.

End-play Device. — In order to prevent the brushes from wearing grooves n the commutator and collector rings a device is mounted upon one end of the haft to move the shaft end-wise back and forth periodically. In small ma-

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chines this is a mechanical device consisting of a ball running between tw warped surfaces. In large machines it consists of an electromagnet whi periodically pulls out the armature a short distance. The magnetic pull of t main field poles pulls the armature back.

Speed-limiting Device. — In case a converter should be disconnected fro the main a-c. generating circuit and still remain connected so that it wou tend to operate from the d-c. side there is danger of its speed becoming dange ously high. To avoid this a centrifugal governor is placed on the shaft a arranged to electrically operate the main d-c. switches of the converter.

VOLTAGE REGULATION. — There are several methods of regulati the voltage delivered by the commutator of a converter.

Compound-wound Converter with External Reactance. — This meth is automatic and will give about 10 per cent variation in voltage. It is standa practice for railway work; see also *Substations, Railway*.

Regulating or Split-pole Converter. — With this type of converter t voltage regulation is gradual and normally accomplished by hand, but by t addition of an automatic voltage regulator may be made automatic.

Shunt-wound Converter with Induction Regulator. — A large variati in voltage is possible but this method does not respond to quick changes. is quite generally used in lighting work.

Shunt-wound Converter with Synchronous Booster. — A synchrono generator is carried on the same shaft as the converter and connected in ser between the transformers and the collector rings of the converter. The meth is good but expensive. G. A. Juhlin (*Inst. El. Eng. J. 55, p. 241, Apr. 191* gives a detailed discussion of the relative advantages of reactance and boost regulation.

Shunt-wound Converter and Taps on the Transformers. — The volta ratio of the transformers may be varied. This is usually accomplished by co necting the line to different taps on the primaries, which involves opening t circuit or short-circuiting a portion of the transformer at each change.

WEIGHTS, SPEEDS AND COSTS: — The weights, speeds and costs four commercial lines of converters are given in the following table. T **costs are based on the 1921 price level.** The first group is a line 25-cycle converters without commutating poles, the second 25-cycle converte with commutating poles. The third and fourth groups refer to 60-cycle co verters without and with commutating poles respectively. It will be not that the smaller ratings are three-phase machines while the greater ratings a six-phase machines. The six-phase connection makes possible a saving material at the expense of increased cost in manufacturing labor. The u of commutating poles also makes possible a considerable reduction in size machine at the expense of increased labor, therefore all the higher capaci machines have commutating poles. The costs given are only approximate, such figures vary greatly with commercial conditions. The machines lis are 600-volt converters for railway purposes. Machines for lower voltages wo be somewhat less expensive.

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WEIGHTS, SPEEDS AND COSTS

25 Cycle non-commutating pole type, 600 volts

Poles	Kw.	R.P.M.	Phases	Weight, pounds	Cost, dollars per kw. in 1921
4	200	750	3	18,000	16
4	300	750	3	20,000	12.50
4	500	750	6	24,000	11
6	500	500	6	27,000	13

25 Cycle, commutating pole type, 600 volts

4	500	750	6	15,000	11
4	1000	750	6	25,000	9
6	1500	500	6	37,000	8
8	2000	375	6	54,000	8
18	4000	167	6	180,000	11

60 Cycle, non-commutating pole type, 600 volts

6	200	1200	3	11,000	12.50
6	300	1200	3	13,000	12
8	500	900	6	18,000	11

60 Cycle, commutating pole type, 600 volts

6	500	1200	6	10,000	10
8	1000	900	6	23,000	12
16	2000	450	6	70,000	17

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CONVEYORS. — (*See also Power Stations; Telpherage.*) A conveyor is a mechanical device for the continuous handling of materials along a horizontal or inclined plane. There are four general types of conveyors, viz., the scraper or flight, the screw, the bucket and the belt.

THE FLIGHT CONVEYOR consists of a trough of any desired cross section through which are pulled a series of scrapers or "flights" attached to an endless chain. The improved forms of this type of conveyor have sliding shoes or rollers attached to the flights or to the chains, supported on runways.

Capacity. — The following table by S. B. Peck (*Trans. A.S.M.E., 1910*) gives the capacities of flight conveyors in tons of coal per hour when the conveyor is operated at a speed of 100 feet per minute.

CAPACITY OF FLIGHT CONVEYORS

Size of flight, in.	Horizontal				Inclined		
	Flights spaced			Lb. per flight	10°	20°	30°
	18 in.	18 in.	24 in.		24 in.	24 in.	24 in.
	Tons	Tons	Tons		Tons	Tons	Tons
4 by 10	33.75	30	22.5	15	18	14.25	10.5
4 " 12	42.75	38	28.5	19	24.5	18	13.5
5 " 12	51.75	46	34.5	23	28.5	22.5	16.5
5 " 15	69.75	62	46.5	31	40.5	31.5	22.5
6 " 18	.....	80	60	40	49	40.5	31.5
8 " 18	.....	120	90	60	72	57	48
8 " 20	.....	...	105	70	84	66.5	56
8 " 24	.....	...	135	90	120	96	72
10 " 24	.....	...	172.5	115	150	120	90
10 " 30	.....	...	220	147	184	146	116
10 " 36	.....	...	268	179	225	177	142
10 " 42	.....	...	315	210	264	210	167

Power Required. — The following formula gives approximately the horse power at the head wheel required to operate flight conveyors:

$$\text{H.P.} = (ATL + BWS) \div 1000.$$

T = tons of coal per hour; L = length of conveyor in feet, center to center; W = weight of chain, flights and shoes (both runs) in pounds; S = speed in feet per minute; A and B constants depending on angle of incline from horizontal and have the following values.

Angle, deg.	A	B	Angle, deg.	A	B	Angle, deg.	A	B
0	0.343	0.01	10	0.50	0.01	30	0.79	0.009
2	0.378	0.01	14	0.57	0.01	34	0.84	0.008
4	0.40	0.01	18	0.63	0.009	38	0.88	0.008
6	0.44	0.01	22	0.69	0.009	42	0.92	0.007
8	0.47	0.01	26	0.74	0.009	46	0.95	0.007

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For suspended flight conveyors take B as 0.8 and for roller flights as 0.6 of the values given in the table.

Screw Conveyors. — Screw conveyors consist of a helical steel flight, either in one piece or in sections, mounted on a pipe or shaft, and running in a steel or wooden trough. These conveyors are made from 4 to 18 inches in diameter, and in sections from 8 to 12 feet long. The speed ranges from 20 to 60 r.p.m. and the capacity from 10 to 30 tons of coal per hour. It is not advisable to use this type of conveyor for coal, except the smaller sizes, as the flights are easily damaged by any foreign substance of unusual size or shape.

BUCKET CONVEYORS are of two types, having rigidly connected and pivoted buckets respectively. The buckets are carried by an endless chain driven by sprockets or pawls. Rigid buckets are used to convey coal and other materials over considerable distances when there is no intermediate point of discharge. They are built to carry as much as 2 tons of coal per minute.

Pivoted buckets may be used both as conveyors and elevators, and are particularly well adapted to the handling of coal and ashes in power plants. Their advantages are slow speed, silent operation, adaptability to change of direction without transfer, high efficiency and easy renewal of worn parts. Their disadvantages are danger of buckets sticking or upsetting and jamming in the supports, and the difficulty of preventing spill at the loading and turning points. Spilling in loading may be prevented by the use of special loading devices, by providing overlapping lips on the buckets or by placing small buckets between the main buckets to catch the spill.

Capacity. — Buckets are usually of 2-feet pitch, and range in width from 18 to 48 inches. They run at low speeds, usually not over 50 feet per minute, 30 feet per minute being the usual speed. At the latter speed the capacities when handling coal vary from 40 tons per hour for the 18-inch width to 120 tons per hour for the 48-inch width.

Power Required. — Prof. E. F. Miller gives the following formula for calculating the power required for a bucket conveyor making a rectangular circuit:

$$P = 0.004\,CL,$$

where P is the horse-power required, C is the capacity of the conveyor in tons of coal per hour, and L is the total lift in feet. This is an empirical formula deduced from numerous data on coal conveyors having capacities of from 20 to 150 tons and operating at speeds of from 40 to 55 feet per minute, and making lifts of from 40 to 80 feet. The power given by the above formula is for the conveyor loaded to its full capacity. The conveyor when running empty will require from 40 to 60 per cent of this. The smaller the conveyor the larger the percentage of power empty to power loaded.

BELT CONVEYORS. — Rubber and cotton belt conveyors are used for handling coal, ore, sand, gravel, etc., in all sizes. They combine a high carrying capacity with low power consumption. In the majority of cases the belt is troughed by means of idler pulleys set at an angle from the horizontal and placed at intervals along the length of the belt. Belt conveyors may be used for elevating materials up to about 23° incline. The belt may be run at any speed from 200 to 800 feet per minute, and may be from 12 inches to 60 inches in width. The most serious objection to belt conveyors is the lack of durability of the belts, their liability to destruction from accidental causes and the expense of their frequent renewals.

Link belts (*see Chains and Chain Drive*) are also used for conveying purposes.

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Capacity. — The following table gives the capacity of the more common size of belt conveyors:

CAPACITY OF BELT CONVEYORS IN TONS OF COAL PER HOUR

Width of belt, in.	Velocity, feet per minute			Width of belt, in.	Velocity, feet per minute				
	300	350	400		300	350	400	450	500
12	34	..	...	20	96	112	128	...	...
14	47	..	...	24	139	162	186	210	...
16	62	72	82	30	218	254	290	326	...
18	78	91	104	36	315	368	420	472	520

For materials other than coal, the figures in the above table should be multiplied by the coefficients given in the table below:

Material	Coefficient	Material	Coefficient
Ashes (damp)	0.86	Earth	1.4
Cement	1.76	Sand	1.8
Clay	1.26	Stone (crushed)	2.0
Coke	0.60		

Power Required to drive a belt conveyor (*C. K. Baldwin, Trans. A.S.M.E. 1908*) depends on a great variety of conditions, as the spacing of idlers, type of drive, thickness of belt, etc. In figuring the power required, the belt should run no faster than is necessary to carry the desired load. If it should be necessary to increase the speed, the load should be increased in proportion and the power figured accordingly.

For level conveyors the horse-power required is

$$P = C \times T \times L \div 1000.$$

For inclined conveyors

$$P = (C \times T \times L \div 1000) + (T \times H \div 1000).$$

C = power constant from table below; T = load, tons per hour; L = length of conveyor, center to center, feet; H = vertical height material is lifted, feet; S = belt speed, feet per minute; B = width of belt, inches.

For each movable or fixed tripper add horse-power in column 3 of table. Add 20 per cent to horse-power for each conveyor under 50 feet long. Add 10 per cent to horse-power for each conveyor between 50 and 100 feet long. The formulas above do not include gear friction, should the conveyor be gear driven.

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	1	2	3	4	5
Width of belt, Inches	*C* for material weighing from 25 lb. to 75 lb. per cu. ft.	*C* for material weighing from 75 lb. to 125 lb. per cu. ft.	H.P. required for each movable or fixed tripper	Minimum plies of belt	Maximum plies of belt
12	0.234	0.147	½	3	4
14	0.226	0.143	½	3	4
16	0.220	0.140	¾	4	5
18	0.209	0.138	1	4	5
20	0.205	0.136	1¼	4	6
22	0.199	0.133	1¼	5	6
24	0.195	0.131	1½	5	7
26	0.187	0.127	2	5	7
28	0.175	0.121	2½	5	8
30	0.167	0.117	2½	6	8
32	0.163	0.115	2¾	6	9
34	0.161	0.114	3	6	10
36	0.157	0.112	3¼	6	10

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COOLING SYSTEMS FOR POWER STATIONS. — When t supply of cooling water is limited or expensive, economy requires that it sh be artificially cooled and used continuously. This cooling is accomplished natural or forced evaporation in open ponds, spray fountains, a series of artific cascades or in cooling towers. The latter device is largely used.

COOLING TOWERS. — Cooling towers are usually made in the sha of large cylinders of sheet steel, filled with narrow boards or laths arranged geometrical forms, or hollow tile, or wire network, so arranged that while t water, which is sprayed over them at the top, trickles down through the spa it is met by an ascending air column. The air is furnished either by disk fa at the bottom or is drawn in by natural draft. In the latter case the tow is made very high, say 60 to 100 feet, so as to act like a chimney.

Make-up Water. — When used with jet condensers, the water produc by the condensation of the exhaust steam is sufficient to make up for the evap ration in the tower, and therefore only enough water for the boiler feed ne be supplied continuously. In fact, the condensed steam is, as a rule, more th sufficient to make up for the loss due to evaporation, and there results a slig overflow, which carries with it the oil from the engine cylinders and tends clean the system of the oil that would otherwise accumulate in the hot-well.

When a cooling tower is used with a surface condenser make-up water m be added to the cooling water, the amount ranging from 3 to 15 per cent, b in this case the boiler feed water can be used over and over again with b slight loss, provided the oil (there is none with turbines) is eliminated by su able separators.

Reduction in Temperature Obtainable. — With a properly design cooling tower the temperature of the hot water (and condensed steam in t case of a jet condenser) can be reduced 40 to 50° F. The water can usually cooled to within 2 to 5 degrees of the wet bulb air temperature.

Power Required for Forced Draft in Tower. — The power requir for the fan, when forced draft is used, averages 2 per cent of that developed the main engines during the summer months, when maximum volume of is required, and about 1 per cent during the winter months.

Cooling Ponds. — Where water for condensing is scarce it is found economi to store it in reservoirs where it is cooled by evaporation. Under the con tions prevailing in northeastern United States it has been found that a surf of 250 sq. ft. is sufficient to cool the condensing water required for one boi horsepower (34.5 lb.) at 26-inch vacuum. In countries where the evaporati coefficient is higher, smaller surfaces may be used; see Ruggles, *Transacti A.S.M.E., Vol. 34, p. 561.*

Spray Ponds. — Where the area available for water storage is small recou must be had to the spray system. Here the warm condensing water is spray into the air above the small pond; a portion evaporates, cooling the remaini portion, which falls to the tank to be used again. The sides of the tank are tended to prevent the spray from being carried away by the air currents. Ab 4 sq. ft. of surface are required for one boiler horsepower of steam condensed 26-inch vacuum. It is even possible in small plants to have the spray pond on t roof of the power house. These ponds should not be used in crowded localit as the spray of water is likely to be a nuisance. The loss of water varies betw the amount of boiler feed and twice that amount.

COSTS (Pre-war figures). — Cooling-tower costs vary greatly with clima and operating conditions. When these are relatively favorable the cost may kept as low as $2.50 per kilowatt for natural draft towers and $3.60 for fan dra

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ler ordinary central-station conditions the costs will probably average $3.50 $5.00 per kilowatt respectively for the two types of towers. Assuming ch vacuum, 70° air and 70 per cent humidity, forced-draft cooling towers about $250 per 1000 lb. of steam condensed. For 24-inch vacuum the cost be one-half this. Natural-draft towers cost about one-half to one-third as th as the forced-draft towers. As a general rule cooling towers do not pay n the pumping head exceeds 75 feet.

lhe following data on spray cooling ponds were given in the *Elec. World*, p. 808, Oct. 9, 1915:

Steam ndensed k. per hr.	Circ. water, gal. per min.	Number of nozzles	Size of pond, ft.	Total cost, pond and equipment	
				Concrete basin	Clay basin
:...000	1320	35	50 ×128	$3385	$2105
2. 500	2420	60	90 × 90	4825	3205
3. 000	4320	110	112 ×120	7710	5010

BIBLIOGRAPHY. — Additional data on cooling towers, ponds and spray ntains and numerous references to original papers will be found in Gebhardt's m *Power Plant Engineering;* Fernald and Orrok, *Engineering of Power* nts; Thomas, C. C., *The Cooling of Water for Power-plant Purposes*, A.S.M.E. ns. Vol. 39, p. 625. See also Kent's *Mechanical Engineer's Pocket-Book*.

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COPPER. — (*See also Electrochemical Processes, Industrial; Wires and Cab Bare.*) The following discussion applies primarily to copper for electri conductors. Copper mined in the vicinity of the Great Lakes is almost pu That derived from the compound ores of the metal must be refined (usua electrolytically) to reduce it to the same degree of purity.

ROLLING-MILL PROCESSES. — The refined copper comes to the r mill in bars weighing about 200 pounds each. These bars frequently ha ridges along the sides, due to faults in castings, and the surface is often cove with a layer of oxide. They are heated in a furnace until sufficiently soft rolling and are passed through a series of rolls diminishing in size until a r of the proper diameter is obtained. The rod is then coiled up and immer in a pickling liquid (10 per cent H_2SO_4) in order to dissolve the oxide form during rolling. It is then washed and dipped in a fluid tallow mixture.

WIRE-MILL PROCESSES. — The rods having cooled are connected gether by brazing and are drawn through a series of dies of decreasing diame The dies give the wire a dense hard exterior coating which increases its tenac As the strength obtainable is almost a direct factor of the work expended up the wire, the smaller the size the greater the tensile strength per square in so that the strength of the wire is readily varied by changing the size of rod and the number of dies.

Defects in Wire. — One of the most serious defects occurring to wire this point is from ridged bars as above described. Ordinarily the bar will be sufficiently heated to dissolve the copper oxide on the surface so that as softened bar enters the first passes of the rolls, the ridges are lapped over, closing the oxide scale. The subsequent passes and the drawing through dies obscure this flaw almost entirely, but it remains a serious menace to toughness and the resistance to wear of the copper.

A second cause of trouble arises at the same point by overheating the cop in the softening furnace, in which case copper oxide is formed on the surf and quickly dissolves through the entire bar, thereby increasing the oxide c tent and tending toward the production of brittleness. Both of these dang can be avoided by careful selection of the bars and by proper regulating of temperature of the softening furnace.

As the production of the hard surface from drawing is at best a rather delic operation, careless handling, uneven welding of the rods and unequal temp ature of the wire while passing through the dies will all produce noticeable effe in the quality of the finished wire, so that care throughout the mill is absolut necessary for the best results.

It, therefore, appears that the most efficient wire must possess not only h conductivity but the maximum torsion and tensile strength possible in co mercial copper and that to obtain this it is first necessary to use high-grade cop and to prevent an excess of cuprous oxide entering it at any stage of the ma facture, and, secondly, to select as perfect bars as possible and to observe extr care in every treatment through which they pass. (*Adapted from article Carl F. Woods, Electric Railway Journal, 1909, Vol. 33, p. 195.*)

ANNEALING. — All wire when first drawn is more or less hard. It may softened by annealing, i.e., by heating to a temperature between 250° to 400 The hardness is not affected by the rate of cooling. Annealed copper has a c talline structure, whereas hard-drawn copper consists of grains elongated in direction of drawing.

MECHANICAL PROPERTIES. — (*See Wires and Cables, Bare, for ta of tensile strength, etc., of various sizes of wire.*) The more important mechan properties of copper are discussed in some detail below,

Tensile Strength and Elongation of Soft Annealed Copper. — The ten- strength of soft annealed copper is about 30,000 to 33,000 pounds per square h with an elongation of about 25 per cent (in 10 inches) at the fracture. It no true elastic limit, permanent elongation being produced by very small ds.

Tensile Strength and Elongation of Hard-drawn Copper. — (*See Wires d Cables, Bare, for tensile strength of various sizes of wire.*) Modern hard-drawn per is equally affected by drawing throughout the section, no hard skin being duced. According to D. R. Pye, hard-drawn copper in wires up to ½ inch meter varies in tensile strength with the diameter according to a linear law the form

$$T = 70{,}000 - 45{,}000\,D,$$

ere T = tensile strength, pounds per square inch, and D = diameter of wire, hes.

The above constants agree approximately with the tables of the American iety for Testing Materials and represent values somewhat under those usu- obtained.

The elongation at fracture is approximately represented by

$$E = 4\sqrt{D},$$

ere E = per cent elongation at fracture.

Tests by G. C. Batson on 50-foot lengths of hard-drawn copper showed a ile strength only ½ per cent less than that of 10-foot lengths, a fact which licates that the material is very uniform.

Modulus of Elasticity of Hard-drawn Copper. — The modulus of elas- ity of hard-drawn copper varies from 16×10^6 to 20×10^6, the higher values pying to small wires. The following tests by G. C. Batson are typical of mercial copper.

Diameter, in.	0.158	0.138	0.112	0.094	0.079	0.066	0.049
Modulus, lb. sq. in. units	17.7×10^6	17.9×10^6	17.5×10^6	17.7×10^6	17.1×10^6	19.5×10^6	19.2×10^6

An apparent modulus of 12×10^6 is often obtained from an initial test, due to ightening-out. (*See also Wires and Cables, Bare.*) The modulus decreases temperatures above 150° C.

Elastic Limit of Hard-drawn Copper. — The true elastic limit of hard- wn copper, or load at which permanent set begins, is not the same as the point ere the strain begins to increase more rapidly than the stress. The latter nt is usually between 30,000 and 35,000 pounds per square inch and the ner, somewhat below (*see Wires and Cables, Bare*).

Compression Test. — Copper of good quality does not fracture under com- ession; it yields and flattens. According to Thurston the resistance to com- ession may be calculated, within the limits $e < \frac{1}{2}$, from the formula

$$C = 145{,}000\sqrt[3]{e}$$

ere C = resistance in pounds per square inch of original area,
e = fractional compression.

Miscellaneous Mechanical Properties. — The torsional strength, shearing ength, hardness, resistance to impact and fatigue of copper are all discussed Bureau of Standards Circular No. 73 on *Copper*.

Density. — The density of copper or, for all practical purposes, its speci gravity referred to water, is 8.89 at 20° C. This is the value which has be adopted as standard by the American Institute of Electrical Engineers, and mo other authorities in the past. Recent measurements by the Bureau of Standar the Calumet & Hecla Smelting Works, and the Reichsanstalt have indicat this as a mean.

CONDUCTIVITY AND RESISTIVITY. — (*See also Resistance and Co ductance; Wires and Cables, Bare.*) F. A. Wolff and J. H. Dellinger give t resistivities of 89 samples of commercial copper from 14 important refiners a wire manufacturers in this and other countries. The mean for annealed wire Resistivity in ohms per meter-gram at 20° C. = 0.15292; per cent conductivi = 100.25. (Per cent conductivity is computed on the basis of 100 per ce conductivity corresponding to the standard resistivity of 0.15328 ohm p meter-gram at 20° C.) The mean result of data furnished by a large wi manufacturing company, representing tests on more than 100,000,000 poun of copper, is also given; for example, for annealed samples: Resistivity in ohi per meter-gram at 20° C. = 0.15263; per cent conductivity = 100.42.

Conductivity of Hard-drawn Copper. — The conductivity of hard-dra No. 12 B. & S. wires was found to be less than the conductivity of anneal wires by a mean value of 2.7 per cent. The difference between the conductivi of annealed and hard-drawn wires increases as the diameter of the wire decreas The lowest resistivity and highest conductivity found for a hard-drawn w were: Resistivity in ohms per meter-gram at 20° C. = 0.15386; per cent co ductivity = 99.62; and for annealed wire were: resistivity in ohms per met gram at 20° C. = 0.15045; per cent conductivity = 101.88.

Effect of Bending on Conductivity. — Copper wire apparently decreas in conductivity when bent, but the greater part of this is caused by local chang in cross-section. This effect is negligible unless the wire is bent to a very sm radius.

Effect of Melting. — Electrolytic copper which is drawn without havi been melted has a higher conductivity than that which has been melted, J. Dellinger recording copper thus drawn as having a conductivity as high 101.71 per cent after annealing at a dull-red heat. Lake copper likewise dra without having been melted gave conductivities as high as 101.88 after annealin

Temperature Coefficient of Resistivity. — It has been found by J. Dellinger (*Bulletin No. 147, Bureau of Standards, 1910, Vol. 7, No. 1*) that t temperature coefficient of copper is proportional to the conductivity instead being virtually a constant, as hitherto assumed. This fact may be expres by saying that the change of resistivity per degree C. of a sample of copp is 0.000597 ohm per meter-gram or 0.00681 micro-ohm per centimeter cub (Dellinger's original figures were subsequently changed slightly; *see Circ. No. of Bureau of Standards, 1912 ed.*) The 20° C. temperature coefficient of sample of copper is found by multiplying the per cent conductivity 0.0039; and dividing by 100. These rules apply only to copper furnished f electrical use and to the temperature range of 10° C. to 100° C. over which t temperature coefficient was found to be linear. The following table gives t temperature coefficients a_T in the formula:

$$R_t = R_T[1 + a_T(t - T)].$$

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ms per ter-gram 20° C.	Per cent conductivity	α_0	α_{15}	α_{20}	α_{25}	α_{30}
1.6134	95	0.00403	0.00380	0.00373	0.00367	0.00360
1.5956	96	0.00408	0.00385	0.00377	0.00370	0.00364
1.5802	97	0.00413	0.00389	0.00381	0.00374	0.00367
1.5753	97.3	0.00414	0.00390	0.00382	0.00375	0.00368
1.5640	98	0.00417	0.00393	0.00385	0.00378	0.00371
1.5482	99	0.00422	0.00397	0.00389	0.00382	0.00374
1.5328	100	0.00427	0.00401	0.00393	0.00385	0.00378
1.5176	101	0.00431	0.00405	0.00397	0.00389	0.00382

The boldface values in the table have been adopted as standard by the American Institute of Electrical Engineers.

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CORONA, ELECTRIC. — (*See also Electron Theory; Spark Gap; Transmission Lines.*) If a potential difference is established between smooth parallel wires, or between concentric cylinders, and gradually increased, a voltage finally reached at which a hissing noise is heard. If it is dark, a pale glow, called the electric "corona," will be seen to surround the wires. When wattmeters are inserted in the line a loss is noticed to start at this critical voltage. There is also noted the characteristic odor of ozone, and the air around the wires becomes ionized. These phenomena are referred to as "corona effects."

The corona starts at the conductor surface, because the voltage stress per unit distance, or "voltage gradient," is highest there. The break-down or corona extends out to a point where the stress is below the break-down point of air. If the wires are close together, so that the stress is fairly uniform, the break-down immediately extends from conductor to conductor without corona, and this phenomenon is called a "spark-over." The spark and corona are exactly the same phenomenon. The corona may be considered as a spark-over from conductor to space, as distinguished from a spark-over from conductor to conductor. The spark-over does not extend to the other conductor when the separation is large compared to the wire diameter, because it reaches a point in space where the gradient is below the break-down gradient of air. Increasing the voltage after the corona point is reached causes the corona to extend until finally a spark occurs from conductor to conductor. The power loss increases very rapidly with increase in voltage above the critical point.

Corona is caused by either a-c. or d-c. voltages, and starts at approximately the same maximum stress. At the critical voltage, corona occurs only at the crest of the alternating wave. As the voltage is increased above the critical point the loss extends over a greater portion of the wave. In the a-c. corona the eye sees a superposition of the corona caused by the plus and minus half-cycles of the a-c. waves. If the effects of the half waves are viewed separately, it is noticed that a reddish haze surrounds the wire while it is negative, whereas the surface of the wire glows bluish-white while it is positive. Positive and negative d-c. corona have exactly the same appearance as the positive and negative corona of the correspodning a-c. half-wires. When a negative wire becomes oxidized reddish tufts appear. If there are rough spots on the wire the corona starts at these points at a lower voltage. At points the positive corona extends out as a bluish-white spray; the negative corona appears as a red tuft.

Corona is also caused by transient voltages. Corona produced by voltage lasting less than a millionth of a second can be seen by the eye and distinction can be made between a positive and negative half-wave.

Corona Voltmeter. — For a given conductor arrangement and air density corona always starts at the same maximum voltage. Use has been made of this fact in the corona voltmeter (*Whitehead and Isshiki, J.A.I.E.E., May, 1920*). For this purpose, a wire in the center of a cylinder is generally used. In one form the voltage is applied and the air density varied until the corona appears. The voltage is then readily calculated or read from a scale. A tapered-wire has also been used. The starting point can be detected by the glow, the noise, the odor or by the conducting ionized air.

Laws of Corona-Formation. — The laws of corona have been quite definitely worked out. The chief factors affecting corona formation are:

For a given spacing and air density the corona starting voltage is lowered by decreasing the wire diameter.

Increasing the spacing increases the corona starting voltage but the effect of changing the diameter is relatively much greater.

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creasing barometric pressure decreases air density and decreases the corona ting voltage.

creasing temperature decreases air density and decreases the corona start- voltage.

ist, water, etc., on the conductor surfaces lower the corona starting voltage ncreasing the stress.

he *apparent strength* of air is not constant in irregular fields but greater at surface of small conductors than large ones. The strength at the start of ona is always constant, however, at a distance from the conductor which is ion a function of the radius. This corresponds to the strength in a uniform d of 76 kilovolts per inch (maximum value in case of a-c. voltage), which ns to mean that the actual strength of air is 76 kilovolts per inch. In order, ever, that a finite thickness only may be brought to this stress in an irregular d the stress at the conductor surface must be higher. At a given spacing corona always starts at a lower voltage on small wires than large ones, ause, although the *apparent strength* of air at the small conductor surface is ater, the stress produced by a given voltage is relatively much higher for the aller wires.

Corona does not start at exactly the same voltages when the wires are alter- ely plus and minus. The difference is at most a few per cent and is greater small wires than large ones.

he perfectly clean, smooth wires of uniform diameter, there is no loss until visual *critical voltage* is reached, when the loss assumes a *definite value* and reases as the square of the difference between the applied voltage and the uptive *critical voltage*. The *visual critical voltage* takes into account the *appar- strength* of the air, which is a function of the wire diameter; the *disruptive* al voltage corresponds to the constant strength of air for uniform fields, ch is about 76 kilovolts per inch, maximum value. The *visual critical* ge is always higher than the *disruptive critical voltage*. *Due to irregularities re is always a loss below the visual critical voltage*. This loss follows the prob- ity curve, because the loss occurs at chance rough spots, but on practical nsmission lines the quadratic law is generally approximated even on this tion of the curve. This is especially so for large conductors at low altitudes, ere the difference between the visual and disruptive critical voltages is not eat

Corona loss increases with increasing frequency.

The formulas for calculating corona on transmission lines are given below.

CORONA ON TRANSMISSION LINES. — It is of great importance the design of high voltage transmission lines to know the various factors that luence the corona formation and to be able to estimate accurately the starting oltage and loss for a given line.

The various characteristics may be calculated from the following formulæ:

Let e = r.m.s. value of the kilovolts to neutral $\left(= \frac{1}{\sqrt{3}} \text{ kilovolts between wires for 3-phase; } = \frac{1}{2} \text{ kilovolts between wires for single-phase} \right)$.

t = temperature in deg. F.,

b = barometric pressure, in inches,

$\delta = \frac{17.9b}{459 + t}$ = specific gravity of air, referred to air at 77° F. and 29.9 inches barometric pressure,

r = radius of conductor, in inches,

$g_0 = 53.6$ = disruptive critical gradient, kilovolts per inch, r.m.s. value,

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$g_v = g_0\delta\left(1 + \frac{0.189}{\sqrt{\delta r}}\right)$ = visual critical gradient, kilovolts per inch, r.m.s. value,

s = distance between conductor centers, in inches,

f = frequency, cycles per second.

Then the **disruptive critical voltage**, r.m.s. value of kilovolts to neutral

$$e_0 = 2.302 m_0 g_0 r\delta \log_{10}\left(\frac{s}{r}\right),$$

where $m_0 = 1$ for polished wires, $= 0.98$ to 0.93 for roughened or weathered wires, $= 0.87$ to 0.83 for seven-strand cables.

The **visual critical voltage**, r.m.s. value of kilovolts to neutral, is

$$e_v = 2.302 m_v g_v r \log_{10}\left(\frac{s}{r}\right),$$

where $m_v = 1$ for polished wires, $= 0.72$ for local corona all along cable, $= 0.6$ for decided corona all along cable.

The **power loss in fair weather**, in kilowatts per mile of single conductor

$$p = \frac{390}{\delta}(f + 25)\sqrt{\frac{r}{s}}(e - e_0)^2 \times 10^{-5}.$$

The **power loss in stormy weather**, in kilovolts per mile of single conductor is approximately,

$$p_s = \frac{390}{\delta}(f + 25)\sqrt{\frac{r}{s}}(e - 0.8e_0)^2 \times 10^{-5}.$$

Example. — To illustrate the use of the above formulas consider the case of a three-phase, 60-cycle line, No. 0, A.W.G. stranded cable (diameter 0.374 in.), spacing 120 inches, length of line 100 miles, temperature 100° F., barometer 28.85 inches.

Then $$\frac{s}{r} = \frac{120}{0.187} = 642,$$

$$\log_{10}\left(\frac{s}{r}\right) = 2.81,$$

$$\sqrt{\frac{r}{s}} = \sqrt{\frac{0.187}{120}} = 0.0394,$$

$$\delta = \frac{17.9 \times 28.85}{459 + 100} = 0.925,$$

$$\sqrt{\delta r} = \sqrt{0.925 \times 0.187} = 0.426,$$

$$g_v = 53.6 \times 0.925\left(1 + \frac{0.189}{0.426}\right) = 71.6,$$

$$m_0 = 0.87.$$

The disruptive critical voltage is then,

$$e_0 = 2.302 \times 0.87 \times 53.6 \times 0.187 \times 0.925 \times 2.81,$$

$$= 52.0 \text{ kilovolts to neutral.}$$

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The power loss is,

$$p = \frac{390}{0.925}(25 + 60) \times 0.0394(e - e_0)^2 \times 10^{-5}$$
$$= 0.014(e - e_0)^2 \text{ kw. per mile of conductor}$$
$$= 0.042(e - e_0)^2 \text{ kw. per mile of line.}$$

The conductor would begin to glow ($m_0 = 0.72$) at

$$e_0 = 2.302 \times 0.72 \times 71.6 \times 0.187 \times 2.81$$
$$= 62.6 \text{ kilovolts to neutral}$$
$$= \sqrt{3} \times 62.6 = 108.3 \text{ kilovolts between wires.}$$

The glow would be pronounced ($m_0 = 0.82$) for

$$e_0 = \frac{0.82}{0.72} \times 108.3 = 123.4 \text{ kilovolt between wires.}$$

The power loss per mile of line under storm conditions would be,

$$p_0 = 0.042(e - 0.8 \times 52)^2$$
$$= 0.042(e - 41.6)^2 \text{ kw. per mile of line.}$$

This last calculation assumes a storm over the whole line at the same time; a condition that is most unlikely to occur. The storm loss will generally be less due to lower temperatures.

The loss on a transmission line will vary from day to day depending upon the temperature and weather conditions. The above losses are calculated for summer temperature. For winter the losses would be much lower.

Methods of Increasing Size of Conductors. — For equal conductivity an aluminum conductor has about a 25 per cent greater diameter than a copper conductor, and, therefore, approximately 25 per cent higher critical voltage.

The advantage of aluminum may be still further increased by the addition of a steel cable core. Such a cable has been in use for several years on a 165–154 kilovolt line in California.

A copper tube may also be used or a copper cable with a suitable core.

Another means of increasing the corona voltage for a given amount of metal is to arrange several conductors of the same potential close together.

Arrangement of Conductors. — In the above formulas it has been assumed for three-phase lines that the conductors are so arranged that they form the edges of an equilateral prism. When the conductors are not so arranged, but are placed symetrically in a plane, corona will start at a lower voltage on the center conductor than on the outside conductors. The actual critical voltage on the center conductor will be approximately 4 per cent lower, and on the outside conductors 6 per cent higher, than for the equilateral prism arrangement with the same spacing.

Voltage Variation Along Line. — In practice, due to the drop in voltage along the line, the corona loss will be different at different points on the line. This may be allowed for by calculating the loss per mile at various points, and plotting a curve with loss per mile as ordinates and length in miles as abscissa. The area of this curve then represents the total loss.

If an isolated system is operating near the critical corona voltage and one conductor becomes grounded, the corona loss will be quite high.

The Corona Limit of High Voltage Transmission Lines. — Safe and Economical Voltages. — It will generally be found that it is safe and economical to operate a line up to, but not above, the fair weather value of the disruptive critical voltage (that is, up to the value of e_0 given by equation 1 for average barometer and summer temperatures. This will give loss during storms, but as storms do not extend over the whole line at one time, it will generally not be serious. During cold weather the critical voltage will be higher and storm loss less.

Besides the loss of energy, corona loss may be undesirable from another standpoint, viz., since the loss occurs only on part of the wave, it may introduce harmonics if it is excessive.

Tables I and II give the values of the fair weather disruptive critical voltage in kilovolts *between wires*, for various conductors at various spacings, at a barometric pressure of 29.9 inches = 760 mm. (standard pressure at sea level) and 77° F. = 25° C.

Table III gives the factors by which these voltages must be multiplied to give the corresponding disruptive critical voltage at various elevations. The correction factor is equal to the ratio of the barometric pressure at the given altitude to the barometric pressure at sea level.

TABLE I.—CORONA LIMIT OF VOLTAGE—SOLID WIRES

(Kilovolts between lines, three-phase, sea level, 25° C)

Size, A.W.G.	Diameter, inches	Diameter, cm.	Spacing in feet									
			3	4	5	6	8	10	12	14	16	20
			Spacing in centimeters									
			91	122	152	183	245	305	366	426	490	610
4	0.204	0.520	51	54	56	58	60	62	64	65	66	68
3	0.229	0.581	...	59	62	64	66	68	70	72	74	76
2	0.258	0.655	...	...	69	70	74	76	78	80	82	84
1	0.289	0.734	...	...	75	77	81	83	86	88	90	92
0	0.325	0.826	...	...	...	85	89	92	95	97	99	102
00	0.365	0.928	...	...	...	94	98	102	105	107	110	113
000	0.410	1.04	...	...	...	...	109	113	116	119	121	124
0000	0.460	1.17	...	...	...	...	120	125	128	131	134	138

Agreement of Calculated and Measured Losses on Actual Transmission Lines. — In most cases where losses have been measured on transmission lines the check is in close agreement with calculated values. The agreement is in fact within the limit of error of the measurements on commercial lines. Apparent discrepancies have generally been due to the fact that the measurements are often made at voltages below the *visual critical voltage*, when the loss depends upon irregularities, as discussed above. The loss between the *visual critical voltage* and the *disruptive critical* voltage closely follows the quadratic law for large conductors, but for new conductors, and especially for small

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BLE II.—CORONA LIMIT OF VOLTAGE—7-STRAND CABLES
(Kilovolts between lines, three-phase, sea level, 25° C.)

Size W.G. or c. mils	Diameter inches	Diameter cm.	Spacings in feet									
			3	4	5	6	8	10	12	14	16	20
			Spacings in centimeters									
			91	122	152	183	245	305	366	426	490	610
4	0.230	0.584	...	56	58	60	62	64	66	68	69	71
3	0.261	0.663	...	62	65	67	70	72	74	76	77	80
2	0.290	0.736	...	...	71	73	76	79	81	83	85	87
1	0.330	0.839	...	...	79	81	85	88	91	93	95	97
0	0.374	0.950	...	...	...	90	95	98	102	104	108	109
00	0.420	1.07	...	...	...	98	104	108	111	114	117	121
000	0.470	1.19	...	...	...	...	114	118	121	124	127	132
0000	0.530	1.35	...	...	...	...	125	130	135	138	141	146
250000	0.590	1.50	...	...	...	...	138	144	149	152	156	161
300000	0.620	1.57	...	...	...	...	...	151	156	161	165	171
350000	0.679	1.73	...	...	...	...	...	161	166	170	175	180
400000	0.728	1.85	...	...	...	...	...	171	176	180	185	192
450000	0.770	1.96	...	...	...	...	...	178	184	190	194	200
500000	0.818	2.04	...	...	...	...	...	188	194	199	205	210
800000	1.034	2.62	...	...	...	...	...	...	234	241	244	250
1000000	1.152	2.92	...	...	...	...	...	...	256	264	270	281

TABLE III.—ALTITUDE CORRECTION FACTOR AT 25° C.

Altitude		Correction factor	Altitude		Correction factor
Feet	Meters		Feet	Meters	
0	0	1.00	5,000	1525	0.82
500	152	0.98	6,000	1830	0.79
1000	305	0.96	7,000	2135	0.77
1500	459	0.94	8,000	2440	0.74
2000	610	0.92	9,000	2745	0.71
2500	765	0.91	10,000	3050	0.68
3000	915	0.89	12,000	3660	0.63
4000	1220	0.86	14,000	4270	0.58

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conductors at high altitudes, when the difference between e_0 and $e_{0'}$ is large, the loss will generally fall below the quadratic curve.

Special Calculations. — For small conductors the loss, in kilowatt mile of conductor, is given by the expression,

$$p = \frac{390}{\delta}(f + 25)\sqrt{\frac{1 + \frac{0.93}{s} + 0.016}{s}}\,(e - e_d)^2 \times 10^{-5},$$

where $$g_d = g_0\delta\left[1 + \frac{0.189}{\sqrt{\delta r}}\,\frac{1}{(1 + 148\sigma r^2)}\right]$$

and $$e_d = 2.302 m_0 g_d r \log_{10}\left(\frac{s}{r}\right).$$

BIBLIOGRAPHY. — Peek, *Dielectric Phenomena in High Voltage E neering;* Lewis, *Some Corona Tests*, G. E. Review, May, 1920; also nume articles by Peek, Whitehead, Ryan, and others in the *Trans. A.I.E.E.*, to date and in the *Jour. A.I.E.E.* to date.

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UPLINGS, DIRECT. — (*See also Belts and Belting.*) Couplings for con-ng electrical apparatus together or to other machines can be divided into distinct classes, namely, solid and flexible.

OLID COUPLINGS (Fig. 1) are usually of the flanged type and consist two steel castings rigidly bolted to-er. This type should be used where two machines are mounted on a com-n iron base and where an exact align-t is possible. Large flanges should be vided for overcoming bending stresses ch may occur when the couplings carry t of the load such as, for example, in e bearing sets. See also article on *Ma-e Tools, Electrical Operation of.*

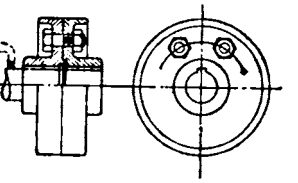


Fig. 1. Solid Flange Coupling

LEXIBLE COUPLINGS are mainly used to connect machines which not be lined up properly or where there is fear that alignment cannot be ntained. Many different kinds of flexible couplings are in use, and they be divided in two general classes, insulated and uninsulated. The insu-d couplings are composed of castings separated by leather or rubber, as a ble and insulating medium. The principal types of flexible couplings in are the leather link, the laced belt, the rubber buffer and the mill-type pling.

Leather-link Flexible Couplings (Fig. 2) consist of two iron castings con-ted together through leather punchings fastened at the ends by bolts to the rnate halves. For the smaller sizes e links are usually replaced by a gle leather disk which connects both lves by means of bolts alternately ned through opposite halves. The ving stresses are transmitted through e links or disks to the bolts which ten them to the castings.

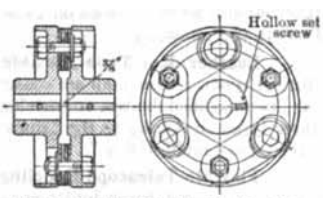


Fig. 2. Leather-link Flexible Coupling

In order to allow sufficient play for t heads of the bolts, alternate holes t bored to a large diameter, the bolts rurately fitting the other holes in the castings. By this means flexibility is ained and a small amount of end or side play is permissible between the fts of the two machines to which each half coupling is securely keyed. is type of coupling is recommended for shafts up to 3½ inches in diameter. shafts between 3½ inches and 5 inches in diameter either this type or the ther-laced type may be used.

Leather-laced Flexible Couplings (Fig. 3) are recommended for shafts er 3½ inches in diameter on ac-nt of their structural advantages. ey consist of two steel rings, an ter and an inner, with cast-iron bs bolted to them. Slots are med in these rings through which endless leather belt is interwoven.

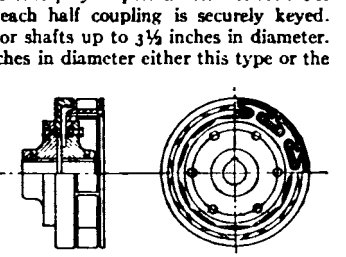


Fig. 3. Leather-laced Flexible Coupling

is construction not only gives great flexibility but, due to the two rings ing concentric, it is not subjected to bending strains and therefore is espe-

cially adapted for transmitting a high torque commensurate with the stren of the belt and the size of the coupling employed.

As the outer ring of the coupling is only connected to the shaft of the mach through the coupling hub which is keyed to the shaft, machines using this fo of coupling can be readily disconnected without unlacing or interfering with t coupling belt. To do this it is only necessary to remove the bolts, holding t outer ring to the hub. This partial disassembling also aids in the replacing o worn-out belt without removing the coupling from the machine.

Rubber-buffer Flexible Coupling. — This coupling is made up of two ca iron spiders, the small interlocking arms of which are separated by cylinders soft rubber. The rubber cylinders are held in place by projecting plates screw to the arms of one of the spiders. The construction of this type of coupli affords great flexibility as well as insulating qualities. This type of coupli was once much used on account of its high-insulating qualities but is now to great extent being superseded by the two previous types.

Mill-type Flexible Coupling (Fig. 4). — Where the conditions are t severe for the belt or rubber of the flexible couplings described above, that where there is much grit or hot vapor present and where noise is not objectionable, the mill-type flexible coupling shown in Fig. 4 should be used. This is a rough sturdy coupling consisting of three steel castings, two of which are identical and called the "pods," while the center is called the "box." The most extensive use for this coupling has been in steel mills. Best results are obtained fr this coupling when it is used on a constant load, as the noise under these con tions is at a minimum.

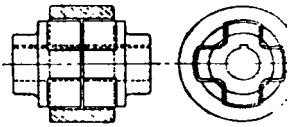


Fig. 4. Mill-type Flexible Couplin

Leather Key Type Flexible Couplings. — These are made in thr distinct types, although all are constructed on the same fundamental princip viz., two modified flanges, one driving the other by means of leather keys, t three types are known as the "single key," "two-piece multiple key," and t "three-piece multiple key."

Flexible Telescope Couplings. — This coupling is specially design for use with motor driven Jordan engine in paper and pulp mills. On the Jord side of the set it consists of a stout split cylinder on which are mounted fo radial columns of leather washers securely bolted. The motor half is a sp cylinder slotted to take the columns of the other half.

PROPER SIZE OF COUPLING. — The selection of the proper coupli should be determined by calculation and not by the method of choosing the bo corresponding to the shaft diameter. The coupling should have sufficie capacity to take care of the overload capacity of the motor or generator, as t case may be.

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ANES. — (*See also Blocks and Tackle; Controllers; Hoists, Electric; Tel-*
rage.) A hoist is a machine for raising and lowering weights. A crane is a
s with the added capacity of moving the load in a horizontal or lateral direc-
. That part of a crane carrying the hoist and movable with respect to the
e structure of the crane is called the "trolley." Cranes are divided into
o classes as to their motions, viz., rotary and rectilinear.

Rotary Cranes may be classified as follows:

Swing-cranes. — Having rotation, but no trolley motion.

Jib-cranes. — Having rotation, and a trolley traveling on the jib. When
jib or boom is movable, carrying a sheave on the end, the device is called
ewrick.

Column-cranes. — Identical with the jib-cranes, but rotating around
ixed column (which usually supports a floor above).

Pillar-cranes. — Having rotation only; the pillar or column being
pported entirely from the foundation.

Pillar Jib-cranes. — Identical with the last, except in having a jib and
lley motion.

Derrick-cranes. — Identical with jib-cranes, except that the head of
ast is held in position by guy-rods, instead of by attachment to a roof or
ing.

Rotary cranes arranged so that they may be readily moved from place to
ce may be classified as:

Walking-cranes. — Consisting of a pillar or jib-crane mounted on
heels and arranged to travel longitudinally upon one or more rails.

Locomotive-cranes. — Consisting of a pillar-crane mounted on a truck,
d provided with a steam-engine capable of propelling and rotating the crane,
d of hoisting and lowering the load.

Rectilinear Cranes may be classified as follows:

Bridge-cranes. — Having a fixed bridge spanning an opening, and a
lley moving across the bridge.

Tram-cranes. — Consisting of a truck, or short bridge, traveling longi-
dinally on overhead rails, and without trolley motion.

Traveling-cranes. — Consisting of a bridge moving longitudinally on
erhead tracks, and a trolley moving transversely on the bridge.

Gantries. — Consisting of an overhead bridge, carried at each end by
restle traveling on longitudinal tracks on the ground, and having a trolley
oving transversely on the bridge.

Rotary Bridge-cranes. — Combining rotary and rectilinear movements
d consisting of a bridge pivoted at one end to a central pier or post, and
pported at the other end on a circular track, provided with a trolley moving
ansversely on the bridge.

For descriptions of these several forms of cranes see Towne's *Treatise on*
ranes.

HAND-OPERATED TRAVELING CRANES. — The weight of a hand-
perated traveling crane depends not only upon the capacity of the crane and
e length of the span, but also upon the particular design. The following
pproximate formula will serve as a rough guide when actual data are not avail-
ble:

$$W = KCL,$$

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where W is the weight of the crane in tons, C the capacity of the crane in to
L the length of the span in feet and K a constant ranging from about 0.01
L = 10 feet to 0.012 for L = 75 feet.

ELECTRIC OVERHEAD TRAVELING CRANES. — Electric travel
cranes usually have 3 motors, one for the hoist, one for the trolley traveling
the bridge and one for moving the bridge. Cranes of over 15 tons capac
are usually provided with an auxiliary hoist of from 1/10 to 1/8 the capacity
the main hoist. Automatic brakes are used to sustain the load when lift
and to regulate the speed when lowering, the hoist motor usually having
drive the load down.

Speeds of Electric Traveling Cranes. — The standard speeds at wh
the various parts travel in the cranes manufactured by Pawling and Harnischfe
are as follows:

STANDARD SPEEDS OF ELECTRIC CRANES, IN FEET PER MINU
(Pawling & Harnischfeger)

Capacity, tons (2000 lb.)	Hoisting speed, ft. per min.	Bridge travel, ft. per min.	Auxiliary hoist	
			Capacity, tons	Speed, ft. per min.
5	25–100	300–450	..	.....
10	20–75	300–450	3	30–75
25	10–40	250–350	3	50–125
			10	25–60
40	9–30	250–350	5	40–100
			10	25–60
50	8–30	200–300	5	40–100
			10	25–60
75	6–25	200–250	15	20–50
125	5–15	200–250	25	20–50
150	5–15	200–250	25	20–50

Trolley travel speed from 100 to 150 feet per minute in all cases.

Weight and Dimensions of Electric Traveling Cranes. — Let

C = capacity of crane, in tons (2000 pounds),
W_B = weight of bridge alone, in tons,
W_T = weight of trolley alone, in tons,
W = total weight of crane, in tons.

Then

$$W_B = K_B CL, \qquad W_T = K_T C,$$
$$W = W_B + W_T = C(K_B L + K_T),$$

where K_B and K_T have the following approximate values (*see paper by S. Wales, Proc. Eng. Soc. Western Pa., 1902, Vol. 18, p. 146*).

L	K_B	C	K_T
25	0.012	1–25	0.3
50	0.012	25–75	0.4
75	0.013	75–150	0.5
100	0.015		

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For example, for a 50-ton crane for a 60-foot span, the bridge alone would ...gh $0.013 \times 50 \times 60 = 39$ tons, the trolley would weight $0.4 \times 50 = 20$ tons, ... the total weight would be 59 tons, approximately. If the bridge is equipped ... 2 wheels at each end, the maximum load on each wheel when the trolley, ...ying full load, is at the end of the bridge would be approximately

$$\frac{39}{4} + \frac{20 + 50}{2} = 45 \text{ tons},$$

If there are 4 wheels at each end, the maximum wheel load would be 22.5 tons. The following table is taken from a catalogue of the Alliance Machine Co.

DIMENSIONS AND WHEEL LOADS OF ELECTRIC TRAVELING CRANES

60-foot span and 25-foot lift; wire-rope hoist

Capacity, ...ns (2000 lb.)	Distance from runway rail to highest point		Distance from center of rail to ends of crane	Wheel base of end truck		Maximum load per wheel; trolley at end of bridge
	Feet	Inches	Inches	Feet	Inches	Pounds
5	6	0	9	9	0	20,000
10	6	6	10	10	0	27,000
25	7	4	12	11	6	51,000
40	8	0	12	12	3	82,000
50	8	9	12	12	6	48,000*

* Has 8 track wheels on bridge.

Standard cranes are built in intermediate sizes, varying by 5 tons up to 40 ...

Power Required. — The following is adapted from the paper by S. S. Wales ...ve referred to. The frictional losses will of course depend to a certain extent ...n the design of the crane, the use of rope or chain, etc., but the constants ...n below represent fair averages.

The same notation as in the previous section is used. In addition let

R_B = tractive effort in pounds per ton required to move the bridge,
R_T = tractive effort in pounds per ton required to move the trolley,
S_B = speed of bridge in feet per minute,
S_T = speed of trolley in feet per minute,
S_H = speed of hoist in feet per minute.

...en the power required, at shaft of bridge motor, to drive the bridge at speed ... is

$$P_B = \frac{(C + W_B + W_T)\, R_B S_B}{33{,}000} \text{ horse-power.} \qquad (1)$$

The power required, at shaft of trolley motor, to drive the trolley at speed ... is

$$P_T = \frac{(C + W_T)\, R_T S_T}{33{,}000} \text{ horse-power.} \qquad (2)$$

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The power required, at shaft of hoist motor, to drive the hoist at speed assuming 60 per cent efficiency of gearing and hoisting tackle, is

$$P_H = \frac{CS_H}{10} \text{ horse-power.}$$

For *constant-speed running*, Wales gives the following values for R_B and the former varying with L and the latter with C.

L	R_B	C	R_T
25	30	1–25	30
50	35	25–75	35
75	40	75–150	40
100	45	.....	....

If the moving member is *accelerating* at the rate of a ft. per sec. per to the value of R given in the above table should be added an amount

$$R_a = 64\,a.$$

The power as calculated by the above formulas is the power *output* of motors; to obtain the power input divide by the motor efficiency, which ra from 80 to 90 per cent.

Motor Equipment. — (*See also Motors, Industrial Applications of*). bridge motor should have a 30 minute rating, 1.8 times the calculated po for constant full-load speed, the trolley motor 1.5 times the calculated po for full-load speed, whereas the rating of the hoist motor should be t equal to the calculated power for constant full-load speed. This is a g approximation, but for accurate work the torque capacity of the bridge m should be checked against the rate of acceleration required. A full discus of the motor equipment of cranes is given by McLain and Jackson in the *Elec. Rev. 19, p. 506, June, 1016.*

Both direct-current and alternating-current motors are successfully used crane work. The series direct-current motor has speed-torque characteris especially well adapted for crane service. At light loads the speed incre and at heavier loads the lifting is slower and the raising effect consequer stronger. This characteristic of the series motor often results in consider saving of time, due to the fact that the majority of loads in factories are li so that the increased speed of lift enables work to be performed in a sho time. For a-c. motors a normal operating speed about 25 to 50 per cent hig than for d-c. motors is therefore generally selected and the slowing down for he work is accomplished by inserting resistance in the phase-wound rotor circ

Example. — Crane of 50-ton capacity, span 70 feet, bridge speed feet per minute with full load, trolley speed 100 feet per minute with full lo hoist speed 15 feet per minute with full load. Then $C = 50$, $W_B = 4$ $W_T = 20$, $R_B = 40$, $R_T = 35$, and

$$P_B = \frac{115.5 \times 40 \times 200}{33{,}000} = 28 \text{ horse-power,}$$

and the motor required for the bridge would be $28 \times 1.5 = 42$ horse-power, the nearest commercial size over 42, say 50 horse-power.

$$P_T = \frac{70 \times 35 \times 100}{33{,}000} = 7.43 \text{ horse-power,}$$

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l the size motor required for the trolley would be $7.43 \times 1.25 = 9.28$ horse-wer, or say 10 horse-power.

$$P_H = \frac{50 \times 15}{10} = 75 \text{ horse-power,}$$

d a motor of this rating would be used for the hoist.

Control of Crane Motors. — The control equipments for crane motors ould be of the regulating and reversible type. The starting and speed regu-tion of series motors is generally accomplished by inserting resistance in ies with the armature and field, and with induction motors, resistance is erted in the phase-wound secondary or rotor circuit. For cranes which do ge amount of lowering, dynamic control is becoming very generally used, d is very readily accomplished with direct-current motors. This also occa-nally is used with a-c. motors of 200 h.p. and above, when direct current is ilable for excitation. On smaller a-c. motors a system of regenerative ering in combination with solenoid load brakes is used.

Drum Versus Magnetic Controllers. — Both hand- and magnetic-con-l equipments are in general use. The former are satisfactory for small and ium-size motors, and consist simply of a drum-type controller with a set of arate resistances. For large-size motors too much physical effort would be uired to move a controller of the necessary size and the magnetic control ld then be selected. A magnetic-control equipment consists of a master troller, a contactor panel and the resistances. The contactor panel contains contactors for cutting in or out the resistances, the interlocks and the current-it relays for automatically controlling the sequence and rapidity with which contactors operate. The master-controller handle can be thrown to the full-ed position quickly without causing an overload on the motor, since the cur-t-limit relays automatically prevent the contactors from cutting out the istances too rapidly.

Dynamic Control. — With dynamic control of d-c. motors the field is arately excited and the armature is connected to the line voltage with one tion of a rheostat in series with it, and another section of the rheostat in allel with it. This is accomplished by means of the controller, whose duty to make each step on the lowering side keep the speed of the motor under trol no matter whether the motor has to drive a light hook downward or ld back against a heavy load. In the former case the current which passes ough the series rheostat also passes through the armature and produces the ired torque. The speed is controlled by varying the value of this rheostat e as in hoisting. If the motor has to act as a brake, the power generated in armature is expended in the parallel rheostat and the speed is controlled by ying this rheostat. In actual practice the two rheostats are varied simul-neously so that if a certain point on the controller tends to cause the motor to ve a load at a high speed it will also cause the motor to hold back at a high ed. The practical result is that an operator always has his load under con-l, and does not have to worry about dropping his load. On the lowering side the controller, a motor holds back against its load even when power fails, ause the motor then acts as a self-excited series generator, and consequently solenoid brake alone is not depended on to prevent the load from falling.

In the case of a phase-wound induction motor it is necessary to excite one rtion of the primary winding with direct current in order to generate a voltage the secondary winding. A rheostat is then connected to the secondary wind-s of the motor and the speed can be controlled as with d-c. motors. As direct rent is necessary for excitation dynamic braking is not very often used with crane motors.

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Solenoid brakes are also provided for holding the load when the hoist mo is stopped. If dynamic braking is not provided, mechanical brakes must provided in addition to the solenoid brakes to assist in holding the load when motor is stopped and for regulating the speed when lowering.

Solenoid brakes are, as a rule, applied by gravity when the armature curren shut off and released by the solenoid which is energized when the controlle thrown on the first notch. The solenoids of direct-current motors are gener connected in series with the motor circuit, although with polyphase induct motors they are connected directly across one phase thus receiving the full voltage.

All crane motors should also be protected by safety-limit switches arran to cut off the supply current when the limit of motion is reached and thus au matically provide against accidents from over-travel.

SPECIFICATION FOR ELECTRIC CRANE. — The following me randa are intended to assist in writing specifications. See also *Specification*

Principal Characteristics and Conditions of Service. — Span betw crane rails and load to be lifted on main hoist and on auxiliary hoists, if a Characteristics of current, a-c. or d-c. (phases, cycles and voltage).

Style and Description of Apparatus. — Structural work of open-hea steel according to some standard steel specifications. Maximum stresses allo able. Whether hand operation is to be provided for. Distance of hook fr crane rails, vertically and horizontally, when at extreme limits of its mot Details of brake. Description and characteristics of motors to be suppli Whether or not a foot-walk is to be supplied. Whether trolley is to be ab bridge or submerged. Hoisting drum to have bronze bearings. Track wh shall have chilled treads, ground true, with double flanges, and shall be ke to their axles. Axle bearings shall be bronze. Details of lubrication bearings. Location of carriage. Details of control. All gearing (exc when shrouded) shall be cut, etc. Wiring details. Controller details.

Dimensions. — Supply a diagram of clearances.

Work Done by Other Contractors. — Track rail and weight thereof.

Performance and Tests. — Speeds of main travel, lateral travel and hoi Time to get up speed or acceleration rates.

COST OF CRANES (Pre-war figures). — The cost of cranes depends so great an extent upon the design, motor equipment, etc., that no relia average figures can be given. As a rough approximation the cost of a ha operated traveling crane may be taken as from about 5 to 7 cents per pound total crane weight and the cost of an electric traveling crane as from ab 10 to 13 cents per pound of total crane weight.

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ROSS ARMS. — (*See also Poles for Overhead Lines; Insulator Pins; nsulators.*) Cross arms are usually of wood though sometimes of iron. ack arms" or "reverse arms" are cross arms attached to a pole at right gles to the principal arms, and are used for taking off wires at right angles the line, either at the junction of intersecting lines or at services. "Double ms" are pairs of cross arms attached to opposite sides of a pole so as to act one compound arm. Double arms are used to increase the strength of an m and to permit the use of two pins and two insulators for supporting a ge wire where additional strength is required.

Cross arms are used principally for supporting pins, insulators and wires, ough lightning arresters, transformers, switches and other miscellaneous pliances are often mounted on them, usually for the purpose of keeping the e free of incumbrances so that it will be more easy to climb.

Alley Arms. — When city distribution lines are located in alleys it is common locate poles next to the property line. Where it is not permissible to let ms overhang private property special arms may be used which extend on one le of the pole only. These must be well braced and should not be used for d ending wires. A better construction is obtained by locating two poles on posite sides of the alley and putting special cross arms across the alley be- en them.

ORCES ON AND STRESSES IN CROSS ARMS. — The forces which ss arm resists are:

(a) Vertical forces due to weight of pins, insulators, wires (with sleet) and idental loads due to linemen standing on arms, etc.

(b) Transverse horizontal forces due to wind pressure on the wires (with at right angles to the line.

(c) Longitudinal horizontal forces due to the pull of the wires where the pull unbalanced. Unbalanced pull is usually due to an angle in the line, the end- of the wire at the arm, a change in the size of wire at arm and an unequal sion in the spans on the two sides of the arm.

The principal internal stresses produced in an arm from these forces are:

(1) A bending force in a vertical plane due to vertical forces (a).

(2) A bending force in a horizontal plane due to horizontal forces (c).

(3) A twisting force about the longest axis of the arm due to the "pin lever- e" of the horizontal forces (c). The pin leverage is the distance from the ter of the wire to the axis of the arm.

Of these stresses the most destructive is probably the twisting stress which ds to split the arm in a vertical plane through the pin holes and along the in of the wood. On this account the pin and insulator should be no taller an necessary, the pin should extend completely through the arm to give the st distribution of bearing pressure and, where stress is heavy, the arm may strengthened by two "strengthening bolts" (machine bolts with nut and shers) put horizontally through the arm one on each side of the pin, one being ar the top and the other near the bottom of the arm.

The vertical and horizontal bending stresses are of some importance and may computed by the usual beam formula (*see Structures, Simple*). Data of tests strength of cross arms for these stresses are given below.

Strength Tests of Cross Arms. — (*Forest Service, Cir. No. 204.*) Tests made 3¾ in. by 4¼ in. by 6 ft., 6-pin air-dried cross arms with vertical load distributed ually at each pin hole gave the results at top of next page.

The tests showed that for ordinary use the strength, for vertical loads of 6-pin ms, need not be considered in calculations of line construction, except in the re case of abrupt change of the grade of the line.

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Kind of wood	Av'ge max. load in lb.
Longleaf pine, 75 per cent heart	10,180
Longleaf pine, 100 per cent heart	9,780
Shortleaf pine	9,260
Longleaf pine, 50 per cent heart	8,980
Shortleaf pine, creosoted	7,650
Douglas fir	7,590
White cedar	5,200

DIMENSIONS AND RATING. — Cross arms are rated in terms of number of pins they are designed to carry, 2-pin arms being the minimum 10-pin arms the maximum ordinarily used.

Cross-section. — When arms are made directly from the original logs t are sometimes dimensioned in even inches, i.e., 4 in. by 5 in., 5 in. by 7 in., In most cases they are made from lumber in stock and when finished are a quarter of an inch or more under the even sizes. Several "standard" dimensions have been adopted for distribution arms. In the accompanying table Standard I is that given by Miller (*American Telephone Practice*) and found in various catalogues of dealers in electrical supplies. It is the standard of the American Elec Railway Engineering Association for light service cross arms. Standar is that given in Report of Committee on Overhead Line Construct of the National Electric Light Association, and Standard III is that of American Electric Railway Engineering Association for heavy service cross a

Size of arms	Width, inches	Dept inch
Standard I....	3¼	4½
Standard II....	3½	4½
Standard III....	3¾	4½

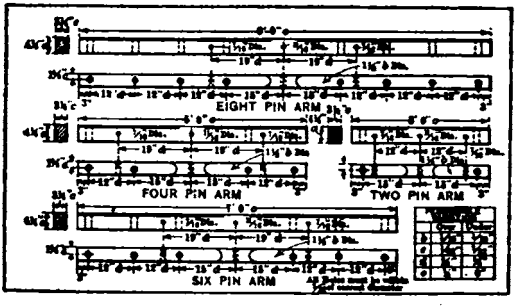


Fig. 1. Standard I Cross-Arms

Distance between Pole Pins. — It is desirable to have the space betw pole pins (i.e., the two pins on opposite sides of the pole) as large as poss to give a clear space for climbing the pole. It usually varies from 16 in 30 in.

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Distance between Other Pins. — This usually ranges from 10 in. to 21 Under ordinary circumstances 12 in. has been found sufficient to prevent s on adjacent pins swinging in contact in the middle of the span. Where ll wires (such as No. 10 telephone wires) are used on long spans (150 ft. ore) contact is to be expected occasionally where 12 in. spacing is used.

Distance from End Pin to End of Arm. — This is usually 3 or 4 in., ich is about the minimum that can be used without the arm splitting due to leverage.

h order that a line may have a neat systematic appearance it is desirable that pin spacing be the same for all arms, whether 2 pin, 4 pin, etc. In the tabula- s below the arms included in each standard (defined above under *Dimensions Ratings*) have been grouped on this principle which shows that Standard I ly consists of one regular group and 5 odd arms while Standard II consists 2 regular and 1 odd arm. Referring to Standards I and III it will be noted t the length of arm is always a multiple of one foot.

STANDARD DISTANCES BETWEEN PINS

Standard	Group	Number of pins	Length of arm	End pin to end of arm	Between pole pins	Between other pins
			Ft. In.	In.	In.	In.
	Regular	4	4 0	4	16	12
	Regular	6	6 0	4	16	12
	Regular	8	8 0	4	16	12
	Regular	10	10 0	4	16	12
I	Odd	2	3 0	4	28	..
	Odd	4	5 0	4	18	17
	Odd	4	6 0	4	22	21
	Odd	4	6 0	4	24	20*
	Odd	6	8 0	4	18	17½
	Odd	8	10 0	4	17½	15⅝
	Regular	4	5 7	4	30	14½
II	Regular	6	8 0	4	30	14½
	Odd	8	9 2	4	30	12
	Regular	2	3 0	4	28	..
	Regular	4	5 0	4	28	12
III	Regular	6	7 0	4	28	12
	Regular	8	9 0	4	28	12
	Regular	10	11 0	4	28	12

* Alternative found in some catalogues.

Pin Holes. — 1½ in. diameter is standard for wood pins. N.E.L.A. specifications require that holes shall be tested with steel gauges taking one of the nominal size without forcing but not taking one 1/32 in. larger.

Bolt Holes. — For fastening the arm to the pole there is usually one 1 1/16 or 1-in. bolt hole at the middle of the arm. For fastening cross-arm braces there are two 5/8 or ¾-in. bolt holes located 38 in. apart (Standard II) or 40–42 in. apart (Standard III).

High-tension Wooden Cross Arms.—These are not standardized but are specially designed and made as required. They differ from distribution arms in being wider and deeper with larger pin holes and wider pin spacing. The

following tabulation will give data on some arms that have been used for diffe voltages.

Voltage	Number of pins	Width of arm	Depth of arm	Length of arm	Spacing of pins	Pin ho diamet
		Inches	Inches	Inches	Inches	Inches
25,000	2	6	6	64	48	2¼
55,000	2	5	7	88	72	2½

Special high-tension arms are usually unnecessary for circuits of 5500, 6 11,000 and 13,200 volts. Standard 2200-volt distribution arms may be u the wire spacing being increased by not using certain pins. Thus a stand 2200-volt 6-pin arm may be used for a 11,000-volt 4-pin arm by leaving middle pin holes vacant. For higher voltages the strength of arm and siz pin hole is usually insufficient.

SPECIFICATIONS. — (*See article on Specifications.*) The points to covered in a set of specifications are:

Material. — Usually pine or fir, sometimes western hemlock. (*See Poles Overhead Lines.*)

Quality of Material. — Usually should be "straight grained, free from kr (or free from large, loose or unsound knots), sapwood, pitch pockets, shal checks, loose heart, rot, worm holes or other defects." The strictness of specifications, or of the inspection, must, however, be governed in these respe by local conditions. In some localities a quality of material can be obtai cheaply, and should be required, which would be unreasonable to expect wh wood is expensive.

Wood should be dried before manufacture. (When arms are dried af drilling, the pin holes become elliptical, i.e., smaller across the grain, due shrinkage of the wood and the pins do not fit well.)

Dimensions, Pin holes, etc., as noted in preceding section.

COST. — The cost of cross arms is subject to considerable variation a depends largely upon the locality in which they are purchased. The follow figures are rough approximations and are exclusive of freight.

APPROXIMATE COST OF CROSS ARMS

Cents per linear foot

Kind	Washington fir, F.O.B., Seattle	Longleaf pine, "75 per cent heart," F.O.B., New Orleans	Commercial yellow pine F.O.B., New Yo
3¼ by 4¼ inches.....	5	6	5
3½ by 4½ inches.....	7	10	...
3⅝ by 4⅝ inches.....	8	...	...

In car load lots about 25 per cent less than above.

BIBLIOGRAPHY. — American Electric Railway Engineering As *Engineering Manual*, and Committee Reports; Kapper, F., *Overhead Tra mission Lines and Distribution Circuits* New York, 1915; National Elec Light Assn. Committee Reports; Lundquist, R. A., *Transmission Line C*

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DAMS. — (*See also Hydraulics; Hydrology; Power Stations; Structures, Simple*). A dam is a structure built to interrupt a stream's flow and raise the level of the water, thereby impounding water which may be used for power development, water supply, navigation, irrigation or numerous other purposes.

Coffer-dam. — A dam built for the purpose of holding back water from an area, which would otherwise be flooded, and making it accessible for construction purposes, is called a coffer-dam. It is generally a temporary affair.

Diversion Dam. — This name has been applied to dams built for the purpose of diverting the whole or a portion of a stream into a side channel or pipe line by which it is conducted to one or more places where it is used for power or other purposes.

Storage Dam. — A storage dam is built for the purpose of storing flood waters for use during periods of low stream flow. In many power developments a storage dam is essential to continuous output. Storage dams are sometimes used as diversion dams.

Wing Dam. — In swiftly flowing streams having steep slopes, a diversion dam is sometimes built out from one shore diagonally upstream toward the other, but not to it. This special form of diversion dam is known as a wing dam.

Classification with respect to Materials and Design. — According to the materials used and the design, dams may be classified as:

Wooden dams	Masonry dams
Earth dams	Solid gravity
Rock dams	Hollow gravity
	Arched

By a **gravity dam** is meant one in which the force of gravity is relied upon for resisting the thrust and overturning moment of the water. Earth and loose rock dams, timber cribs and most masonry dams are of this type.

By an **arched dam** is meant one which in plan forms an arch, convex to the up-stream side. The ends of the arch terminate in the valley walls, which thus act as abutments to the arch so formed.

Often a gravity dam has been built in the form of an arch, using the possible arch action as a factor of safety, and depending wholly on the gravity action to resist the thrust of the water. Many of the highest dams in existence are so constructed and are generally in localities where the stream's valley is relatively narrow and deep.

LOCATION AND HEIGHT OF DAMS. — For power developments the location of the dam depends largely on the topography and geological formation of the site. The total fall in a stream to be utilized for power may be developed in whole by a dam or in part by a dam and in part by a canal, flume or pipe to the power-house. Thus the location and height of the dam is fixed by economic considerations to develop the whole head at the least cost, consistent with safety and reasonable operation and maintenance expense. The cost of lands to be overflowed has considerable influence.

WOODEN DAMS. — Wooden dams are made in a variety of forms. The most common form of wooden dams consists of a crib of timbers filled with broken rock and covered on the top and up-stream face with wooden sheeting.

EARTH DAMS. — A typical earth dam is indicated in Fig. 1. No dam is absolutely watertight. The successful construction of a dam of any type embodies the condition that leakage or seepage will not be sufficient to endanger

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the structure or its foundation and that an excessive amount of impound water will not be wasted.

An earth dam and its foundation must be made sufficiently tight that seepage of water through it will not be great enough to move the minute partic of which it is composed.

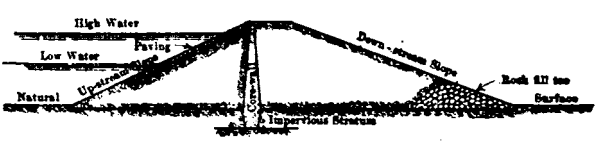


Fig. 1. Typical Earth Section

Materials and Details. — The materials used in the construction of ea dams are loam, sand, gravel and clay of various proportions. The dam is appr imately trapezoidal in section, having a top width and side slopes which determined by the materials used. The best of the available materials used to provide a selected impervious part. The impervious part or core m be placed near the upstream face; but, as impervious materials are relative unstable when saturated, the core is usually placed in the center of the da and supported on each side by the more stable pervious materials. The dow stream toe is often built of loose rock or otherwise well drained to preve slipping when saturated by water seeping through the dam.

Cores of masonry, clay puddle or other materials are sometimes built in t center of the dam, extending into the foundation to an impervious stratu Timber cores above the water gradient are not sufficiently durable for a perm nent structure. Masonry core walls usually have a top width of from 2 to 4 fe with side batters of ½ to ¾ inch per foot down to the foundation, but, if w reinforced may be much thinner. There is a divergence of opinion amo engineers regarding the practical use of masonry corewalls for earth dam However, it has not been shown that they impair the safety of the dam and th are often imperative to guard against burrowing animals.

The downstream slope of the dam should be protected from rain scour b sodding or seeding it. For long slopes, provision is often made for draining the rain water by building berms, a few feet wide every 30 feet or so on the slop containing gutters for lateral drainage.

Riprap, hand laid paving or masonry is used on the upstream face to prote it from the action of waves and ice. Solid paving should be laid on a layer well-drained broken stone or gravel to prevent internal pressure on the pavi when the pond is drawn down rapidly.

Dimensions. — The top width of the dam is often determined by requir ments for a roadway. Where not so fixed it may be made approximatel equal to one-fifth the height of the dam plus five feet. The top of the da must be built sufficiently high to prevent overtopping by waves during extrem high water.

Simple rules cannot be given governing the side slopes of earth dams. Fro the nature of the materials available, this angle of repose when placed in th dam must be determined by tests or practical experience. The upstream fac is continually saturated and the downstream face is more or less damp, render ing the materials less stable than when in a dry embankment. High dams ar usually given flatter slopes than low dams and often the lower part has flatte slopes than the upper part. Low dams often have up and downstream slope

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to 1. The Ticitus Dam (New York State) is 110 feet high, has an upstream pe of 2.4 to 1 and a downstream slope of 2.5 to 1 with a 30 foot top width. Gatun Dam (Panama) is 115 feet high, has an upstream slope of 4 to 1 a downstream slope of 16 to 1 with a top width of 100 feet. It is thus seen the variation in practice is very great, depending upon the nature of the erials and the methods of placing them in the dam.

Foundations. — In preparing the foundation for earth dams the surface is stripped to a depth sufficient to reach sound material, and all loose stones, mps, roots, etc., removed. If the foundation is rock, the surface is cleaned and in making a good bond with the earth. The foundation should be mined for perviousness. If deemed necessary, one or more trenches should ng to an impervious stratum and refilled with impervious material. Between earth dam and a rock foundation is a plane of weakness which is usually rded against, in the absence of a masonry corewall, by building several low ls of masonry across the site to resist seepage of water along the rock surface.

Construction of Rolled Earth Dams. — The material for rolled earth ms is placed in layers 6 inches to 12 inches thick and well rolled with a rowed roller or otherwise compacted while damp. Sprinkling may be essary during the compacting process. It is often provided that each shed layer shall be harrowed and dampened to provide a bond with the t layer above.

Hydraulic Fill Earth Dams. — Hydraulic fill earth dams are constructed sluicing the materials into place. If available material is found at an ele- ion higher than the crest of the dam and other conditions at the site are orable, the materials are washed out of the borrow pits by a stream of water der heavy pressure, collected by the flow of the water and transported by ity through sluices to the site. The materials are discharged from the ices near the edges of the dam where the coarser particles, possessing the atest angle of repose, remain. The balance of the material is washed by e water towards the center of the dam, the particles depositing automatically d progressively according to size until only the finest particles reach the center the dam. Here a pond of water is allowed to remain through which the fine terials settle to form an impervious core.

When the materials are not located at an elevation sufficiently high to permit sluicing to the site, they are transported by cars, carts or other means to e edges of the dam and sluiced into place as above described by streams of ter.

The greatest difficulty in the construction of hydraulic fill dams is to obtain core which is composed of sufficiently fine materials to make a tight dam and ll possess adequate stability for a firm structure. If the material in the core too fine to drain properly as the construction progresses, it will exert virtually liquid pressure on the outside embankments which may be sufficient to cause em to slip. The degree of fineness in the core can be regulated by adjusting e elevation of the pool at the center of the dam, the deeper the pool the finer e size of particles deposited in the core.

ROCK DAMS. — In localities where earth is not available, broken rock as been used in the construction of dams. The rock fragments are of a size hat can be most conviently quarried and handled. Such dams are made tight by masonry corewall at the middle of the dam or on the upstream face. The atural angle of repose of loose rock is about 1 to 1 but the side slopes of rock lams should not be steeper than 1½ to 1 unless the face is hand laid to a con- iderable thickness and in any case not steeper than 1¼ to 1.

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MASONRY CONCRETE DAMS. — During the latter part o the century, rubble masonry was used extensively for the construction f d but in recent years this type has been practically superseded by plain nd forced concrete. In massive structures cyclopean concrete is gener: ly consisting of plain concrete containing a liberal percentage of large ton "plums." The usual mix for masonry dams consists of 1 : 3 : 6 (cle concrete for solid gravity and large arch dams; 1 : 2 : 4 to 1 : 2½ : 5 f inf concrete for thin arch dams; 1 : 2 : 4 reinforced concrete for decks a d s of hollow dams and 1 : 2½ : 5 to 1 : 3 : 6 reinforced concrete for butt ess hollow dams. Special provision for water tightness must be made, par icul for solid gravity dams where water pressure in horizontal joints incr ases overturning moment to be resisted.

Foundations for Masonry Dams. — Most masonry dams over 30 high require solid rock foundations. From this all soil and disintegra ed is removed and the surface scrubbed clean. All cracks and fissures at the and for some distance above it must be located and grouted. Often, in rock, a longitudinal trench is taken out and refilled with masonry to form impervious barrier to the passage of water. This is placed at the upstr face or heel of the dam (see Fig. 3).

For dams on earth foundations, a masonry or sheet piling cut-off is bu into the foundation at the heel of the dam extending down to a stratum impervious material. Where this is impractical, undermining by seepage m be prevented by providing a path of enforced percolation of sufficient leng This varies from 5 to 18 times the head on the dam according to the materia of the foundations. The proper length of path may be obtained by one or mo cut-offs, by a downstream apron, by an upstream apron or by a combinati of these. The length of the path of percolation, as affecting uplift and ero force is the length of the actual plane of contact between the structure and t earth including aprons and both sides of all cut-offs, providing the cut-offs a not closer together than twice their depth. The foundations below the da must be adequately protected from wash by proper paving.

Dimensions and Cross-sections of Solid Gravity Dams. — Typical hi solid gravity non-overflow and spillway dams are indicated in Figs. 2 and

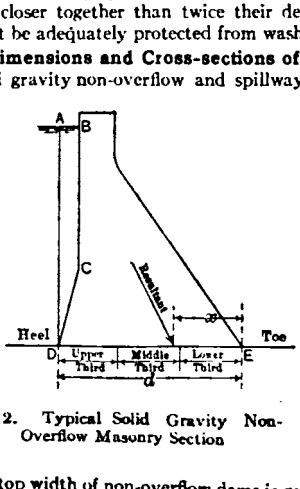


Fig. 2. Typical Solid Gravity Non-Overflow Masonry Section

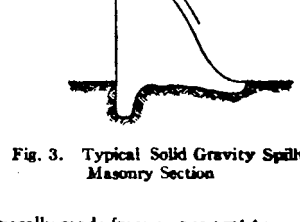


Fig. 3. Typical Solid Gravity Spillwa Masonry Section

top width of non-overflow dams is generally made from 10 per cent to 14 pe of the height of the dam and is placed at or a few feet above high water su

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. For spillway dams the top is made approximately parabolic to conform the natural path of the water as it leaves the crest. If the descending sheet free of the face of the dam, a partial vacuum will occur behind it and the spheric pressure on the upstream side will become effective as an overturning . The curve or "bucket" at the downstream side of the base is for the pose of deflecting the water and protecting the foundation. This may be ted for low dams on hard rock.

he proportions of the section below the top are possible of mathematical rmination once the forces acting on it are known. A common method is "cut and try" by which a profile is first assumed and then investigated h regard to the conditions of stability previously given. It is then adjusted l again tested until it results in a satisfactory section. It is customary to rt at the top and design the dam progressively towards the base.

l series of imaginary horizontal joints are arbitarily assumed. When the on has been tested for stability at the highest joint and has been properly sted to conform to the conditions of stability, the section of the dam is d and is not influenced by the design of the lower part of the dam. The on above the next lower joint is then tested and adjusted by changing slope of the up- or down-stream faces or both between that and the ning joint. The section to this joint is then fixed and other joints treated ke manner. This method of design applies to all types of gravity dams. ction below on *Forces Acting on Dams.*

llow Concrete Dams. — A hollow concrete dam consists of an inclined ing of reinforced slabs or arches resting on a series of parallel buttresses

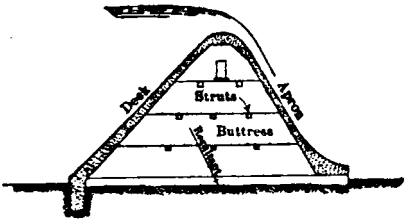


Fig. 4. Typical Hollow Gravity Spillway Section

ch have their footings on the foundations. Fig. 4 shows a section of such m designed for a spillway. With a low dam and rock foundation, the down-am decking or apron may be omitted and the face made vertical.

ability against overturning and sliding is obtained by providing a con-rable batter to the upstream face, thereby obtaining a large vertical com-ent of head water pressure to add to the weight of the structure.

rched Concrete Dams. — A typical arch dam is indicated in Fig. 5. A e of this type consists of a single masonry arch spanning the valley and is pplicable to narrow sites having steep rocky sides.

rch dams are usually treated as sections of simple cylinders and the thick-s at any elevation determined by the equation

$$t = \frac{pr}{s},$$

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where t = the required thickness in feet,
p = the horizontal load on the dam in pounds per square foot,
r = the radius of the dam in feet,
s = the allowed unit stress in pounds per square foot.

As the arch is fixed at the base and at each end, the actual stresses are in enced by expansion and contraction due to changes in temperature and mois

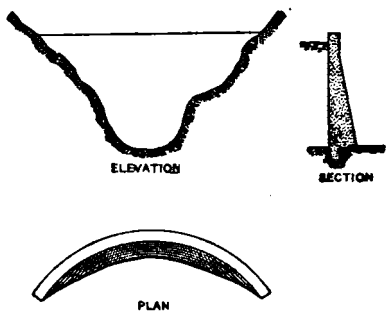


Fig. 5. Typical Arch Dam

contents, contraction due to setting of the concrete and the application of loading, variations in span and radius at different elevations and other consid tions. Theoretical analysis of these influences are considered by most engin to be impractical and allowances for deviation of stress from that indicated the foregoing equation is made in the adoption of low working stresses. T stresses should not exceed ⅛ to ¹⁄₁₂ the ultimate stress of the masonry or f about 30,000 to 40,000 pounds per square foot.

FORCES ACTING ON DAMS. — The forces usually considered in design of dams are water pressure, earth or silt pressure, ice pressure, weigh the dam and the reaction of the foundation. One linear foot is usually con ered in the design of solid dams and the distance center to center of buttre in hollow dams.

Water Pressure. — The weight of water per cubic foot is usually ta equal to 62.5 pounds.

It facilitates computations if the horizontal and vertical components of water pressure are considered separately instead of the resultant pressure.

When the water surface is at or above the top of the dam, the total horizo pressure, in pounds is,

$$P = 62.5\frac{(h_2^2 - h_1^2)l}{2},$$

where h_2 and h_1 are the vertical distances in feet of the bottom and the top the dam respectively below water surface, and l is the length in feet of d considered in the design. The location of the resultant horizontal press above the base of the dam is

$$x = \frac{3h_1h + h^2}{6h_1 + 3h},$$

where h is the height of the dam.

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the water surface is below the top of the dam, the total horizontal pressure is

$$P = 62.5\frac{h_3^2 l}{2},$$

e h_3 is the depth of water in feet. The location of the resultant above the of the dam is

$$x = \frac{h_3}{3}.$$

vertical faces the vertical component of water pressure is zero; but for ned faces the vertical component is the actual weight of water $A\,B\,C\,D$ 2), directly above the face. The resultant vertical water pressure passes ugh the center of gravity of $A\,B\,C\,D$.

he uplift pressure per square foot of the base of solid dams, due to water ing through the dam, is,

$$p = 62.5\,ch_c,$$

re c is the percentage of the area assumed to be subjected to uplift. The d. h_c, is considered to vary uniformly from headwater pressure at the heel to l water pressure at the toe. The value of c cannot be unity unless the dam re earth foundations. For rock it has been assumed variously from zero to % according to the nature of the foundation.

Total uplift pressure is,

$$P = 62.5cdl\frac{h'_2 + h''_2}{2},$$

ere h'_2 and h''_2 are head and tail water pressures respectively, d is the width d l the length of the base.

The distance of the resultant uplift pressure from the heel of the dam is,

$$x = \frac{2h'' + h'}{3(h'' + h')}d.$$

ift is also considered as existing in any horizontal building joint as well as at base. Drains are sometimes placed in dams to reduce possible head water ft pressure. Head water uplift pressure is never considered to exist to an preciable extent in hollow dams. Uplift from tail water is always present.

Earth Pressure. — Submerged earth or silt deposited against dams exerts a ssure on the structure in addition to the water pressure. The amount and ution of this pressure can be determined by the ordinary methods for retain- walls if the weight and angle of repose when submerged are used. An approx- te method for determining silt pressure is to assume it a liquid weighing 5 pounds. It will then exert a pressure equivalent to additional water pres- e of the same depth.

Ice Pressure. — Much uncertainty exists in the determination of ice pres- e on dams. Pressures amounting to 47,000 pounds per lineal foot of dam e been used in the design of important dams in cold climates. The con- uction of the gorge above the dam has considerable influence on the possible thrust. The reader is referred to the late C. L. Harrison's paper on this ject (*see Bibliography*).

Weight of the Dam. — The weight of masonry varies from 130 to 165 nds per cubic foot. The weight most commonly adopted for concrete is 140 to 150 pounds per cubic foot.

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Reaction of the Foundation. — The resultant of all forces acting on dam, including the weight of the dam, must be balanced by an equal and oppo reaction of the foundation.

Requirements for Stability. — A dam may fail by sliding, by overtur or by crushing of the materials in the dam or the foundations. This may o at the base or at any horizontal plane above the base. Sliding has been kn to occur on clay-filled seams below the base after the foundation near the has become eroded by the flowing water. A dam must therefore be inv gated for stability at various elevations, considering for each elevation those forces acting above it as though the base of the dam or a horizontal b ing joint actually existed at that elevation. The following are the fundame conditions for the design of gravity dams.

(*a*) At any elevation the resistance to sliding shall be greater than the h zontal component of all forces acting on the dam above that elevation. A sion of the dam at any horizontal joint or at the base is not considered exce an additional factor of safety. The angle that the resultant of all forces m with a vertical line must therefore not exceed the angle of repose of mas on masonry or masonry on the material composing the foundation, as indic by laboratory tests of smooth specimens. The natural or artificial rough of rock foundations and projecting plums in horizontal joints provide the ne sary margin of safety. For dams on good rock the tangent of the angle of inc tion of the resultant force with the vertical should not exceed 0.75. For d on earth foundations the tangent should not exceed 0.1 to 0.2, depending the materials, or the dam should be well anchored to deep cut-off walls piling.

(*b*) To prevent overturning, the resultant of all forces above any joint pass inside the extremity of the joint. To provide a margin of safety an prevent the existence of tension the resultant must intersect the joint at a tance from the extremity equal to at least one-third the width of the joint. other words, the resultant must fall within the "middle third" of the j and this applies to the condition of full or empty reservoirs, as tension is al objectionable. It can be shown that, if the resultant falls within either out third of the joint, tension will exist at the opposite side of the dam.

(*c*) The compressive stresses in any part of the dam must not exceed working values. The unit stress on any joint is assumed to vary as a stra line from the heel to the toe. If the resultant force intersects the joint a exact center, the unit stress will be uniform over the joint. If the resul intersects at any other point, the stress will be a maximum at the edge of base nearest the point of intersection and a minimum at the other end.

In Fig. 2, let

p' = the unit *vertical* stress at E;
p'' = the unit *vertical* stress at D;
x = the distance from the resultant to point E;
d = the width, DE, of the joint;
l = the breadth of the joint;
w = the vertical component of all forces on the dam above the joint inc ing uplift at the joint;
p'_u = the unit uplift at point E;
p''_u = the unit uplift at point D.

Let these quantities be expressed in feet or pounds per square foot. T if the resultant intersects the joint within the middle third and the joi rectangular,

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$$p' = \frac{2w}{ld}\left(2 - \frac{3x}{d}\right) + p_s',$$

$$p'' = \frac{2w}{ld}\left(\frac{3x}{d} - 1\right) + p_s''.$$

he maximum *inclined* stress in the dam may be twice the value given by e equations for *vertical* stresses. Therefore due allowance must be made in selection of working *vertical* stresses or the maximum inclined stresses mined by extended calculations.

ertical pressures should not exceed ½1 of the ultimate strength of the masonry, om about 16,000 to 22,000 pounds per square foot.

PPENDAGES TO DAMS. — The more common appendages to dams the following:

hice Gates. — As their name implies, these are large gates placed in the l for the control of the water level, or for relieving the dam in times of flood. mmon type of gate is the so-called Tainter gate, which is slightly curved revolves about its axis of curvature. A later improvement on this is the ll gate, which permits of finer regulation.

Flash Boards. — These are light boards, or their equivalent, placed on the p of the spillway held in position by light rods or frames. Their object o temporarily increase the height of the dam during the dry season so as to serve the water which would otherwise be wasted over the spillway at times en the wheels were not running. They are made light not only to facilitate idling, but also that they may give way quickly in emergency before a dan- ous head could be created by sudden flood.

Log Runs. — On any stream where the driving of logs is practiced, it is gen- lly a requirement that provision be made in a dam for the sluicing of logs. is is accomplished by a chute or trough placed generally near the spillway, th its upper end slightly below the pond level and closed by a sluice gate. this the logs are guided by log booms fastened to the dam and cribs along shore.

Fish-ways. — A fish-way is a gradual incline connecting the water below dam with the pond above. A constant stream of water passes through it th a velocity against which the fish may readily swim. This is sometimes tained by using baffles across a portion of the stream, leaving a passageway the side. The slope of a fish-way should not be greater than 1 in 4 and its ds should be well beneath low water level. Fish-ways are generally more or s covered in order to protect the fish from interference, but should never be ole dark, as they would not be used by the fish. Fish-ways are generally quired by State law on all natural water ways.

COST OF DAMS (Pre-war figures). — It is difficult to give items of cost r dam construction, due to the great influence of local conditions. As earth bankments should not be attempted in places where material is not available ar the site, the figures for unit cost may be fairly well approximated. Exca- tion in earth will cost from 20 to 30 cents per cubic yard; embankment 25 to cents; puddle cores 45 to 70 cents; hand-laid paving $2.00 to $3.00; rip-rap .50 to $2.00; sodding 20 to 30 cents per square yard. Figures for masonry sts depend largely on the ease with which the materials may be brought to e site. The following figures serve to show approximately the unit costs der conditions normally favorable. Rock excavation $1.00 to $2.00; rubble

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masonry laid in natural cement $3.00 to $5.00; same laid in Portland cem
$4.00 to $6.00; concrete masonry, Portland cement, $5.00 to $7.00; reinfo
concrete $7.00 to $11.00; rock-faced stone masonry $10.00 to $15.00; dimen
stone masonry $15.00 upward.

BIBLIOGRAPHY. — Some of the more important books treating of d
are the following: Creager, *Engineering for Masonry Dams;* Smith, *Const
tion of Masonry Dams;* Wegmann, *Design and Construction of Dams;* Morr
and Brodie, *Masonry Dam Design;* Parker, *The Control of Water;* Bligh,
Practical Design of Irrigation Works; Etcheverry, *Irrigation Practice and F
neering,* Vol. III; Thomas and Watt, *Improvement of Rivers;* Mead, W
Power Engineering.

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CIMAL EQUIVALENTS. — The following table will be found useful nverting common fractions into decimals.

10ths	32nds	64ths	Decimal	8ths	16ths	32nds	64ths	Decimal	8ths	16ths	32nds	64ths	Decimal
		1	0.015625			11	22	0.34375				43	0.671875
	1	2	0.03125				23	0.359375		11	22	44	0.6875
		3	0.046875	3	6	12	24	0.375				45	0.703125
1	2	4	0.0625				25	0.390625			23	46	0.71875
		5	0.078125			13	26	0.40625				47	0.734375
	3	6	0.09375				27	0.421875	6	12	24	48	0.75
		7	0.109375		7	14	28	0.4375				49	0.765625
1 2	4	8	0.125				29	0.453125			25	50	0.78125
		9	0.140625			15	30	0.46875				51	0.796875
	5	10	0.15625				31	0.484375		13	26	52	0.8125
		11	0.171875	4	8	16	32	0.5				53	0.828125
3	6	12	0.1875				33	0.515625			27	54	0.84375
		13	0.203125			17	34	0.53125				55	0.859375
	7	14	0.21875				35	0.546875	7	14	28	56	0.875
		15	0.234375		9	18	36	0.5625				57	0.890625
2 4	8	16	0.25				37	0.578125			29	58	0.90625
		17	0.265625			19	38	0.59375				59	0.921875
	9	18	0.28125				39	0.609375		15	30	60	0.9375
		19	0.296875	5	10	20	40	0.625				61	0.953125
5	10	20	0.3125				41	0.640625			31	62	0.96875
		21	0.328125			21	42	0.65625				63	0.984375

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DEMAND METERS. — (*See also Ammeters; Ampere-hour Meters; W hour Meters; Wattmeters.*) For some time past various attempts have b made to inaugurate systems of charging for electric energy which would more equitable to both the consumer and the central station than a flat kilo or kilowatt-hour rate. The so-called "maximum demand system" has fo favor with many, and may find a much more general application.

The system is based on the fundamental assumption that the charge to consumer should be made up of two parts; one part fixed by the maxim power in watts demanded by the consumer at any time during a certain defi period, and another part fixed by the total energy in kilowatt-hours used du the same period. The object of the demand system of charging is the impro ment of the load factor of the station and the more equitable distribution o fixed charges among its customers.

Demand metering cannot be regarded as an exact science, because of large number of variables involved and the various ways in which they e the problem. These include the capacity of generators, lines and transform and the diversity factor, load factor, and power factor of the system. No p tical meter can be devised to take care of all these variables, consequently char based on the use of demand meters in addition to the usual energy meters m necessarily be somewhat arbitrary.

Requirements of a Demand Meter. — The kilowatt-hours supplied the consumer are readily measured by a watthour meter (q.v.); to record maximum power (kilowatts) taken by the consumer, various forms of "maxim demand meters," usually called simply "demand meters," have been devis In the case of a practically constant d-c. voltage at the consumer's premise device which measures the maximum current is as satisfactory as one wh measures maximum power, but when the voltage or power factor (in case of a-c. system) varies, the maximum current indicator is not suitable.

In any case the device should be one in which the demand measured is the instantaneous peak of the load demanded by the consumer, but is the av age of the power demanded over an appreciable time interval, for the maxim demand recorded should not be influenced by short-circuits, excessive curr flow in starting motors, or by any abnormal consumption of energy that cov too short a time to have any real effect on the capacity which must be provi by the central station to take care of the demand.

The time interval over which the demand should be taken should theor cally differ with the character of the installation and the relation of the maxim power demanded to the maximum capacity of the central station. In relativ large consumers' installations the time should be carefully chosen with ref ence to the time that the central station can endure an overload successfu Hydroelectric plants have a very definite power limit which is reached w maximum gate opening, while steam-power plants have considerable ther inertia and their boilers and generating apparatus can usually carry relativ large overloads for a considerable time. These considerations require m shorter time intervals for large users of hydroelectric power than would necessary in steam plants of corresponding magnitude.

Demand intervals of 15 minutes, 30 minutes, and 1 hour are those in gen use at the present time. For very special installations, intervals as short 1 minute and as long as 3 hours have been used. The general tendency is to the use of a single interval for a given system, and toward the use of inter larger than those formerly used.

On account of the desirability of improving the load factor, the off-p system has been developed, which gives a preferential rate to customers u

current during the times of low load on the central station. Demand meters ng time of day as well as demand are used for this class of metering.

he general subject of demand meters has received considerable attention ng the past five years and many devices have been developed and placed he market. The whole question of charging for electric service, including ecessary devices to be used, is still in a transition state, and is complicated the inclusion of the power factor and balance of the customer's load as ele- ts in determining the cost of supply.

lassification of Demand Meters. — Demand meters may be classified) (1) curve-drawing instruments, giving the load-time curve of the installation; integrated-demand meters, consisting of an integrating meter combined h a device which registers the energy consumption from time to time in such ay as to indicate or record the maximum demand; (3) lagged-demand ters, which require a certain time interval for the indication to reach the value responding to the load. Under each of these types there are a number of ther distinctions, such as length of demand interval, whether the demand rvals begin at specified times of the day or may be so chosen as to include the ximum average load during any time interval of the given length, and whether maximum demand is simply indicated without reference to time or is recorded hat the time of its occurrence may be determined. Some of the types of meters in commercial use are briefly described below.

Curve-drawing Instruments as Demand Indicators. — (*See also Watt-ter*.) The most complete knowledge of the conditions attending the con- er's use of energy may theoretically be obtained by using a curve-drawing ttmeter, with which the average demand for any time interval may be found d also the time at which it occurred. This statement, however, requires siderable modification in practice. Unless the paper speed is fairly high, e lines will run together so as to make it difficult or impossible to determine e demand with any approach to accuracy. Curve-drawing wattmeters are expensive in first cost for any but comparatively large installations, and e of the simpler and cheaper devices described below is ordinarily used. The fications of a curve-drawing wattmeter are difficult of comprehension for the inary customer who knows nothing of integration. Such wattmeters are d largely by central stations to accumulate demand data. Curve-drawing meters may be used on the assumption of constant voltage and power factor, t do not give as accurate information as wattmeters.

Integrated-Demand Meters Indicating Maximum Demand Only. — he Type M-4 demand meter of the General Electric Company consists essen- lly of a demand-registering and a timing mechanism mechanically connected d mounted within the same case. The demand-registering element is electric- ly operated by means of a contact in the register of the watthour meter in con- ction with which the demand meter is used. The registering element consists a train of gears which drive a demand pointer forward over a dial. This ain is actuated by a ratchet and pawl mechanism operated by an electromag- t which receives an impulse every time a certain amount of energy is regis- red by the watthour meter. The speed of advance of this pointer is therefore portional to the power. In order that the meter may show the demand for iven time interval, it is necessary that the pointer-driving mechanism shall reset to zero position at the end of each time interval, leaving the pointer lf in the highest position reached. This resetting is accomplished by a e hanism controlled by a constant-speed motor similar in construction and peration to the motor element of an induction watthour meter. This demand ter is for use on a-c. circuits, and is arranged for intervals of 15, 30, or 60 inutes. The Type M-5 demand meter for d-c. circuits is similar to the pre-

ceding, but has an 8-day keywind clock to give the time interval. The T
M–6 demand meter differs from the M–5 in having a small d-c. motor to k
the clock movement wound. The latest development of this series is the I
demand meter register, Fig. 1. This replaces the standard register of either

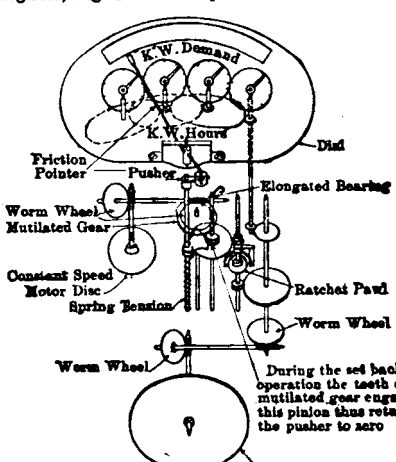


Fig. 1. Type M–7 Demand Meter Register.

I–14 or D–6 watthour meter. In addition to the usual four kilowatt-h
dials, it contains a demand dial. The principle of operation is the same
that of the other demand meters of the Type M series, but the timing devic
a small disk-type constant speed induction motor built into the register.
the M–7 the demand registering mechanism is thus mechanically connec
to the watthour meter, instead of electrically as in the preceding Type M dema
meters. When new I–14 or D–6 watthour meters are supplied with this fu
of demand register they are called respectively Type IM–14 or DM–6 wa
hour demand meters.

The Type RO watthour demand meter of the Westinghouse Company i
combination of induction watthour meter, induction wattmeter, and an esca
ment mechanism. The auxiliary disk of the wattmeter is located in the sa
air gap as the watthour meter disk, and tends to move against the torque o
spring. This tendency is checked by an escapement controlled by the rotati
of the watthour meter disk. The auxiliary disk thus advances step by st
at a speed proportional to the load until the driving torque is equal to the spri
torque. Starting from zero, the time required to reach equilibrium on a
constant load is a constant, since the deflection and the rate of deflection va
in direct proportion. The auxiliary disk drives a demand pointer through a d
and a ratchet holds it in the highest point reached, until released by hand.
second ratchet allows the auxiliary disk to fall back to the position of equilibri
with the spring tension whenever the load drops, but prevents it from advan
ing except as controlled by the escapement.

**Integrated-Demand Meters With Arbitrary Time Interval, Recordi
all Demands and Time of Occurrence.** — The earliest instrument of t

was the printometer, later made by the General Electric Company as the : P demand meter. This instrument is designed to print on a paper tape guiar time intervals the time of record and the consumption of energy up nt time, the energy consumption being that registered by a watthour r connected to the circuit. The instrument contains a set of cyclometer wheels which are moved forward at a rate proportional to the rate of energy mption in the circuit. This is accomplished by a solenoid, the energiz- ircuit of which is closed through a contact wheel fixed to one of the spindles e gear train of the watthour meter. The reading of the cyclometer is printed paper tape (see Fig. 2) by a rubber platen and a copying ribbon, the rubber n being actuated by a solenoid which is energized at regular time intervals eans of a contact making clock. The time is also printed opposite each

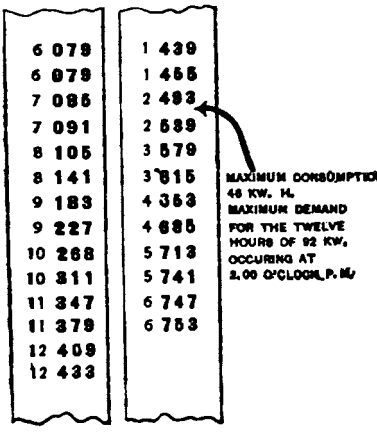


Fig. 2. Record Made by Type P Demand Meter.

ometer reading. Thus, the difference between consecutive records on the pe is proportional to the energy consumption in watt hours in the circuit ring a definite time interval. The average demand over a period of time, responding to the interval between successive operations of the printing lenoid, is obtained by dividing the watthours of energy consumption during time interval by the length of the interval.

The Type RA recording-demand watthour meter of the Westinghouse Com- ny consists of a polyphase watthour meter combined with a mechanism for taining a permanent graphic record of the integrated demand over successive determined time intervals. The total energy consumption is shown in the ual way by the register of the watthour meter. The time interval is con- lled by a clock which requires winding once a month. A separate spring chanism advances the record paper. The pen is moved across the paper by e gear train of the watthour meter, and at the end of each time interval a lease mechanism frees it from the gear train and allows a weight to move it ck to zero where it is again meshed with the gear train to repeat its advance ring the next time interval. Just before the release occurs, the record paper advanced slightly (see Fig. 3) so that the pen makes a distinct record of the aximum travel, which is a measure of the integrated demand. The time of

occurence is shown by the time figures printed on the paper. This met made with time intervals of 15, 30, or 60 minutes. It is a self-contained ture, with the metering and demand-recording mechanisms mechanically nected.

The Piek demand instrument, which was the forerunner of the Type demand meter, is very similar to the latter, but uses the same clock to esta the time intervals and to drive the chart.

The Type G demand meter of the General Electric Company is used in nection with a watthour meter, and gives a graphic record on a circular of the demands integrated over definite time intervals, with the time of and day of week of their occurrence. It consists essentially of a regist element and a timing element. The registering element is electrically conne

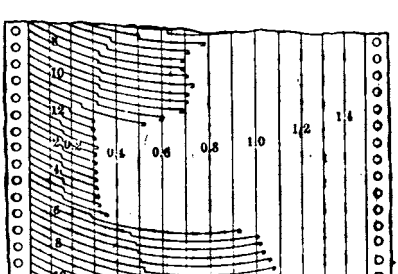


Fig. 3. Record Made by Type RA Recording Demand Watthour Meter.

to the watthour meter, which has a contact device on one of the spindles of register. This contact device alternately makes and breaks the circuit solenoid in the registering element each time that a definite amount of ene is registered by the watthour meter. An armature operates a ratchet and p mechanism to advance the stylus by a small step for each operation of the tacts. At the end of each time interval a cam mechanism operated by the ing device allows the stylus to return to the zero position, where it is re-enga ready to integrate the energy used in the following interval. The timing mech ism rotates the chart continuously, giving a record in the form of a saw-to polar curve. The chart gives a record for one week. The time interval is eit 15, 30, or 60 minutes.

Integrated-Demand Meters Recording Time and Equal Amou of Energy, Non-Arbitrary Time Interval. — The Ingalls demand records operated in connection with a watthour meter. It contains a clock wh uniformly advances a tape upon which a mark is made by a printing sole energized through contact in the meter register. Each mark corresponds t predetermined amount of energy. The number of marks in a given time int val is proportional to the average power.

Thermal-Storage Lagged-Demand Meters. — These meters all al maximum demand only, and the indication depends on the duration of the l as related to the "demand interval" of the meter, as well as on the previ history of the load. The demand interval of this type of meter is usually tal as the time required for the indication to reach 90 per cent of the full value e steady load which is thrown suddenly on it. In principle, all such meters differential thermometers.

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le **Wright demand** indicator, manufactured by the General Electric Com-, is a **differential** air thermometer having one of the bulbs surrounded by a ing **element.** The expansion of the air in this bulb drives a liquid over into iduated **tube,** giving a measure of the ampere demand. It is suitable for n constant-voltage circuits, either direct current or alternating current nstant power factor. It leaves no record of the duration of the maximum nd nor of the time at which it takes place. After the indicator has been there is no original record of previous maximum demands.

le Type H—2 demand indicator of the General Electric Company is an re-demand instrument also based on the differential thermometer prin-, but using a pair of strips of thermostatic metal. One of these is in prox-y to a heating element traversed by the load current, while the other nomi-y follows the room temperature. The two strips tend to move in opposite ctions, and with no current flowing through the heating device the pointer ains at zero in spite of changes in room temperature. Current flowing ugh the heating device heats the adjoining strip and moves the pointer r the scale. The pointer remains at the highest point reached until manually e.

he Westinghouse Type RH demand meter employs the principle of the hot-r wattmeter, and thus takes account of watt demand. It contains two heat-elements which tend to move a demand pointer in opposite directions. The rical arrangements are such that the difference in the heating is propor-nal to the power in the circuit, and the thermal capacity of the heating ele-nts makes the reading depend also upon the storage of heat in them. The and pointer remains at the highest point reached until manually reset.

Overdamped-Wattmeter Lagged-Demand Meter. — The Type W poly-se demand indicator of the General Electric Company consists essentially a polyphase watthour meter with a system of springs opposing the rotation he disk and thus converting it into a polyphase wattmeter. A large number damping magnets are used, giving heavy overdamping and preventing the er from recording demands of short duration. The rotation of the disk inst the opposing springs moves a demand pointer forward, and this pointer ains at the highest point until manually reset. This type of demand meter ow but little used.

Demand Devices Taking Account of Power Factor. — The increasing reciation of the effect of low power factor on the cost of energy supply is ining to show in the development of demand devices taking power factor account. For example, the Westinghouse Company has made an instru-t consisting of two Type RA watthour demand meters in one case with r charts interlocked and driven by the same clock. One of these meters is nected to record power demand and the other records reactive-component rand. The same object is also attained by the General Electric Co. with Type P demand meter used in connection with a watthour meter and a ctive voltampere-hour meter.

COSTS. — The following figures are approximate and are intended as a gh guide.

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Type	Description	P
Integrated-Demand Meters, maximum demand only:		
Types M–4 and M–5	15, 30, or 60 min. interval....	$22 t
Type M–6.....		
Type M–7 Demand Meter Register.....	.....	17 t
Type IM–14.....	2-wire or 3-wire single-phase..	25 t
Type DM–6.....	3-wire polyphase.....	49 t
Type RO.....	2-wire or 3-wire single-phase..	29 t
Type RO.....	3-wire polyphase.....	57 t
Integrated-Demand Meters, all demands and time:		
Types P–2 and PS–2.....	.....	118
Type RA (Polyphase).....	15 30, or 60 min. interval....	115 t
Type G–2.....	15, 30, or 60 min. interval....	65
Lagged-Demand Meters:		
Type H–2 Demand Indicator.....	Maximum amperes 2 to 25..	6
Type RH Demand Meter...	5 to 30 amps., 110 volts; used with instrument transformers for higher capacities...	22 t

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See also Section X of the *Code for Electricity Meters*, prepared by the cal Testing Laboratories for the Joint Meter Committee of the Associ Edison Illuminating Companies and of the National Electric Light Asso This section is given in the 1920 Report of the Committee on Meters National Electric Light Association.

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RECIATION. — Depreciation is loss of value due to expiration of use-
fe. It is brought about by wear and tear and the action of the elements
l eventually make replacement necessary. *Service value or serviceability*
ar may not suffer diminution as depreciation accrues. Depreciation does
roperly include loss of value due to accidental damage, to obsolescence,
adequacy or to price changes. Replacements due to accidents such as
ay be covered by insurance. If not, they should be charged directly to
ition or amortized over a reasonable period. Replacements due to obso-
ce or inadequacy should be financed from the savings resulting from the
f the more modern or adequate equipment. As for market or price changes,
impossible to show property on the books at its value under constantly
ating prices. The accounting problem involved in making replacements
id at changed price levels is discussed below. Depreciation as specifically
ed * is accrued liability to replace and it involves four problems which may
scribed as follows:

First, *physical*, to determine the amount of the liability at any time and the rate of its accrual.
Second, *financial*, to make provision for meeting the liability.
Third, *accounting*, to keep the proper records.
Fourth, *management or regulation*, to determine the effect of the accrued and accruing liability on the economic position of the enterprise whose assets are under consideration.

HE PHYSICAL ASPECT. — A piece of property whose useful life has
d has suffered depreciation to the extent of the difference between its
e when new and its scrap value. This difference is called the wearing
e. Various assumptions may be made as to the distribution of the depreciа-
over the life of the property, but the usual practice is to assume it uniform.
a the annual depreciation is equal to the wearing value divided by the life
ears. The accrued depreciation at any time is equal to the product of the
al depreciation and the age in years.
ore the extent and rate of depreciation must be known while the property
ll in service, if proper provision is to be made for replacement, the life used
letermining the annual depreciation must be a prediction. Such a predic-
can be made only on the basis of experience, and is a subject for the best
neering judgment, since many factors, such as severity of use, quality of
erial and of workmanship, and climatic conditions, must be considered.
les of lives of various classes of property have been prepared, but should be
l with discretion, since they are unreliable, for the following reasons among
rs. First, many of the renewals considered by the compilers to be due to
reciation were due to obsolescence or inadequacy. Second, improvements
he arts are continually increasing the durability of many classes of equip-
t. Third, replacements are at times postponed past the time when true
omy would dictate replacement because of the financial situation of the
ing company, and as a result, the experience recorded becomes an unreliable
le. In the bibliography appended reference is made to tables of lives which
be used as a guide to judgment.
requently it is desired to create a reserve which will provide for replacing
perty made up of parts having different lives whose independent replace-

* The term "depreciation" has through use by courts and regulatory commissions
e to have the specific and somewhat narrow construction defined above. In gen-
usage, the word "depreciation" denotes decrease in value from any cause, but
mission is here confined to the more technical use of the term.

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ments are to be charged to depreciation, and it is desired to place a lif piece of property as a whole. This is properly done by dividing the su wearing values of the parts by the sum of their annual depreciations, the being the composite life. The weighted average life of the parts, the v figures being the wearing values of the respective parts, cannot be use of the composite life defined above. To be correct, the average life further weighted by the relative frequencies of renewal of the respecti The test of a composite life is that the wearing value of the property covers shall, when divided by it, give the annual depreciation for t property. This the first method assures, but the second does not.

The scrap, or salvage value of a piece of property is a subject for en estimate. The expense involved in preparing for market and marke scrap is a deduction from the scrap value but the cost of removing th be replaced is a charge to operation.

In certain types of property, life can better be measured in service u in time units. However, in the case of a large and varied property, thi of general application, forms the most satisfactory basis for computing tion.

As the operation of a property continues, the engineers responsible f mining depreciation must constantly check up and revise their opinions lives of various units, basing their conclusions on the frequency of r due to depreciation, as proved in practice. The rate of accrual of dep should be refigured from time to time on the basis of these studies. At an estimate should be made of the depreciation accrued on the prope making this estimate it must be understood that accrued depreciation o liability to replace is a physical fact, independent of the assets accrued the liability as reflected by the balance sheet, and the estimate must b titative statement of that physical fact, as nearly as it can be determine

THE FINANCIAL ASPECT. — As depreciation and the co replacement liability accrues, it is necessary to build up assets to offse this end a portion of the revenue derived from the operation of the should be retained by the corporation for that purpose. Building u to offset the depreciation liability gives assurance that the property will tained in its full usefulness and earning power in so far as these are gov its physical condition. In public utility mortgages, it is frequently that a certain percentage of the gross operating revenue shall be exp reserved for the maintenance of the property. Such provisions ha thought to be particularly necessary where, (*a*) operation cannot be disco (*b*) property cannot be removed to another location, (*c*) scrap or recove of physical property is so small a proportion of original cost as to be of n importance to the creditor. These reasons, while controlling with the do not prove the value of this method of measuring maintenance and tion requirements.

Building up assets offsetting accruing replacement liability serves tain the equity of the stockholders as well as to protect the physical and the earning power of the creditor's security. If the funds required care of replacement are paid out in dividends a partial liquidation tak which may or may not be sound business, but in any event the fact s clearly understood by all concerned, and clearly reflected by the books of

In the case of a property made up of many parts having different liv time, after the initial construction, will all parts be new at once. T the assets reserved to offset depreciation will never all be needed for f replacements. From this it may be argued that it is necessary to rese enough funds to meet such abnormal amounts of replacement expendi

sionally occur. Under this plan no distinction would be made between ntenance and depreciation, so much each month being set aside out of ne, the amount being revised from time to time as found necessary, and all maintaining the property paid out of the reserve. If this plan is followed st be recognized that the company's assets have been allowed to decrease that the depreciated value of the property, plus the reserve, is less than its nal cost. This consideration is particularly pertinent in the case of a lated utility.

reserving funds for effecting replacement due to depreciation various hods are used for determining the amount to be periodically set aside. metimes it is made a fixed percentage of the gross receipts. Sometimes it is nform amount arbitrarily fixed. These methods have only simplicity to mmend them. The correct system is to make the reservations in accord- with the accrual of depreciation as determined by the engineers. Two hods have been generally used. One is the straight line method in which set up for each piece of property is equal to the wearing value of that piece perty divided by its life. The other is the sinking-fund method in which set-up for each piece of property is of such amount that, when the piece of perty has reached the end of its life, the sum of the set-ups made on its unt shall, with the compound interest accumulated on those set-ups, equal wearing value. In the second case the reserve fund must be credited period- ally with interest upon accumulated balances at the rate used in computing set-ups. This interest may be charged either against income or surplus. latter method is well adapted to the case of regulated utilities, as will be ussed later.

The assets set aside or retained to offset depreciation may be handled in ious ways. Specific assets, such as bank deposits and interest-bearing securi- s may be designated as a depreciation reserve fund, and kept equal to the reciation liability as shown on the books, or the offsetting assets may be ed to remain a part of the general assets and used in the business. The ter method is usually preferred, since a going concern can, as a general thing, ve a larger return from capital used in the business than in that invested side. However, care must be exercised that there is always a sufficiency of ck assets to meet any sudden demand. In theory, when expected replace- ts become necessary, they may be financed by borrowing money on the erity of the property in which the reserve against depreciation has been sted. This, however, is not generally practicable due to the provisions of r liens.

The Accounting Aspect. — It is highly important that the accounting atment of depreciation reflect accurately both the lessening of remaining life physical plant and the financial plan by which provision is being made for lacement. The accounting processes involved are primarily: (*a*) Current ges to depreciation reserve either by charges to income or appropriation of plus.* (*b*) The crediting of interest to the reserve where current reservations calculated on the sinking fund basis. (*c*) The segregation of assets against reserve liability or funding. (*d*) The auditing of charges against the reserve the purpose of determining their propriety in the light of the basis on which dits to the reserve have been made.

There is not always a clear distinction between maintenance charges to be ded in current operating expenses, and replacement charges to be made

*In the case of a company which has not from the beginning made provision for lacement of physical property, and in which considerable depreciation has already rued, the initial charge in establishing such a reserve, if it is to cover depreciation rued, must be against surplus.

against the reserve. The final test must always be whether or not th has been built up from credits calculated to cover charges such as th question. In a business where assets are progressively exhausted, as in of a mine, the reserve account may be dispensed with by making the dep credits direct to property. This practice is not proper in the case of a co enterprise.

Expenditures which serve to increase the investment in a prop chargeable to construction. When a piece of property is replaced by which by reason of greater size, superior quality, or higher price level co than the original piece, the procedure is as follows, assuming that an equal to the wearing value of the original property has been accrue depreciation reserve. The amount realized from scrap or salvage is cr the depreciation reserve to bring the amount in the reserve up to the full cost of the item to be replaced. The original cost is then written out of and plant account and depreciation reserve concurrently reduced. Th of the cost of the replacing unit is then added to property and plant acc result being to increase property and plant account by the excess cost of property. In case the new property costs less than the old, there will credit to property and plant. This is sound accounting, since the account should represent the actual cost of the existing property at all

In case the piece of property is replaced for reasons other than depr the depreciation accrued should be charged against the reserve, and the re of the cost of replacement cared for in other ways. For example, if a mated to last 30 years is accidentally destroyed at the end of 10 years, on of its cost will have been accumulated in the reserve. The balance of the at which the car is carried in the property account must either be appr from surplus, charged to operation, or set up as a suspense item, and a over an appropriate period. The latter method would be used ordina in cases where large amounts are involved. The proper division of ch such cases involves engineering judgment.

Reference has been made to periodic engineering estimates of the accrued depreciation. These estimates should be used to check the ba

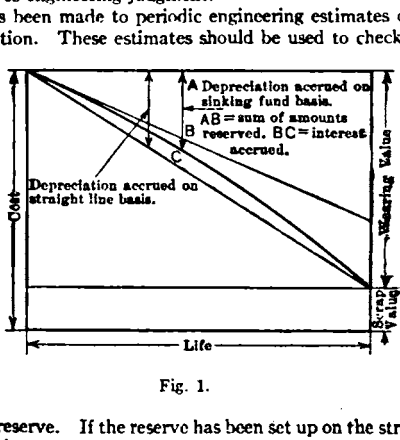


Fig. 1.

the depreciation reserve. If the reserve has been set up on the straight li and the accrued depreciation estimated on the same basis, the two shou general agreement. If the reserve has been set up on the sinking fund should be somewhat smaller than the depreciation estimated to be acc the straight line basis since in the case of any given piece of property, the

als including interest will be more rapid in the latter part of its life than in
arlier part. (See Fig. 1.) If the reserve is found to be too large or too
l by a substantial amount, the amounts currently reserved should be
ased or increased with the object of bringing the balance in the reserve
into line. Usual practice does not provide for accumulating an amount
e reserve in excess of original cost less salvage, therefore cost of removing
nit to be replaced must be charged to operation.
he foregoing comments on the accounting aspects of depreciation further
e the engineering problems involved, rather than accounting procedure.

The Management or Regulatory Aspect. — In the case of property
in unregulated competitive business, the value at any time is the cost at
nt prices of a property which can be used for the same purpose, less the
ued depreciation, the latter being computed as the product of present cost
salvage, and the percentage of expired life. It is necessary to deduct the
eciation in order to obtain a measure of the service which can still be
ained from the property. It is necessary to know the rate of accrual of
eciation in order that the management may know whether or not the busi-
is presently profitable and to know the accrued depreciation in order that
balance sheet may show the true condition of the property.
In the case of regulated utilities, frequently, though inaccurately, described
non-competitive, value is fixed by a regulatory body subject to judicial
view. No final rule of general application has been enunciated, though vari-
elements of value have been specified and defined. It is generally agreed,
ever, that, in any event, the rates allowed must provide for current operat-
expenses and reserve for depreciation, before they can provide for return on
value fixed. Since the function of the depreciation reserve is to provide for
acement at original cost, (increases or decreases in cost being cared for
ugh capital account) "original cost," not "present value," is considered here.
the depreciation reserve accumulates and is invested either in extensions to
utility's plant, or independent thereof, it furnishes a source of income aside
n that earned by the original property.
f the reserve has been set up on a straight line basis, the original cost of the
erty, plus the assets which offset the reserve, less depreciation accrued,
s the original investment. If the offsetting assets are invested so as to
a return equal to that allowed on utility property, it is fair to fix the earn-
from utility operation so as to yield a return on the property at its
ciated value, but if this is done the earnings of the reserve are a part of the
porate revenues and should go to the owners. But it is seldom possible to
vest so advantageously and still fulfill the essential requirement of having
assets readily available for financing replacements. If a return is allowed
the undepreciated cost of the property, then the income from the invested
ve should be considered part of that return and the balance collected in
n. If, however, the depreciation reserve is set up on a sinking fund basis,
earnings of the reserve are needed as a part of the reserve, and are not
ilable as return. Then the company must be allowed in rates a return on
undepreciated cost of its property. As the income from the reserve appears
porate income, the interest payments to the reserve should be made out
rporate income. Since normally a part of the reserve will be invested in
ity property, and part in quick assets, the interest rate used in calculating
its to the reserve must be a compromise between the return allowed on
ity property and that obtainable from quick assets.
In cases where the depreciation reserve is less than the accrued replacement
ity, to the extent that returns to investors have been excessive, it may
rly be considered that partial liquidation has occurred. Where returns

have not been excessive and rates have been insufficient to permit full rese tion to cover replacement liability, equitable consideration must be give that fact.

Calculations. — The following notes are illustrative of the calculations ne sary to determine the proper amounts to be currently reserved for the pur of financing replacements.

Let C = cost of property,
S = scrap value,
n = life in years,
r = annual interest rate,
A = annual reserve credit,
M = monthly reserve credit.

Then, on the *straight-line* basis:

$$A = \frac{C-S}{n},$$

$$M = \frac{A}{12} = \frac{C-S}{12n}.$$

On the *sinking fund* basis:

Assume first that the reserve credit is made annually and interest is cred annually, then:

Case I.—If interest *is* allowed each year on that year's reserve credit, set-up made at beginning of year:

$$A = (C-S)\frac{r}{(1+r)^{(n+1)}-(1+r)}.$$

Case II.—If interest *is not* allowed each year on that year's reserve credit, set-up made at end of year:

$$A = (C-S)\frac{r}{(1+r)^{n}-1}.$$

Assume next that the reserve credit is made monthly and interest is cred monthly, then:

Case III.—If interest *is* allowed each month on that month's reserve cre *i.e.*, set-up made at beginning of month:

$$M = (C-S)\frac{\frac{r}{12}}{\left(1+\frac{r}{12}\right)^{(12n+1)}-\left(1+\frac{r}{12}\right)}.$$

Case IV.—If interest *is not* allowed each month on that month's rese credit, *i.e.*, set-up made at end of month:

$$M = (C-S)\frac{\frac{r}{12}}{\left(1+\frac{r}{12}\right)^{12n}-1}.$$

Illustrative Example: Cost of property $1000. Net scrap value $200. I 10 years. Interest rate on depreciation reserve 4%.

On the straight-line basis:

$$A = \frac{1000-200}{10} = \$80,$$

$$M = \frac{80}{12} = \$6.67.$$

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On the *sinking fund* basis:

Case I.

$$A = (1000 - 200)\frac{.04}{(1.04)^{11} - 1.04} = \$64.07.$$

Case II.

$$A = (1000 - 200)\frac{.04}{(1.04)^{10} - 1} = \$66.63.$$

Case III.

$$M = (1000 - 200)\frac{.00\frac{1}{2}}{(1.00\frac{1}{2})^{121} - 1.00\frac{1}{2}} = \$5.41.$$

Case IV.

$$M = (1000 - 200)\frac{.00\frac{1}{2}}{(1.00\frac{1}{2})^{120} - 1} = \$5.43.$$

In large enterprises it is the usual accounting practice to make credits to the reserve each month. It will be seen that the difference between the monthly reserve credits determined under Case III and Case IV are less, in proportion, than the probable error in the life assigned to the property.

Composite Life. — A piece of property is made up of two parts. The first part has a wearing value of $2000 and lasts 20 years; the second part has a wearing value of $1000 and lasts 10 years. Depreciation reserve is credited on the straight-line basis:

W. V.	Life	Annual Set-up
2,000	20	100
1,000	10	100
3,000		200

The composite life is 3000 divided by 200 = 15 years. If life is weighted by wearing value, it averages as follows:

W. V.	Life	Product
2,000	20	40,000
1,000	10	10,000
3,000		50,000

The weighted average is 50,000 ÷ 3000 = 16⅔ years. Dividing the wearing value by this gives 300 ÷ 16⅔ = $180 for the annual reserve credit which is sufficient by $20. If frequency of rewewal is introduced we have the following:

W. V.	Relative Frequency of Renewal	Product	Life	Product
2,000	1	2,000	20	40,000
1,000	2	2,000	10	20,000
		4,000		60,000

The weighted average is 60,000 ÷ 4000 = 15 years, which is correct.

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TABLES OF LIVES OF PHYSICAL PROPERTY AND ANNUAL PER CENT DEPREC

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Numerous Commission decisions contain data on life of physical pr those most quoted being the decisions of the California and Wisconsin R Commissions.

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RIVATIVES. — (*See also Equations, Differential; Integrals; Maxima and ima; Series, Mathematical*).

ifferentials. — Let y be a function of x, i.e., a quantity which varies tinuously with variations of x. If x be increased or decreased by the smallest ant conceivable, y will change by a correspondingly small amount. Such ll variations are called "differentials," and are symbolized thus: dy and dx, ere d is not a quantity but a symbol meaning "the smallest conceivable ue of" y or x.

Derivative or Differential Coefficient. — The ratio $\frac{dy}{dx}$ is the rate of nge of y with regard to x and is called the "derivative" or "differential fficient" of y with respect to x.

Geometrical Meaning of a Derivative. — If a curve be plotted between nd y for any equation $y = f(x)$, and a tangent drawn to the curve at any nt, Fig. 1, then the tangent of the angle θ between

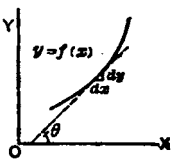


Fig. 1

s tangent and the axis of x is equal to $\frac{dy}{dx}$.

Differentiation. — Differentiation is the process of taining the derivative of a function. If $y = f(x)$

$$\frac{dy}{dx} = \frac{df(x)}{dx}$$

$$= \frac{f(x+dx) - f(x)}{dx}.$$

Example. — If $y = ax^2$

$$\frac{dy}{dx} = \frac{a(x+dx)^2 - ax^2}{dx}$$

$$= \frac{a\,dx\,(2x+dx)}{dx}$$

$$= a\,(2x+dx).$$

dx is the smallest conceivable value of x, it is so small compared to x that it y, with the smallest conceivable error, be neglected. Hence,

$$\frac{dy}{dx} = 2ax.$$

Formulas for Differentiation. — (u, v, x and z are variables; a is a constant.)

$$\frac{d}{dx}(u+v) = \frac{du}{dx} + \frac{dv}{dx}$$

$$\frac{d}{dx}(au) = a\frac{du}{dx}$$

$$\frac{d}{dx}(uv) = v\frac{du}{dx} + u\frac{dv}{dx}$$

$$\frac{d}{dx}\left(\frac{u}{v}\right) = \frac{v\frac{du}{dx} - u\frac{dv}{dx}}{v^2}.$$

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When x is itself a function of some other variable s,

$$\frac{du}{dx} = \frac{du}{ds} \cdot \frac{ds}{dx}.$$

TABLE OF DERIVATIVES

Function $f(x)$	Derivative $\frac{d}{dx} f(x)$	Function $f(x)$	Derivative $\frac{d}{dx} f(x)$
x^n	nx^{n-1}	$\tan^{-1} ax$	$\frac{a}{1+(ax)^2}$
$\sin ax$	$a \cos ax$	$\sinh^{-1} ax$	$\frac{a}{\sqrt{1+(ax)^2}}$
$\cos ax$	$-a \sin ax$	$\cosh^{-1} ax$	$\frac{a}{\sqrt{(ax)^2-1}}$
$\tan ax$	$\frac{a}{\cos^2 ax}$	$\tanh^{-1} ax$	$\frac{a}{1-(ax)^2}$
$\sinh ax$	$a \cosh ax$	$\log_a x$	$\frac{1}{x} \log_a e$
$\cosh ax$	$a \sinh ax$	$\log_e x$	$\frac{1}{x}$
$\tanh ax$	$\frac{a}{\cosh^2 ax}$	$\log_{10} x$	$\frac{0.4342944819}{x}$
$\sin^{-1} ax$	$\frac{a}{\sqrt{1-(ax)^2}}$	a^x	$a^x \log_e a$
$\cos^{-1} ax$	$-\frac{a}{\sqrt{1-(ax)^2}}$	e^x	e^x

Note: See also Table of Integrals in article on *Integrals* noting that the col there headed "Function" is the derivative of the column headed "Integral."

Second Derivative. — The derivative of a derivative, i.e., $\frac{d}{dx}\left(\frac{dy}{dx}\right)$, is ally written $\frac{d^2y}{dx^2}$. Similarly $\frac{d}{dx}\left(\frac{d^2y}{dx^2}\right)$ is called the third derivative and is wri $\frac{d^3y}{dx^3}$, and so on.

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SPATCHING OF TRAINS BY TELEPHONE. — (*See also articles Telephony.*) Up to 1907 train dispatching was done almost entirely by the graph. In that year the telephone began to replace the telegraph for purpose. At the beginning of 1920, 83 railroads in the United States, rating 120,000 miles of line, had abandoned telegraphic train dispatching in r of the telephonic method.

Telephone train dispatching has many advantages over the former method. dispatcher's work consists in the main of gathering information and issuing rs for train movements. These operations are much quicker by the use of telephone and are no less accurate. Special training in the use of the apparas not as necessary as when telegraphy is employed. All the agencies are ught into closer personal relations, with the result that there is better coation and better discipline. The dispatcher can call and speak at the same e, which is impossible by telegraph.

It now is possible to operate dispatching lines as long and with as many stations railway conditions may permit. The length of line and number of stations not limited by the nature of the electrical equipment. Lines of 300 miles gth are in operation, and 65 stations on one line are in successful use. More n 65 stations could be operated successfully if desired.

Dispatching circuits are multi-station lines, like the telegraph-dispatching es they displace. Broadly speaking, they are selective party lines, but are pped with systems of apparatus which allow the placing of many more staons on a line than is possible with any other party-line system so far developed. Several train-dispatching systems are on the market, the principal ones being own as the Gill System, the Western Electric System, the Cummings-Wray tem, and the Kellogg System. These are in general similar in that the dister has means of calling any station selectively. In some systems he can l several stations at once by setting keys for them in advance and operating ommon calling key.

Each way station is equipped with a device called a selector. These selectors n be operated only by the dispatcher. They work on the step-by-step principle d the whole object of the device is to close a contact at the station called and s to ring a bell. No provision is made for cutting the way-station telephone on and off the line, as secrecy is not aimed at. Any way station may comnicate with the dispatcher at will by lifting the telephone receiver. The patcher wears a head telephone constantly and so listens upon the line at all es.

Train orders are written as given and received and are read back to the disher by each station, the dispatcher underscoring each word once for each rect repetition from a way station.

BIBLIOGRAPHY. — See Bibliography in article on *Telephone Instruments d Circuits.*

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DISTRIBUTION LINES. — (*See also Conduits and Conduit Lines; L tribution and Transmission Systems; Transmission Lines; Wires and Cabl Wiring of Buildings.*) Two types of construction are employed, overhead a underground. Overhead construction has the following advantages (1) lo first cost, (2) easier to repair, (3) easier to change, (4) adaptability to hig voltages; while underground construction has the advantages (5) less unsight (6) less dangerous to the public, (7) less subject to damage by external agenci The majority of circuits in use are overhead. Underground circuits are pri pally used in the central portions of the larger cities. When undergrou circuits are used a large part of the construction consists of a composite of und ground and overhead construction.

MATERIALS FOR LINE CONSTRUCTION. — The principal eleme for wood-pole construction are the conducting wires, insulation on the wi insulators, tie wires, pins, cross arms, cross-arm braces, bolts, poles, guy wi guy anchors. For underground construction, see *Wires and Cables, Insulat* and *Conduits and Conduit Lines.*

Wires for Overhead Construction. — The conducting wires are usua of copper, sometimes of aluminum. Iron is not used as it costs more th copper for equal conductivity. Aluminum is used to a much less extent th copper; see articles on *Aluminum* and on *Copper*. Soft-annealed copper is u ally employed for ordinary distribution work, as it has the greatest conductiv and is the easiest to work with. Medium hard-drawn and hard-drawn wi are used in lines where great mechanical strength is necessary.

For overhead city distribution copper wires ranging in size from No. 6 B. & (or A. W. G.) to 500,000 circular mils are used; see *Wires and Cables*. Si larger than No. 0000 B. & S. are usually stranded. Conductors as small No. 14 B. & S. have been used for overhead work but are too small, as they frequently broken by wind and sleet.

Standard Sizes of Wire. — Of the gage numbers between No. 6 B. & and 500,000 circular mils (*see Gages, Wire*), some are but little used beca (1) the difference between consecutive sizes is less than is found necessary usual practice and (2) the difference is too small to be readily detected by ordinary lineman or stock keeper. In practice the number of sizes to be u and carried in stock has usually been reduced by omitting certain sizes: No. and 1 are nearly always omitted; practice regarding the omission of larger s varies. The most commonly used are No. 6, 4, 2, 0, 0000 B & S. and 500, circular mils.

Wires for Underground Lines. — See *Wires and Cables, Insulated.*

Covering on Overhead Wires. — Overhead conductors for city distri tion are covered with weatherproof braid. Two grades are recogni "double braid" and "triple braid," according to the number of coveri though the actual thicknesses are not the same for different makes. Do braid is considered suitable for use on voltages of 600 or less, and triple b for voltages up to 2500 constant potential and on series-arc circuits of voltages. To prevent the possibility of double-braid wire being used voltages over 600 and to reduce the number of kinds of wire used, it is g practice to have all No. 0000 wires and smaller covered with triple br Ordinarily cables larger than No. 0000 are not used on voltages above 600 may therefore be double braided.

Object of Covering on Overhead Wires. — The covering on o head conductors is solely for the purpose of limiting the short-circuit cur due to an accidental cross or grounding. The normal insulation of the lin

intained by the insulators alone (*see below*); any reinforcement obtained
m the insulation on the conductors is neglected in practice. While weather-
of braid is an imperfect insulator, it serves to eliminate the greater propor-
n of the short-circuits and arcs which would occur, due to momentary contact,
re bare wires used. Rubber and other more perfect insulators are not used
ause of expense and the impossibility of maintaining perfect insulation,
e to weakness, against mechanical injury and deterioration.

Bare wire is usually used on circuits operating at 10,000 volts and over to
oid giving a false sense of security. For voltages between 2500 and 10,000
atherproof wire is often used, though the protection afforded against short-
uits is doubtful.

Extra Cost and Weight due to Weatherproof Braids. — In estimating
e cost of a distribution line, the additional weight and cost of the weather-
of braids should be taken into account. The following is a rough comparison
bare, double-braided and triple-braided copper wire, the cost being based on
pper at 15 cents per pound.

OMPARISON OF BARE AND WEATHERPROOF COPPER WIRES

Conductor	Relative weights			Relative Costs		
	Bare	Double braid	Triple Braid	Bare	Double Braid	Triple Braid
No. 6 B. & S., solid	100	123	137	100	127	141
500,000 cir. mil cable	100	112	117	100	115	121

he cost and weight of weatherproof insulation for aluminum wires are greater
an for copper of the same conductance on account of the larger cross-section
conductor required.

Insulators for Overhead Lines. — City distribution circuits are ordinarily
arried on double-petticoat deep-groove glass (D.P.D.G.) insulators; see article
n *Insulators for Overhead Lines*.

Tie Wire. — The conductor is attached to the insulator by a tie wire of
e same material as the conductor, though soft wire is usually employed even
r hard-drawn conductors; the tie wire is either bare or insulated to corre-
pond to the conductor. The size of tie wire is often the same as that of the
nductor; for small wires it is merely a piece of conductor. With large
nductors it may be as much as three sizes smaller. See also the section on
stallation in the article on *Wires and Cables, Bare*.

Pins. — See article on *Insulator Pins*.

Cross Arms. — See article on *Cross Arms*.

Poles. — See article on *Poles for Overhead Lines*.

DESIGN OF CITY DISTRIBUTION LINES. — City distributing sys-
ms should be designed so that service may be given to any building in the
ty and ultimately to every building present and future. On certain streets
de lines may be omitted without defeating this object. The arrangement of
es which will serve scattered customers with the least number of poles will
nally contain many poles which should not be used if the ultimate arrange-

ment were immediately constructed. Preliminary studies and designs sho made, first, of arrangements suitable for servicing the initial expected cu ers, second, of arrangements for ultimately servicing customers on every the city, third, of a plan of extension by which the initial arrangement extended to the ultimate with the minimum expense in changing line services.

The Pole Line. — The pole lines perform two functions: (1) of ca feeders from the station to the mains and (2) of carrying the mains sup services to buildings immediately adjacent. In the old cities of the e part of the United States where the streets are crooked general rules fo tematic line work cannot be followed far. In the newer cities of the We South the streets are laid out at regular intervals and at right angles, di the city into rectangular blocks of equal size. In such cases the foll rules should be followed:

(1) A pole line should continue on the same side of the street throu its entire length and disconnected lines built in the same street should the same side, so that they may be connected when desired without cr the street.

(2) The spacing between poles should be an exact divisor of the lengt block (including cross street), giving a uniform number of poles per bloc

(3) Whenever the line crosses a street where there is, or may be, an secting line there should be a corner pole on the proper side of the inters street for making a junction.

These rules logically lead to the use of corresponding sides of all p streets.

When each block contains lots fronting on all four surrounding stree servicing of every lot in the city would require poles on all streets, thou the streets in at least one direction the lines may be discontinuous. Oft lots all front on the streets in one direction, which are laid out to be pri streets, in which case no service lines are necessary in cross streets, thou intervals connecting lines are necessary.

Trunk Lines. — Where the location of power house or subs is fixed, trunk lines must be laid out from such point, but often a study sible trunk-line arrangements made before the location of the power is fixed will show that other locations are more advantageous. If distril station (power house or substation) is centrally located, there should least four main trunk lines (of poles) from it, say north, east, south and A short distance from the station they should be divided into branches subdivided into smaller branches and finally merge into the service The trunk lines should be laid out: (1) on back streets where the large numerous and heavy wires and heavy guying will not be conspicuous, side streets or streets little built up so that interruption to service due in adjacent buildings will be infrequent, (3) on streets where there ar trees, (4) on streets where there are no jogs or offsets to weaken the lin require heavy guys, (5) on streets which lead directly to the section sup penetrate its center and intersect the maximum number of service lines. when the station location is excellently chosen these desirable conditio have to be compromised to a serious degree.

Street and Alley Service Lines. —With the symmetrical ar ment of lots described above there is often an alley through each block p with the principal streets. Under these conditions there is therefore a of two methods of laying out the lines: (1) run the lines on the principal servicing the houses from the front and (2) run the lines in the alleys ser

houses from the rear. The disadvantages of the first are unsightliness he poles and wires, difficulty of avoiding or of trimming shade trees; the dvantages of the second are discontinuity of alleys, proximity of buildings lammable barns and out buildings in residence districts and of windows and escapes in business districts) and lack of established grade.

omposite Distribution. — The most expensive and difficult part of an erground system is that for taking the current from the conduit to the cus-er's building. This includes underground secondary mains, transformers, tholes, service pipes and wires. Where it is necessary to remove poles n streets but not to remove overhead wires from private property the pole s are replaced by conduits which contain primary feeders and mains only. m the conduit in the street a small branch runs into the interior of each ck where the ducts (usually iron pipes) come to the surface at the foot of a minal pole up which the cables run. At the top the cables connect to over-d wires. The interior of each block contains a complete overhead dis-ution system of poles, transformers, secondary mains and services. Some-es the servicing is done from a single centrally located pole and at others re may be a pole line of several spans length running longitudinally through block. The most serious disadvantage of this method is that the poles and es frequently have to be on private property, where no permanent rights may obtained. Being dependent on concessions from one or more customers, the mpany does not have the independent position that a public service company ould in order to serve all equally and fairly. The poles and circuits are erefore often put up of insufficient size without proper guying.

The composite system has the advantage of the overhead system in less sightliness, less accessibility of public to high-voltage wires and less trouble om trees. In thickly built-up blocks its use results in a tangle of wires over ofs and along walls which may be as dangerous in case of fires or high winds an overhead system. The composite system is used (1) in small cities where e load density is small and (2) in large cities in an annular district between verhead and underground construction; in either case it is usually an inter-ediate step from overhead to underground construction.

Crossing of Waterways; Submarine Cables. — Where a distributing stem is divided by a navigable waterway the connection is usually made y submarine cables laid on the surface of the bottom, or better, below the rface in trenches dredged for the purpose. Cables may be single or multi-le conductors, the latter being usually used for alternating currents to avoid ductance due to wire armor of cable. Two conductor cables may conveniently e of concentric type to give a true circular exterior. In laying cables it is sirable to keep them approximately parallel. Where one crosses under an-ther it may be impossible to remove it. Each cable should be in a single length ithout joints, and the length should be made as short as possible, as repairs are ery difficult and often impossible. At ends unimportant cables may be brought p a pole and connected to overhead wires; important cables should land in a able house with suitable provision for disconnecting the cable or for transfer-ing the overhead circuit to a spare cable in case of trouble, and also with ghtning arresters. Submarine cables are weak links in a distribution system ut may sometimes be avoided by crossing channels at sufficient height to lear the masts of ships.

Calculation of Size of Wires. — The size to be used depends upon the oltage drop which should be permitted, considering the probable growth of he load. The following table of per cent voltage drop in the various lines is epresentative of ordinary practice.

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	For light
	Per cent
House wiring	2
Service wires	2
Secondary mains	5
Transformers	2
Primary mains	5
Primary feeders	10

The drop in the feeders is usually compensated for by raising the volt the substation or power station or by using voltage regulators; see *Distr and Transmission Systems.*

Formulas for calculating the size of wire for a given length of line load and given distribution of load are given in the articles on *Trans Lines* and *Wiring of Buildings.* Due to the uncertainty regarding the p increase of load, a close calculation of the size of wire is seldom made, gineer relying largely on his experience and judgment, making only a calculation as a check. For overhead lines 500,000 circular mils is the largest size used on account of the difficulty of supporting a large greater conductance is obtained by installing parallel circuits. For ground lines No. 0000 B. & S. three-conductor cable is the largest si can be conveniently drawn into the ducts; 1,000,000 c.m. is the usual ma size of single-conductor cable used.

Effect of Diversity Factor. — It should be noted that in a distr circuit the maximum load on a feeder is less than the sum of the ma loads on the mains which it feeds, these in turn are less than the sum maximum loads on the transformers connected to these mains, and Therefore, whenever a circuit divides or subdivides, the aggregate s areas should ordinarily be greater after division than before. The tot in voltage from power house or feeding point to a customer's lamp or is also usually less than the sum of the maximum drops in the parts circuit which are in series (such as house wiring, services, secondary mai because these component drops do not have their maximum value s neously.

Stresses on Poles. — An overhead line is a framed structure. Th are struts resisting the weight of wires, including sleet on the conducto insulators, cross arms and transformers and the downward pull of t wires. The horizontal pull of the line wires is balanced by the hor component of the pull of the guy wires, which transmit it to the grou addition to being struts the poles resist certain bending stresses, bu should be but a small part of the normal horizontal tension of the The principal normal bending stresses are of two classes: (1) constant s due to the unbalanced pull of service and other wires which do no sufficient force to require guys, and (2) variable stresses, due to the the wind at right angles to the line on both the poles and the wires. also resist a twisting force where the tension on one side of an arm is than on the other, due to a difference in the number or weight of ending on the two sides. The poles, wires and guys should be so d that the bending and twisting forces on the poles are insignificant calculation of the strains produced in a pole is given in the article o *for Overhead Lines.*

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rrangement of Wires on Poles.— The arrangement of wires is governed nechanical, electrical and practical considerations. For mechanical reasons desirable that:

The largest wires be on the lowest cross arm, in order to reduce the bend- itress on the pole to a minimum.

The largest wires be on the pins nearest the pole, in order to reduce the ting stress on the cross arm to a minimum.

The wires be arranged symmetrically on the two sides of the pole, espe- ly those which end at the pole, in order to reduce the twisting stress on pole to a minimum

or electrical reasons (which, however, are of minor importance) it is de- ble that:

. The wires of any one circuit be as close together as practicable (on adja- t pins), in order to reduce the self-inductance of the circuit.

. The wires of a three-phase circuit be arranged to form the edges of an ilateral prism and the wires of a two-phase circuit be arranged to form edges of a square prism, in order to render the inductances and capacities the wires respectively equal.

. The wires of different circuits be placed as far apart as practicable, in der to reduce their mutual inductance.

For practical reasons it is desirable that:

. The highest voltage wires be on the top cross arms and on the pins farthest m the pole, in order to reduce the danger of accident to linemen.

. The mains, which have the greatest number of taps, be on the lowest ss arms, in order to avoid danger of accidental crossing (with contact) of e wires.

. The arrangement be systematic throughout; this is absolutely essential r safe and economical operation.

As it is impossible to meet all of these conditions the actual arrangements ed are compromises and are governed by the relative importance attached the several desirable conditions. In some cases the electrical requirements 1 to (6) have been considered of most importance, resulting, for example, n arrangement subordinated to the idea that the three wires of a three- ase circuit must be arranged exactly in an equilateral triangle. It appears, owever, that these electrical requirements are really the least important of he considerations and that in most practical cases can be entirely neglected.

Transpositions. — Due to the effect of mutual electromagnetic induction *see Inductance*) an alternating or varying current flowing in one circuit will nduce a voltage, and therefore a current, in any parallel circuit; and due to the effect of mutual electrostatic induction (*see Capacity*) an alternating r varying voltage in one circuit will induce currents in a parallel circuit, even hough there is no metallic connection between the two circuits. It is possible, however, by properly transposing equal alternate lengths of the wires forming the two sides of each of the parallel circuits, to neutralize these effects. Fig. 1 shows diagrammatically a scheme of transposition whereby a two-wire circuit can be protected from both electromagnetic and electrostatic induction from a parallel circuit and vice versa, provided neither circuit is grounded. The more frequent the transpositions the more thoroughly are the effects due to inequality in the spacing of wires and poles eliminated. Transpositions cannot be made effective in eliminating inductive effects when either circuit is grounded, otherwise than at the neutral point. See also *Transmission Lines*.

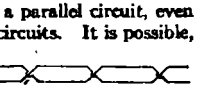


Fig. 1. Transposition of Two Two-wire Circuits

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Methods of calculating the induced voltage and induced currents line due to currents and voltage in a neighboring line are indicated articles on *Inductance* and *Capacity*.

Disturbances in Telephone Circuits due to neighboring power are the most common results of electromagnetic and electrostatic ind When the power circuit is grounded and carries either (1) fluctuating currents (e.g., a d-c. railway) or (2) alternating currents it may pro noise in the telephone receiver, even though both the power circuit an phone line are transposed. See also *Telephone Lines*.

Trees. — Trees constitute the most serious obstacle to the proper pla construction and operation of overhead lines. The principal methods of ing this difficulty are (1) avoiding them, (2) going over them, (3) going them, (4) going through them. In most cases a combination of these m is used. Where trees are a serious factor it is necessary to examine the of every line in detail and the size and location of the trees may becom determining feature of the whole design. In such cases nearly all r good construction and systematic arrangements are violated in the in of expediency.

The methods by which trees may be avoided are: using alleys inst streets, or vice versa, choosing streets without trees for important lines, side of street with fewest trees, and finally the very bad arrangement of c the street back and forth to avoid the trees either individually or in group

The plan of going over the trees is the proper one in the case of all trees and is perfectly satisfactory until the trees grow up and touch the It is therefore only a temporary method, especially where the trees are quick growing varieties. In going over small trees it is well to have tall enough to allow for wires clearing after several years growth. It is u impracticable to go over large full-grown trees because of cost of pole sightliness of very tall poles, and the difficulty of properly guying th resist wind and the unbalanced pull of wires, which is magnified by the leverage. It is also difficult or impracticable to take off service wire the tops of tall trees.

In the case of very large trees it is sometimes practicable to take the under the trees on short poles. Where the wires pass the trunks it m necessary to spread them or necessary to pass between large branches, insulators fastened to the trees to maintain clearance. While such a lin be kept fairly clear under normal conditions, there is apt to be trouble storms from branches falling on the wires or from limbs bent by wind or touching them.

With trees of moderate size it is usually necessary to take the wires th the trees among the leaves and small branches. Such wires are a co source of trouble and expense. The branches and leaves should be tri from around the wires as much as possible, including not only those in c with the wires but such as will be brought into contact by wind or whic grow into contact during the season. In addition it is usual to protec wires in the worse places by tree insulation consisting of split tubes of or bamboo.

Pole Transformers. — The primary (1100- or 2200-volt) mains are u run to transformers mounted on poles and the voltage there stepped do the lamp or motor voltage (110 or 220 volts), and secondary mains run the transformer to the buildings in the immediate vicinity. These transfo usually range in size from ½ to 50 kw., but transformers of ¼ kw. were erly common and transformers larger than 50 kw. are sometimes used in fa districts where the unsightliness of the supporting structure (several poles fr

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ther) does not have to be considered. Very small transformers are ob-
onable because of their poor regulation, lower reliability and the cost of
ently changing them as the load increases.

Use of Single and Polyphase Transformers. — Transformers are
ly of the single-phase type, two being used for motors on two-phase cir-
and two for small motors and three for large motors on three-phase circuits.
e-phase transformers are also used for motors on three-phase circuits, and
the advantage of reducing the amount of wiring on the poles. Single-
e transformers have the advantage of being interchangeable between the
le-phase lighting and polyphase power circuits where the same voltage is
[illegible]

Voltage Ratios of Pole Transformers. — Lighting transformers were
r standardized with voltage ratios based on multiples or submultiples of
1, that is, 1000 and 2000 volts primary to 50, 100 or 200 volts secondary,
040 and 2080 primary to 52, 104 and 208 volts secondary. It was found
on account of the voltage drop in the transformers and secondary mains,
ers wound for this voltage did not operate well. Instead of remedying
difficulty by winding the motors for a lower voltage or by raising the volt-
in the generators and lamps, power transformers were introduced with
ings based on a ratio of 9 : 1 thus giving with $^{1040}/_{2080}$ volts primary a
ndary voltage of approximately $^{115}/_{230}$. It was soon found that many com-
ions followed from the use of transformers of the two ratios, so that
anies dropped one or the other ratio and made their transformers inter-
angeable. Of the two ratios the 10 : 1 ratio is preferable, because it is the
e extensively used, gives a higher voltage for primary distribution and
es better with the general principles according to which voltages have
n standardized.

ervice Wires. — The service wires are those which connect the house
ing with the main on the street. Usually these wires extend in a single
n from the nearest pole to the house. At the house they are fastened to
ators similar to those used on the line and mounted on brackets attached
the house. These brackets are often the ordinary wooden bracket used
ise work, though the special iron brackets made for the purpose are neater
more secure. The bracket should take the strain off the service span,
that where the service passes through the wall it will not be under the strain
the span. The wires should pass through the wall in porcelain bushings
should have a drip loop between the bracket and bushing so that water
not follow the wire into the building. Where service wires do not conven-
ly reach the house at point of entrance, they are carried along the wall
such point, being supported at intervals by insulators on brackets. See
Wiring of Buildings.

At the pole the service wires are sometimes attached directly to the mains
supply them; while this is the easiest method it has the disadvantage
the strain in the service wire will come on the mains, which may also be
ired by the attaching and detaching of numerous service wires. When the
ice wires do not slope upward or downward at a considerable angle they
liable to become crossed with the main of opposite polarity. Since the
eral direction of the service wire is at right angles to the main, the service
should naturally originate on a cross arm at right angles to the arm carry-
the mains. In good service work consequently a cross arm is attached to
pole below the main, and all the service wires to both sides of the street
from this. One tap to each of the wires constituting the main can then
used for a number of service wires.

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Front and Rear Servicing. — When houses are serviced from line on the street the service wires usually enter the front of the hou if serviced from alley they enter the rear. Service wires can be run detached houses from front to rear on brackets on the wall, but this is ur expensive and increases the service wire drop. Service entrances can be by changing the inside wiring, but the expense is usually heavy and the to decoration of rooms sometimes makes it prohibitive. In the wiri building the error is frequently made of bringing out services withou to location of supply lines.

Attic and Basement Servicing. — The service-wire entrance center of distribution in the house is generally in the attic for houses overhead and in basement for those serviced underground. Build ranged for underground service are sometimes supplied from overhe by taking service wires down poles and under sidewalks in iron pipes.

In changing an existing system from a street to an alley distribu from overhead to underground service, the center of distribution in th must be correspondingly changed, or a connection run from the new entrance to old center of distribution large enough to carry the current unduly increasing the drop.

Sectionalizing of Distribution Circuits, Fuses and Cut-Outs. — head alternating-current system supplied from a single bus is sectic (1) at the switchboard in power station or substation into circuits ha external interconnection by knife switches or oil switches with fuses matic trip; (2) at the poles where long branches leave, by transfor outs, either fused or solid, or by pole-type oil switches; (3) at tra primaries by fused cut-outs. Switches and fuses are used but spar the primary mains, and in a small compact circuit none are necessa switches or fuses are ordinarily used on the secondary side of tran or on secondary mains. Occasionally transformers have been provid switches in secondary side so that part of the transformers on a netwo be cut out during times of light load to save core-loss. Such sectic has been little used, as the small savings have not justified the comp care and hazard to service due to mistakes.

When several transformers feed the same secondary main, the op a primary cut-out, either by blowing of fuse or by hand, does not m transformer primary dead, as it is still alive from the secondary side. the fuse of one transformer on a secondary network blows the additio thrown on an adjacent transformer may cause the fuse of that to blow transformers to go out in succession. Under these conditions the fuse be replaced in one transformer at a time. To avoid the interruption t involved in leaving the fuses out until a time of day when one tra can carry the whole load temporarily, or in having the whole primar out while the fuses are replaced, it is sometimes possible to have all th formers on a single secondary network on the same branch of the main, this branch being sectionalized from the rest of the primary ci a switch.

Lightning Protection. — (*See also article on Lightning Protectors.* tically all disturbances from lightning enter a system through the distributing circuits. The most serious effects are not to the dist circuit itself but to the switchboard and machinery in the station. Th on the circuit consist of splitting of poles, puncturing of insulators, pu of transformers, blowing of transformer fuses. There may also be to meters or appliances on the premises of consumers. The protecti cipally used includes (1) lightning arresters and choke coils in the static

tus), (2) lightning arresters at intervals on he lines, (4) lightning rods on poles and (5)

rs. — On alternating circuits lightning arres- primary but not on the secondary circuits. itning arrester will protect is less the more t is impracticable, and probably impossible, gh together to absolutely protect a circuit. sters used should be such that the sum of ightning and the expense of providing and nage is a minimum. The effects of lightning oss due to interruption of service is too in- i.tribution of arresters being determined by een found that when no arresters are used siderable intensity do no great amount of sters are used much of the damage done is hat their failure is a cause of a considerable . It is usually well to begin by using arres- tting additional arresters on if found neces- arresters would be reached when one was k.

otection is greatest in a composite system, r submarine cables should be protected by onnect to exposed overhead circuits. ed over transmission lines but may be used on wires in exposed places. Where adjoin- er than the pole line, these foreign objects e additional screening effect will be obtained

— Overhead line construction is constantly and removal of poles, extension of mains, service, erection and changing of location se with which changes may be made in the ords in such form that any details can be out making a completely new record. The subject to frequent change makes it impra- n compiling a system of records it is therefore eatures should be recorded and what omitted, tion which will be easily corrected. Written though for most purposes the latter gives useful record.

ecome useless, soon after they have been pre- n lack of correction or unintelligible because neations. The following method of keeping ive good results: (1) a map of the circuits ng the circuits on the date of preparation; is tracing and all changes marked in pencil and not the tracing being used for correcting subject to wear or tear; (3) before the blue tion or wear the accumulated corrections are o-date blue print substituted, and the process e blue print can be made by line foremen time that the line changes are made, while le by a draftsman who will make them neatly

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and with minimum damage to the cloth. If no colored inks are use parts subject to change, such a tracing will last a long time and will only to be redrawn when changes have become so numerous or radical as to am to a rebuilding of the circuits.

COST OF DISTRIBUTION CIRCUITS. — So many varying items e into the cost of a complete distribution system that it is impossible to comprehensive figures of general application. A cost of from $150 to $250 kilowatt of maximum load at the distributing switchboard may be take an indication of the magnitude of the total cost of an overhead distribu system for both light and power, including all outside construction from power station or the substation to the customer's service inlet, inclu meters.

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TRIBUTION AND TRANSMISSION SYSTEMS. — (*See Alternating Currents; Conduits and Conduit Lines; Distribution Lines; Electricity and Magnetism, Principles of; Ground Connections; Grounding of Electric uits; Insulators for Overhead Lines; Insulator Pins; Poles for Overhead Lines; r Stations; Substations; Transmission Lines; Trolley Systems; Wiring of lings; Wires and Cables.*)

is article treats of the following subjects:

Constant Current or Series Systems..... p. 373
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design and construction of pole lines and underground circuits are treated tail in the articles on *Distribution Lines, Conduits and Conduit Lines, Transsion Lines, and Wiring of Buildings.* Requirements regarding the grounding circuits and methods of making ground connections are treated in the articles *Grounding of Electric Circuits* and *Ground Connections.*

Circuits designed for transmitting relatively large amounts of power from ated point to another are called transmission lines, while those for delivering small amounts at numerous points are called distribution circuits. Transsion lines usually have no or few branches, while it is characteristic of tribution circuits to have many branches. The various systems of transmitand distributing electric energy for light and power may be classified under general heads, viz., constant current or series and constant potential or ltiple systems, and each of these may be subdivided into direct-current sys- and alternating-current systems.

CONSTANT CURRENT OR SERIES SYSTEM. — The lamps or other vices are connected in series and the current through them is kept constant, voltages varying automatically to increase or decrease the energy delivered. is the principal system used in the United States for street lighting, but is little used for any other purpose. At one time such circuits were extenly used for commercial arc lighting in stores, but the series arc became olete for commercial use when the arc lamp was perfected for use in multiple uits. The value of the current used for street lighting ranges from 1.75 to amp., depending upon the type of lamp used.

Source of Current. — Direct current for series circuits is usually obned from d-c. series generators (*see Generators, Direct-Current*) or from an c circuit by rectifying the alternating current from a constant-current transmer (*see Rectifiers*); adjustable resistance in series in a constant potential d-c. uit is sometimes used. Alternating current is usually obtained from a constantrent transformer on a constant potential a-c. circuit; other methods sometimes used are an adjustable resistance or reactance in series on constant potenal a-c. circuits and by automatic regulating reactance coil on a constant tential a-c. circuit.

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Cut-Outs, By-Passes and Transformers. — Switching out of la series circuits is accomplished by short-circuiting them; this leaves the charged to the potential of that point in the circuit. To make them handle "absolute cut-outs" are used which also disconnect both conduc the lamp, leaving the circuit closed.

To avoid the excessively high voltage which would occur when the opened, due to series incandescent lamps burning out, an automatic is provided in multiple with the lamps, sometimes consisting of a piece o which punctures on a moderate rise of voltage, or of a choke coil whic but little current at normal lamp voltage. Sockets for series incan lamps are arranged to automatically close the circuit when the lamp i drawn.

Transformers, one at each lamp, are sometimes used to insulate the sec circuit containing the lamp from the primary or for reducing the curr low-current lamps used in series with lamps taking higher current.

Advantages and Disadvantages of Series Lighting. — Constant or series systems have the advantage that low-voltage lamps may be high-voltage circuits without the expense, losses or complication of tran tion. They have the disadvantage that the lamps are dangerous to the efficiency is low at light loads and it is impracticable to distribute a amount of power on a single circuit. In the series system the curre consequently the loss in the conductor is the same irrespective of th while in the multiple system, the current is proportional to the load, watts lost in the line therefore vary as the square of the load and the loss directly as the load. For this reason the series system is not an eco one where the load varies and averages much below full load, which is with most commercial loads. For street lighting where all the lamps are on and off at once the efficiency at partial loads is of no importance. In c current systems the resistance of the circuit does not affect the unifor the voltage on the lamps at different parts of the circuit, while with c potential systems it does. For a scattering load of lamps, such as street a uniform light can therefore be obtained from the several lamps, with smaller weight of copper and fewer wires by using the series than by us multiple system.

Thury System. — In Europe the constant-current or series syste direct current of extra high voltage, has been used for long-distance transmission under the name "Thury System." The current is obta connecting several generators in series, and is utilized by a number of mot in series. The advantages are simple switchboards, no transformers an mum strain on line insulators, the latter due first to the fact that i current the effective voltage is as high as the maximum voltage, and that in a constant-current system the working voltage only remains at i imum value during the short period when the load is also a maximum. the disadvantages are the necessity for insulating frames of generat motors, need of speed governors on motors, necessity of converting the by moving machinery in every case where it is used for lighting and cases for power. The Thury System is not used in the United States.

CONSTANT-POTENTIAL OR MULTIPLE SYSTEM. — In this which is the one principally used for electrical distribution, the voltage conductors is kept as constant as practicable and the current varies as t changes. The degree to which the voltage approximates constancy t out the system is called the "regulation" of the system.

Use of Direct or Alternating Current. — Either direct or alternating can be used equally well for certain purposes, principally those for wh

ed, including the lighting of carbon and tung-
g and heating. For certain purposes, where
hysical changes, such as charging storage bat-
current is essential; for other purposes, such
lum incandescent lamps, it is better; whereas
Nernst lamps, the alternating current is better.
urrent is most favorable where acceleration,
peed are desirable, whereas alternating current
unvarying speed is desired. While the fields
a large extent that either kind can be used for
hat it is often more advantageous to use both.
distribution, direct current is advantageous
best be carried on single conductor cables; no
ll, high tension fuses are required.
supplied either directly from the generators
e secondaries of transformers in substations.
either directly from direct-current generators
ee Substations, Railway) supplied with high-

— For a load consisting of both electric lamps
rcuit may be used throughout for both classes
independent circuits may be employed. The
ut for light and power service has the advan-
, transformers and meters, reduced weight of
nsformers and meters, whereas the use of sepa-
has the advantage of requiring less capacity of
, of less weight of wire for the same perfection
rcuits and also simplifies the problem of bal-
distribution (*see below*). In the business dis-
hree-wire direct-current system is used, in which
supplied from the same circuit, the motors as
utside wires. In business districts where the
rrent the lighting is frequently on single-phase
rate polyphase circuits or on 500-volt direct-
districts, where the lighting is done by single-
motors are usually put on same services as the
om 1 to 5 and in some instances as large as 15
meters, services and transformers, but the same
ces. In factory districts when the power is the
ed by polyphase circuits the incidental lighting
services, but usually there are separate meters
arge number of cases where the same polyphase
l light with separate transformers and second-
transformers are usually distributed as equally
al phases, in order to balance the load, though
ed to a single phase. In a few cases the same
ower and light usually on the four-wire three-

There are two methods of providing proper dis-
e area, known respectively as the "tree system"
The former is the most extensively used but
good voltage regulation as the latter.

nected Networks.— The simplest method of
to run one set of wires through the middle of

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the district to be served, running branch wires from them wherever conve for reaching loads at the sides. At the beginning, the single set of wi large enough to carry the whole current, but the size is diminished as the cu branches off. In this system adjacent branches will often have widely diff voltages, due to unequal drop because of varying loads. If wires are run necting the out-lying ends, currents will flow and partially equalize the d ences in voltage. This plan, if carried out systematically, develops in network, usually composed of two sets of parallel mains crossing at right a and connected at each point of crossing.

Feeder and Main System. — It is practicable to keep the voltag the customers' electric lamps within 2 to 5 per cent of being constant, when it is necessary to raise the voltage of the generators from 10 to 20 per from no load to full load, by arranging the distribution circuits on the f and main plan. The area to be served is first divided into compact sect each small enough to be fed from a central point with a voltage drop w the desired percentage. A system of wires called "mains" are run from central point, called the "feeding point," or "distribution center," to customers. The mains form a little circuit originating at the feeding instead of at the power house; they may be arranged on either the tree or i connected network plan. A set of wires called "feeders" is run from the p house to the feeding point. As no current is taken off at intermediate p these wires are not tapered and any desired drop of voltage may occur i feeders without affecting the lamps, provided the power-house voltage is r proportionally.

Two-wire System. — The simplest multiple system is the two-wire sy where all devices are connected directly in multiple. This system is used extensively for direct-current light and power, from isolated plants, for p circuits (usually 500 volts) and railway circuits from central stations. also used for single-phase alternating-current distribution for both pri and secondary circuits.

Edison Three-wire System. — The three-wire system, Fig. 1, is obtain replacing the out-going wire of one two-wire system and the return wire second two-wire system by a single wire, called the "neutral." The voltage between the outside wires is then double the voltage between the neutral and either outside wire. For example, 110-volt lamps may be connected between the neutral and either outside wire, and 220-volt motors may be conn between the two outside wires, and both the lamps and motors be sup with their rated voltage. The neutral wire carries a current which de only upon the *difference* in the loads on the two sides of the system and distribution. As a rule the neutral of a three-wire main is made equal in c section to each outside wire. With perfectly balanced load the three-wire tem with all three wires of the same size results in a saving in copper of per cent as compared with a two-wire system supplying the same load a same regulation.

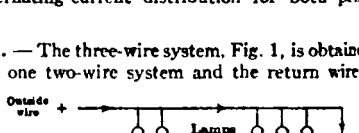


Fig. 1. Three-wire System

The three-wire system is used very extensively for direct-current light power distribution from central stations, also for large isolated plants an alternating current for lighting on the secondary circuit. Three-wire sys are usually 110 volts on each side of neutral, or 220 volts between outs

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gh there are several systems using 220 volts on each side and 440 volts
een outsides.

he Edison three-wire distribution system, as used in the business sections
rge cities, consists of a set of interconnected three-wire mains supplied by
wire or three-wire feeders from one or more power houses or substations.
different feeders feed into the same set of mains at different points. At
power house or substation end the feeders are often all supplied from a
mon bus, though where there is a great difference in the length of the feeders
re are sometimes two busses which are run in multiple when the load is light
separated when it is heavy, the short feeders on one called the "low bus,"
the long feeders on the other called the "high bus," because of the relative
tages. As the feeders from the several substations connect to interconnected mains, the bus voltage in each is raised or lowered in accordance with the
p in its own feeders. All mains which connect feeding points supplied from
ven bus are made large enough to allow large equalizing currents to flow
ough them, without requiring any great drop in the mains, in order to equalize
voltages at these points.

ALTERNATING-CURRENT SYSTEMS. — The simplest form of alternating-current system is the single-phase system, for which the connections are
only the same as for the direct-current systems. Both two-wire and three-
circuits are used, the former for primary circuits and small secondary
and branches, and the latter for large secondary circuits. The principal use of single-phase circuits is for electric lighting and auxiliary uses, such as
heating or cooking, and fan motors. For delivering large amounts of power
two-phase or three-phase system is generally used.

Two-phase Systems. — In this system there are two single-phase currents
having a difference in phase of 90°, or a quarter of a cycle. These currents
may be distributed on the three-wire, four-wire or five-wire system; see also
the *Transformer Connections* in the article on *Transformers*.

Three-wire Two-phase Systems. — Each single-phase current has a
separate outgoing wire but unites in a common return wire. Each two-phase
circuit has two circuits, each connected between an outside wire and the return
wire. The voltage between the two outside wires is 41 per cent greater than
between outside wire and return wire and the current in the return wire is 41
per cent greater than in each outside wire. This is an unsymmetrical system
and has the disadvantage that even a balanced load will cause a distortion and
unbalancing of the delivered voltage of the two phases because of the unsymmetrical drop in the common return wire.

Four-wire Two-phase System. — Each of the two single-phase circuits
is a complete, independent two-wire circuit. There are two variations, first
where the circuits are insulated from each other, in which case a cross between
either wire of one circuit with either wire of the other will change the voltage
from to ground, but will not affect the delivered voltage or cause a short circuit;
second, when the neutrals of the two circuits are connected. In the latter case,
from each wire of one circuit to either wire of the other circuit, the voltage is
71 per cent of the voltage between wires of the same phase. The four-wire
system with insulated phases is probably the most extensively used of the two-
phase systems.

Five-wire Two-phase System. — This is a modification of the four-
wire system, with interconnected neutral in which the common neutral is ex-
tended as a fifth wire. Lamps may be connected from each of the four wires
to the neutral. The five-wire system may be considered as two three-wire
single-phase systems, one for each phase, with a common neutral wire.

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Three-phase Systems. — In this system there are three single-phase nating currents with a phase difference of 120°, or of one-third of a cycle. currents may be distributed on the three-, four- or six-wire systems.

Three-wire Three-phase System. — Each single-phase current separate outgoing wire; the three return currents neutralize so that no retu is required. The three wires are necessarily interconnected, the voltag usually the same between any two and the currents equal in each of the conductors, provided the loads on the three phases are equal, i.e., provid load is balanced. When equally loaded the voltage drops in the three conc are equal and symmetrical. This is the most extensively used of the phase systems.

Four-wire Three-phase System. — This is a modification of the wire system in which a neutral wire is extended as a fourth wire. La transformers may be connected from each of the three wires to the neutral, carries only the unbalanced current, due to the differences in loading three phases. The voltage between the three outside wires is 73 per cent than from each outside wire to neutral.

Six-wire Three-phase System. — If to a three-wire, three-pha tem, three wires are added, one with voltage midway between that of eac of outside wires, lamps may be divided into six groups, between the thre side wires and the three adjacent middle wires. The result is the sa though there were three single-phase three-wire circuits, one for each with the six outside wires combined in pairs giving three common outside in place of the three pairs. When connected in this way, the three middl cease to be neutrals, as between the three there is a three-phase voltage e one-half of that between the three outside wires.

Six-phase System. — This is used for circuits in the interior of subst (q.v.), such as from transformers to rotary converters, but is not used f tribution.

Monocyclic System. — This is a variety of unsymmetrical polyphase s now obsolete. It may be regarded as a species of two-phase system with v on one phase one-fourth of that on the other and with the two wires of the phase acting as a common return for the small phase.

Star or Y, and Mesh or Δ Connections. — See article on *Alter Currents*.

Transformer Connections and Phase Transformations. — See arti *Transformers*.

Transformations of Systems. — Any electric system can be transf to any other electric system by the use of rotating machinery; see *Generators* and *Converters, Synchronous*. This method is used chiefl changing from alternating to direct current and for changing the frequer alternating current. Conversion from alternating to direct current is accomplished by means of mercury arc rectifiers, particularly for serie arc lighting and for charging storage batteries; see *Rectifiers*. Conversion any alternating voltage to any other alternating voltage at the same freq is accomplished by means of transformers (q.v.).

Frequencies in Use in the United States. — At present the two fre cies in most general use and adopted as standards in most new work are

60 cycles per second or 7200 alternations per minute, used by the ma of companies operating alternating-current lighting systems.

25 cycles per second or 3000 alternations, generally used for alterna current railway or power work or where the alternating current is to be conv into direct current before final use.

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requencies ranging from 140 to 25 cycles per

ons. Formerly standard frequency of Ft. ete for new apparatus but still used in many

us. Formerly a standard frequency of West- y Co., now obsolete for new apparatus but

Formerly a standard frequency of General pparatus but still used in many small towns. Used extensively in several large systems

compromise frequency at one time standard on several large systems in that part of New luding the General Electric Co.'s system at n mills in New England and elsewhere. Used on the large system of the T.C.R.T.

Used by the P.G.E. Co., in Portland, Oregon. and 15 cycles or 1800 alternations have been electric railway work and it has even been d for that purpose but at the present time oward their introduction.

or new light and power systems, the choice equency of existing systems in same or ad- ortion of load which will be direct current. e a new system of the same frequency as that adjoining territory, so that a physical con- n or load transferred from one to the other gers. The choice of frequency now (1914) is andard frequencies, 60 and 25 cycles. Aside cent systems, the choice depends principally e converted into direct current. Where all the advantage; where all load is alternating.

— When the bulk of the load is direct current, rt is alternating-current lighting, two fre- etimes used. Sometimes the two frequencies novers, though sometimes all current is gen- le current obtained from frequency changers

O WEIGHTS OF COPPER REQUIRED

— The comparison of the various systems pper required, as tabulated below, is based e energy delivered, (2) that the energy loss e strain on insulation between any wire and or all systems.

nt of the system is grounded, then the maxi- ion to ground is the maximum instantaneous outside wire and neutral. In the case of an he maximum instantaneous value is equal to mined by a voltmeter. When the neutral is ground on any leg will throw full line voltage other leg and ground.

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On this basis of comparison, assuming a sine wave of voltage and 100 p
power factor for the alternating-current systems, the relative voltages b
outside wires and the relative weights of copper are as follows:

RELATIVE VOLTAGES AND RELATIVE WEIGHTS OF COPI

System*	Relative voltages between outers		Relative wei of copper*	
	Grounded neutral	Insulated neutral	Grounded neutral	Ins ne
	Per cent	Per cent	Per cent	Pe
Direct-current (2-wire)	100	50	100	
Single-phase (2-wire)	71	35.5	200	
Two-phase (4-wire)	71	35.5	200	
Three-phase (3 wire)	61	35.5	200	

* Neutral wire not included; when neutral is added increase the figures giv
ratio of weight of neutral to combined weight of the outside wires for the sy
question. For example, the addition of a neutral wire equal in size to either
wire to a d-c. 2-wire system with grounded neutral gives a relative weight of
$100 \times 1.5 = 150$ per cent.

Effect of Power Factor. — To correct the above tabulation for alter
current systems in cases where the power factor is less than unity div
relative weight of copper given by the square of the power factor (i.e
single-phase two-wire system with insulated neutral and 70 per cent
factor the weight of copper will be $800/0.70^2 = 1630$).

VOLTAGES FOR D-C. AND A-C. SYSTEMS. — Unless otherwi
fied the "voltage" of a polyphase system refers to the potential differe
tween adjacent outside wires; see *Alternating Currents* for the relations b
the various voltages.

A considerable number of voltages are standard or semi-standard. In
they may be considered as derived from a lamp voltage of 50 or 100 m
by the factors 2, 3, 5 and 10, and increased by 4, 5, 10, 15 and 20 per
various reasons, principally to allow for line loss. In addition to this
of voltages there is another system which arises from the use of Y and
nections on the three-phase system; these voltages are related to the al
the factor $\sqrt{3} = 1.73$, either as a multiplier or a divisor. For exam
voltage between the outside wires of a four-wire three-phase system su
115-volt lamps connected between each outside wire and neutral is $\sqrt{}$
= 198 volts.

Voltages Commonly Used. — The voltages most used are:

Direct current:

100 to 120 volts	Lighting, small power and field excitation.
200 to 240 volts	Power, lighting and field excitation.
500 to 600 volts	Power, electric urban railways.
1200 to 1500 volts	Interurban electric railways.
2400 to 3000 volts	Electric trunk lines.

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stribution:
g, small power.

ibution:
ng (obsolete).
ng and power.

distribution:
ating station to substation.
ating station to substation.
ating station to substation.
ating station to substation.

transmission:
ating station to substation.
ating station to substation.
ating station to substation.
ating station to substation.
ating station to substation.
ating station to substation.

CITY DISTRIBUTION SYSTEM. — For square, with current generated at one point, at of the following lines: —

to substations; alternating current, 60 cycles, ts.
s in business center; direct current, 110–220

ns in residence district; alternating current, oo volts for house lighting, and alternating cur- se, 6.6 amperes series circuits for street lighting. in factory district; alternating current, 60 oo volts.
direct current, 550 volts.
ing transformers; alternating current, 110–220
rge transformers and alternating current, 110
ll transformers.
er transformer; alternating current, 220 volts,

UTION. — The ratio of the energy registered ch would be so registered if all customers had the generator to the bus-bar in the generating efficiency of distribution. The losses may be loss, transformer loss, converter loss, meter ounted for. For some purposes it is useful to ts of view: (1) as a loss of energy, and (2) as st may be called the energy loss and the second onding efficiencies are usually designated as he full-load or capacity efficiency respectively.

— The total energy loss consists of two com- dent of load, including the core-loss of trans- , friction and windage of rotating converting

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apparatus, the loss in the shunt coils of meters, the copper loss in c current circuits, and the loss in the arc of mercury arc rectifiers for c current circuits; (2) a variable loss proportional to the square of the including the copper loss of constant potential circuits and of transf the armature copper loss of rotating converting apparatus. The effect fixed loss on the per cent efficiency depends on the load factor of the loa that of the variable loss depends both on the load factor and the shap load curve.

Representative Losses. — For a lighting system, the full-load losse mary feeders, primary mains, transformers, secondary mains, services and may be expected to be as much as 17.5 per cent of the power generated daily energy loss 33.3 per cent of the energy generated, giving 82.5 p capacity efficiency and 66.7 per cent energy efficiency respectively.

Effect of Nature of Load. — In making estimates of the efficie particular systems, the effect of the following items should be con (1) relation of transformer capacity to maximum loads, (2) load (3) shape of load curve, (4) power factor, (5) diversity factor.

REGULATION. — An ideal constant potential distribution woul one uniform, unvarying voltage, and would be said to have perfect reg The greater the variation from such constancy the poorer the reg The regulation is usually specified in per cent variation, either "above or a standard mentioned. The standard is usually either the nominal desired or the actual average voltage obtained.

Evil Effects of Poor Regulation. — The evil effects of high volt short life of electric lamps, excessive speed of direct-current motors, e exciting current of induction motors and burning out of motors and other on the other hand, low voltage greatly diminishes both the candle-pow efficiency of electric lamps, decreases the maximum power of motors creases the current which a motor will take for a fixed horse-power As electric lamps are much more sensitive to change of voltage than separate circuits are often used for lighting and power, the former having for regulation which are omitted from the latter.

The following figures give roughly the quantitative effect of voltage va between 5 per cent below and 5 per cent above normal:

Each per cent decrease in voltage decreases candle-power of carbon incandescent lamps ..... 5 Pe
decreases torque of induction motor ..... 2 Pe
Each per cent increase in voltage decreases the life of carbon incandescent lamps* ..... 13 Pe
increases the magnetizing current of induction motors ..... 2 Pe

Ordinary Limits of Regulation. — Roughly, the maximum voltage tion at the lamps on a lighting system should never exceed 5 per cent, i regulation above or below normal should never be greater than 2.5 pe and should be as much less as is economically feasible; the voltage va on power systems is usually 10 per cent (5 per cent above or below norma is sometimes considerably more.

Calculation of Regulation. — In order to calculate the variation in v at any receiving device or group of such devices from no load to full loa voltage at the generating or substation or feeding point being assumed co the impedance drops in all parts of the distribution system must be calc

* Average for 5 per cent increase in voltage; the first per cent increase in decreases the life 18 per cent, the fifth per cent 8 per cent.

properly combined. The various parts of the system to be considered are house wiring, service wires (or leads from street mains to the house), secondary mains, transformers, primary mains, primary feeders. See *Distribution in Transmission Lines; Wiring of Buildings.*

In making such calculations account should be taken of the fact that the maximum currents in the several parts of the system seldom have their maximum values at the same time. The maximum drop in house wiring will not occur simultaneously in all houses nor will the maximum service drop occur together with the services, etc. Furthermore, the maximum house wiring drop for a given house may not occur at the same time as the maximum drop on the secondary mains, transformer or primary mains to which it is connected.

Effect of Line Reactance. — The regulation of an alternating-current system of unity power factor will be poorer than that of a direct-current system of the same copper efficiency (see tabulation above) because of additional drop due to line reactance.

Effect of Lagging Power Factor. — A lagging power factor usually makes the regulation of an alternating-current system worse than it would be for unity power factor and therefore much worse than for a direct-current system of the same copper efficiency.

Effect of Leading Power Factor. — A leading power factor usually makes the regulation better than it would be for unity power factor and may give even better regulation than can be obtained from a direct-current system of the same copper efficiency.

Effect of Currents in Neutral. — Any current in the neutral wire of a balanced system produces a drop which tends to unbalance the voltage of the two sides. In the case of a three-wire direct-current or single-phase system *one per cent drop in neutral produces two per cent difference in the voltages on the two sides.* The drop in the neutral therefore affects more seriously the regulation than an equal amount in the outside wires. If the currents in the neutral all have the same direction, say toward the station, the voltage drops in the various sections of it will be cumulative, and though the drop in each section may be small the total current may actually reach the station, the aggregate effect may be serious. The individual loads on the two sides of the neutral should be connected so that the unavoidable neutral currents flow alternately in each direction, thus causing drops in alternate directions thereby neutralizing each other over the total length of the circuit.

Feeder Neutral in Three-wire Systems. — When the "feeder and main" system is used with a three-wire system, two-wire feeders should be used only for the outside wires, and only a single "feeder" neutral be used. That is, with respect to the neutral, the "tree" system gives better regulation for the same weight of copper than the "feeder and main" system, but with respect to the outside wires the latter system gives the better results. This is a point which has not always been recognized in laying out three-wire systems.

VOLTAGE CONTROL. — (*See also Controlers.*) The more common methods of controlling the voltage at feeding points when the feeder and main system of distribution is used (*see above*) are the single bus system, the high and low bus system, and feeder regulators.

Single Bus System. — (*See also article on Bus-Bars.*) All the feeders may be connected to a single bus and the bus voltage be raised as load increases so as to compensate for average drop of all the feeders on it. This method gives excessive voltage on such feeders as are comparatively short and low voltage for those that are long. Usually maximum voltage is carried in the evening

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during the lighting peak and lower voltage during day giving very p
lation on power circuits having maximum load during the day and
at night. This method is used on most small direct- and alternatin
distribution systems.

High and Low Bus System. — The bus may consist of two pa
may be separated, and operated at different voltages, feeders of greate
drop connected to the "high" (voltage) bus and the others to t
(voltage) bus. The voltage of each bus is raised or lowered in accord
average drop of feeders on it as in the single bus system. This metho
extensively on the Edison three-wire direct-current systems, as note
The unequal drop of the several feeders on same bus are equalized
interconnection through mains.

Feeder Regulators. — A feeder may have a separate regulator a
to compensate for its own drop. This method is sometimes used c
current railway feeders and very extensively on alternating-current
feeders. See article on *Regulators*. A feeder or other distribution circ
contains a voltage regulator is frequently referred to as a "boosted
Boosted circuits are not usually interconnected but may be if the b
of the same nature in each.

Control of Polyphase Systems. — In a polyphase system the l
be as equally divided among the phases as possible and the voltage
with respect to any one phase taken as representing the average of a
lighting load may be connected on a single phase and the voltage regu
this phase alone. The former method is more common, as it permits o
put of all the phases of the generator being used and gives a more equa
on the several phases of polyphase motors.

Transformers as Outside Boosters. — An auto-transformer or an
transformer may be connected to a feeder at any point and used as a "
to raise or lower the voltage. In the case of an ordinary transformer the
and secondary are connected in series thus converting the transforme
auto-transformer; see article on *Auto-Transformers*. Such boosters
adjustable and have a bad effect on the regulation as they give excessiv
on the boosted part of line at light load.

To cut such a booster out of service without taking it off the circuit the
coil must be open circuited and the secondary short circuited. *Caut*
main circuit must be opened before cutting out booster, because if the
is opened while current is flowing in the secondary the booster become
up transformer and may give a dangerously high voltage on the prim
on the other hand the secondary is short circuited first, a destructiv
circuit current may flow through it and the primary, and when the pr
opened a dangerous arc will form.

Use of Lamps of Different Voltage. — Attempts have been made
pensate for the difference in voltage at the various points of a network
lamps of different rated voltage, high-voltage lamps being used near the
supply and low-voltage lamps at the ends of line. This plan has not b
cessful because the difference in voltage between any two points is not c
Frequently some of the high-voltage lamps are used by mistake wh
voltage lamps are intended; the results are then poorer than when no d
is made in lamp voltage. While lamps of two or more voltages may
temporarily as an expedient when regulation is very bad, it is better
to have all lamps on a system of a single uniform voltage.

Use of Transformers of Different Ratio. — Transformers are als
with taps so that a uniform secondary voltage can be obtained with a
primary voltage. The plan is not a good one, because if the difference

correct for uniform voltage at full load it gives unequal voltages at light ad. It also has the very serious disadvantage that the haphazard changing transformer ratios by ignorant linemen to compensate for dim light, due haps to lamps already blackened by excessive voltage, makes it impossible carry out any systematic plan for securing the best average regulation for e system as a whole.

BALANCING OF LOAD. — In three-wire direct-current or single-phase stems and in all polyphase systems supplying single-phase load it is necessary approximately balance the load between the two sides or the several phases the case may be. Unbalanced load has two bad effects: (1) it loads the o sides or phases of the system unequally, making it impossible to get full tput out of the lightly loaded side or phase without overloading the other;) it makes the regulation of the system worse by causing high voltage on the htly loaded side or phase and low voltage on the other.

The first difficulty is not serious, because through the conduction of heat from e loaded to the unloaded coils of transformers and generators the machine pacity is not reduced in proportion to the unbalance; for moderate unbalance, say up to 10 per cent greater load on one side or phase than on the other, is doubtful if any appreciable effect could be discovered. As the total load ually consists of a great number of small parts, a very little foresight in dividing e load in the first place between the sides or phases, and in suitably distributing subsequently connected load, will give a balance good enough for all practical rposes. When polyphase alternators were first installed for supplying existing ngle-phase lighting circuits, it was supposed to be important to have a close alance of load between the phases, and early switchboards were therefore ovided with transfer switches for throwing single-phase feeders from phase phase. It was later found that instead of being necessary to transfer the load om phase to phase, following the diurnal or annual variations of load, that e circuits could stay on the same phase indefinitely and that transfer switches ere unnecessary and undesirable. The time when rebalancing of this kind necessary is usually when new circuits are established, at which time the anges of connections are best made by changing the taps to the bus-bars.

Motor-generator Balancer. — On direct-current three-wire systems the fference in current on the two sides may be balanced without taking the neutral rrent to the generator by a balancer consisting of two similar machines echanically coupled and electrically connected in series. Each machine is ound for the voltage of one side f the system (110 volts for a hree-volt system); the common nnection between the machines connected to the neutral and e other two terminals to the o outsides, see Fig. 2 (the field indings are omitted for clear-ss). The unit acts as a motor nerator (q.v.), whichever ma-ine happens to be on the light de being the motor for the time being and the other the generator. By engthening the field of the one on the side where the voltage is low and akening that of the other, so as to keep the same total voltage, the voltages the two sides as well as the currents may be balanced if necessary.

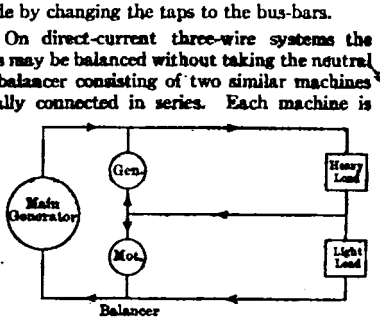


Fig. 2. Motor-generator Balancer

The output of the balancer generator and the input of the balancer motor re practically equal to each other, neglecting the losses in the machines, and ch is equal to

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$$\frac{P_1 - P_2}{2},$$

where P_1 is the load on the heavily loaded side of the system and P_2 the the lightly loaded side. For example, if the load on one side is 110 kw. the other side 90 kw., the load on each unit of the balancer is 10 kw.

It would, however, be unsafe to use a balancer as small as such calcu for the normal unbalancing would indicate as correct, because in case of a circuit on one side of the system, or of loss of a large amount of load on o due say to the blowing of fuses, the balancer would be dangerously over This may not only destroy the balancer, but may burn out many lam motors on one side due to excessive voltage. In small systems, say up t kw. total capacity, the balancer should be able to operate momentaril any loading up to the capacity of the main generator, and in large s should have capacity sufficient to burn off a short-circuit on one side of the without creating an unduly high voltage on the lightly loaded side.

Dynamotor as a Balancer. — A smaller and cheaper balancer is ob by using a dynamotor (q.v.), which is a single machine with two windi one armature and two commutators. The armatures are connected in seri balance the currents, but as there is only one field the voltages can balanced.

Alternating-current Balancing Coil. — On alternating-current single three-wire systems it is usual to obtain the neutral from the middle of the coil of the transformer supplying the current. It can, however, tained at any point of the two-wire circuit without going back to the former by using a balance coil. A balance coil is a transformer with two windings connected in series across the circuit and with the neutral wi nected to the common point between the windings. Whichever coil is lightly loaded side acts as the primary and the other as the secondary, t balancing the circuit by transferring one-half of the difference in load fr heavily loaded side to the lightly loaded side. Such coils, which are esse auto-transformers with a 2:1 ratio, may be used in various ways: to the neutral for an unbalanced three-wire circuit from a two-wire circ supply a 110-volt load from a 220-volt circuit; to supply a large 110-vo from a 110/220-volt circuit without connecting to the neutral. In p balance coils are not much used as the neutral can more cheaply be ob from the transformer.

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RAFT, MECHANICAL. — (*See also Blowers and Compressors; Chimneys; as; Pipes and Piping.*) Any system producing draft either by steam jets or r blowers is called a mechanical draft system. The relative advantages of achanical draft as compared with chimney draft are: (1) The supply of air ay be more readily controlled; (2) a fan permits a lower temperature of flue ses, which increases the boiler efficiency; (3) the boiler may be forced to gh overloads in case of emergency; (4) the draft is uninfluenced by climatic nditions; (5) the system is low in first cost. The disadvantages of mechanal draft are: (1) danger of breakdown; (2) cost of maintenance and operaon; (3) a stack or other means must be provided to carry off the flue gases herever their discharge at low levels constitutes a public nuisance. Many lants with tall stacks are provided with mechanical-draft apparatus as a eans of forcing the boilers in case of heavy overloads. Mechanical draft is so frequently used in connection with fuel economizers.

Steam Jets for producing artificial draft are simple, inexpensive and easily plied, but are very uneconomical, since they require from 6 to 11 per cent f the total steam generated (A. J. Whitham, *Trans. A.S.M.E.*, Vol. 17).

Forced Draft. — A blower system creating an excess of pressure beneath the te is known as a forced-draft system. A single fan is commonly employed to pply a number of boilers through a system of ducts beneath the floor. The ir is sometimes taken from a chamber built around the breeching, thus utilizng a part of the heat energy in the exhaust gases.

Induced Draft. — In the induced-draft system the fan is placed between the eeching and the stack. All leakage of air is inward, avoiding inconvenience hen the doors are opened. This system is frequently used in plants which ave high peak loads, being ordinarily installed in connection with fuel econoizers. A by-pass directly from breeching to stack is usually provided for use hen mechanical draft is not required or in case of accident. A double system f fans is also sometimes provided as a further insurance against accidental terruption.

POWER REQUIRED — SIZE OF FANS. — The power and size of fans equired to operate either a forced-draft or induced-draft system may be roughly alculated by the method given in the article on fans. The static pressure may e roughly approximated from the data given in the article on chimneys, the gures there given for loss of draft being taken as the static pressure to be overcome. The quantity of air required per boiler horse power depends upon the uality of the coal, upon the care taken in firing and upon the efficiency of the oiler and grate (*see Boilers*).

Let R be the number of pounds of coal required per boiler-horse-power hour, W the pounds of air required per pound of coal, P the boiler horse power and $w = \frac{1.33\,B}{460 + t}$ = pounds per cubic foot of gas passing through the fan, where B is the barometric pressure in inches of mercury and t the temperature of the gas in degrees Fahrenheit; then the volume of gas passing through the fan per minute is $Q = \frac{RWP}{60\,w}$. This formula and the formula for w are strictly applicable only to the case of a forced-draft fan, but the two formulas may also be used with but a small error for an induced-draft fan, taking for t in the latter case the temperature of the discharged products of combustion (about 500° F., when no economizer is used and about 300° F. with an economizer). The size of fan and the power required to operate it will be greater for induced draft than for forced draft, since in the former case the volume of gas passing through

the fan is greater. According to Gebhardt the power required to operate forced-draft system for a plant of 1000 boiler horse power or more, will ran from 1 to 5 per cent of the plant capacity.

COSTS (Pre-war figures). — According to Gebhardt the cost of a force draft fan, engine and stub stack for a plant of 1000 boiler horse power or more w approximate 20 to 30 per cent of the cost of an equivalent brick chimney. Th cost of a single induced fan, engine, stack, etc., will approximate 40 to 50 p cent of the cost of an equivalent brick chimney, and the double-fan outfit w be 50 to 60 per cent of that of an equivalent brick chimney. Two per cent is liberal allowance for maintenance and depreciation of a brick or concrete chim ney, while for a mechanical-draft system an allowance of from 4 to 10 per cen should be made. It costs nothing to operate a chimney, while from 1 to 5 p cent of the cost of operation of a boiler plant is chargeable to a mechanical-dra system.

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REDGES, ELECTRICALLY OPERATED. — (*See also Motors, Industrial Applications of.*) Electrically operated dredges are now used very generally, especially in connection with gold mining. This drive has indisputably owed its advantages over steam drive from the standpoint of both operation nd economy, as individual motors can be applied to the various units of the redging machinery, and a larger percentage of the power input can thereby be rectly applied in useful work.

The standard form of dredge is of the continuous-chain, close-connected cket type, ranging in capacity from 3 to 16 cubic feet and with a digging depth from 40 to 60 feet. As the power is mostly obtained by transmission from ne hydroelectric power system or central generating station, alternating rrent is generally used for driving the dredge machinery. For a modern ld-mining dredge this consists of the digger or bucket line, the winch, e high- and low-pressure pumps, the priming pump, the screen and the acker.

Bucket Line. — The bucket line is supported on a sheet-steel or girder struc- re of massive construction, so as to resist the heavy strains while in operation, pecially when striking rock. The speed varies from 50 feet (with from 16 to 25 ckets) to 75 feet (with from 35 to 50 buckets) per minute, depending upon e condition of the ground.

The operation and control of the digger a variable-speed induction motor is ed. This is located on the lower deck and belted to the driving pulley, which enerally situated in the rear of the pilot house on the upper deck. The duty posed upon this motor is severe, as it must operate under conditions calling r power varying from 75 per cent overload down to 25 per cent of its rated pacity. A drum-type controller for forward and reverse operation is pro- ided, including the necessary resistance for continuous operation on any notch f the controller from one-half to full speed. The maximum starting torque is quired and obtained at about the fourth point of the controller, thus leaving ree points on which to bring the motor up to half speed, at which time nearly ll rated torque is required. As a result of these conditions the ordinary motor signed for intermittent service cannot be successfully applied.

The raising and lowering of the bucket-line ladder is generally accomplished y a friction clutch which can be connected to the digger motor. For the larger ne dredges, however, a separate motor is often provided to perform this nty.

Winch. — To keep the dredge in place and to move it about or hold it against e bank when digging, head lines are used, which are controlled from the for- ard end and operated by a six- or eight-drum winch driven by a variable-speed otor. The winch motor, though of smaller capacity, is of the same staunch nstruction as the digger motor and is equipped with a suitable controller and sistance to permit its continuous operation from one-half to full speed. It as been found advisable to equip the motors for this service with solenoid brakes, y means of which the motor can be brought to a standstill almost instantly. t is then ready for the reverse operation without the usual reversing of the motor hrough the controller, which is not only bad practice but may result in a burn- ut due to the heavy strain on the windings.

Pumps. — The high- and low-pressure pumps for supplying water to the screens nd sluices are generally connected to individual motors. Constant-speed quirrel-cage motors of compact construction and large overload capacity, with speed of from 600 to 900 r.p.m., are usually installed for this work.

To prevent the filling up of the basin, in which the dredge floats, when dig- ing in shallow water, it is sometimes found necessary to install a sand pump,

which carries the fine tailings from the sluice boxes to the top of the rock way of the stacker.

Priming Pump. — A priming pump is required for priming the large or for supplying water on the tables during the "clean-up." It genera sists of a small centrifugal pump driven by a high-speed direct-connected s cage induction motor.

Screen. — Either a shaking or revolving screen is used to separate th from the clay and permit the fine particles containing the gold to pass t on to the gold tables and sluices below. For this service a constant-spee is recommended, which can be placed on the upper deck and belted dow driving pulley of the screen.

Stacker. — After screening the large rocks are carried on a belt conv the end of the stacker and deposited on the spoil in the rear of the dredg operating this conveyor a constant speed motor is installed at the extre of the stacker, where it can be readily housed.

Monitor. — When a dredge is working in a high bank of hard materia experience has demonstrated that it is advisable to lower the water leve pit and cut the bank down with a "Giant," water being furnished by a t four-stage, high-pressure centrifugal pump driven by a phase-wound in motor. The Giant is mounted on the bow of the boat, and as the dredge from one side of the cut to the other, the stream of water is thrown agai bank about two feet above the water level. This undermines the bank, the material to cave into the pond where it is brought up by the buck The Giant is also used in localities where the water in the pond cannot b high enough to bring the bucket line near the top when the dredge is s ahead.

Power Required. — The sizes of motors required for driving the ma of some dredges of different capacities are given in the following table proper speeds will depend on whether the motors are to be belted or dire nected to the machines which they are to drive.

SIZES OF MOTORS FOR DREDGES

Machinery to be driven	3 cu. ft. dredge, 40-ft. digging depth		5 cu. ft. dredge, 40-ft. digging depth		7 cu. ft. dredge, 40-ft. digging depth		13½ cu. ft. dredge, 40-50 ft. digging depth		16 c dred ft. d de
	H.P.	R.p.m.	H.P.	R.p.m.	H.P.	R.p.m.	H.P.	R.p.m.	H.P.
Bucket line	75	720	100	720	150	600	300	514	400
Winch	15	720	25	720	25	720	35	600	50
High-pressure pump	40	900	50	900	50	900	150	720	150
Low-pressure pump	25	600	25	600	25	600	75	600	100
Priming pump	7½	1200	7½	1200	7½	1200	25	1200	35
Screen	25	900	25	900	25	600	75	600	150
Stacker	20	900	20	900	25	600	50	600	50

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oltage of Motors. — The power for operating a dredge is generally trans-
ed from some existing power system, and the connection between the line
the dredge is, as a rule, made by means of armored cable carried on floats.
n this transmission can be economically carried out at a voltage of 2200,
customary to provide the motors for this voltage, thus eliminating the ex-
e of installing step-down transformers. When the transmission voltage is
re 2200 volts, it is desirable to step it down to 440 volts and use motors for
voltage. When step-down transformers are required, their capacity is
lly taken as two-thirds of the total horse-power load, allowing one kilowatt
ach horse-power.

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DYNAMOTORS. — (*See also Converters, Synchronous; Motor Gen Transformers.*) A dynamotor is a direct-current device combining both mo generator action in one magnetic field. It has an armature having two s windings and two separate commutators, one at each end of the ar Either winding may be used as the motor winding, and the other as the ator winding. Such a machine performs the same function in a direct- circuit that a power transformer does in an alternating-current circu serves as a means of transforming high-voltage direct current into low- direct current, or vice versa.

Performance Characteristics. — The device corresponds to two mad which there is only one core-loss, one friction loss, one excitation loss, l losses due to RI^2 in the two armature circuits. It is therefore more than a motor-generator set, but less efficient than one machine. Si currents in the two windings flow in opposite directions their resultar netic effect is zero. The machine has therefore no armature reaction for the slight amount due to the current to overcome the losses in the m It is not subject to the troubles of field distortion and bad commutati occur in either motors or generators. It is impossible to compound a motor, since any increase in field strength intended to increase the vo the generator would decrease the speed of the motor by the same amo no change would result. The ratio of the two voltages is therefore fixed number of turns, and only varies from this by the loss due to RI drop windings. These two drops are additive, and therefore the regulation a machine is not very good.

Applications. — Dynamotors are used largely to give large currents other motors, or to give low voltages or a fractional voltage in a multi- system for speed control. The motor of the combination may be wo the line voltage and the generator for any fraction of the line voltage. the combination supplies a large current at a low voltage, which will good starting torque in motors connected to it with a reasonable const of power. They are used as equalizers or "balancers" in three or m circuits, but are not as desirable for this work as motor-generator se compound-wound machines, on account of their poor regulation. T also used to supply a low voltage for such purposes as telephone and te systems and the low voltage and large currents for electrolytic work.

Dynamotors are also used in radio work in connection with vacu detectors and amplifiers, in order to obtain from a battery of 4 to 10 voltage of 300 for operating the tube.

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ECTRICITY AND MAGNETISM, PRINCIPLES OF. — In
article are given definitions of the various electric and magnetic quantities,
ther with a brief statement of the fundamental principles in accord with
ch all electric and magnetic phenomena take place.
he following is a brief table of contents of this article:

Units and Working Hypothesis	p. 393
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NITS AND QUANTITATIVE LAWS. — Three different systems of
rs are in use in terms of which electric and magnetic quantities are expressed.
ese systems are known as the c.g.s. electrostatic system, the c.g.s. electro-
gnetic system and the practical system (*see also Units, Practical Electric*).
e various units in the practical system have been given short names which
e in common use, e.g., ampere, volt, coulomb, etc. For the sake of brevity
corresponding units of the electrostatic system will be designated by these
e names with the prefix "stat," and the corresponding units in the c.g.s.
ctromagnetic system will be designated by these same names with the prefix
b," the latter prefix arising from the term "absolute" sometimes applied to
system.

The use of the electrostatic and electromagnetic systems of units arises from
manner in which certain of the fundamental quantitative relations, or
ws," were originally formulated. The practical system is related to the
ctromagnetic system, by even multiples of ten times the units in the latter,
- 1 volt = 10^8 abvolts, 1 ampere = 10^{-1} abamperes, 1 ohm = 10^9 abohms.

The quantitative relations given below between *electric* quantities are in-
endent of the system of units employed provided *all the quantities involved
expressed in the same system of units.* (*See Units and Conversion Factors.*)
r some of the *magnetic* quantities, certain additional practical units have
n introduced which are not related to the c.g.s. electromagnetic units by
ltiples of 10; consequently, to avoid confusion it is best to reduce all quanti-
s to electromagnetic units before applying any of the formulas given.

**WORKING HYPOTHESIS REGARDING THE NATURE OF
CTRICITY.** — The various facts of experience described as electric and
gnetic phenomena can best be coördinated by assuming at the outset the
stence of electricity as an actual entity, possessing the following properties:

1. Electricity exists in two forms, which for convenience may be called
sitive" and "negative" electricity. These names arise from the fact that
two kinds of electricity produce certain effects which are just the opposite
each other, and, therefore, under certain conditions the external effect of one
d of electricity may completely neutralize the effect of the other kind.
A given quantity of electricity is called an "electric charge."

2. All matter contains electricity of both kinds, even when in the neutral or
uncharged" state. An uncharged body contains in every elementary portion
molecule) equal quantities of positive and negative electricity, so thoroughly

"mixed" that no external effects are produced, unless the two kinds of electri ity are constrained to take up a definite position or to move in a definite manne

3. A body or portion of a body can be charged with electricity of either kin either by adding to it electricity of that kind or by taking away from it electri ity of the other kind. In general only the *surface* of a body can be charged, i. the excess or deficit of charge exists only at the surface of separation between th body and some other body, the interior elements of the body containing, as the neutral state, equal amounts of electricity of opposite kinds.

4. It is impossible to charge a body with electricity of one sign without pr ducing on the same or on some other body an equal charge of the opposi sign.

5. Forces can be produced on the electricity in a body by various extern agents, without necessarily producing a force on the body as a whole. Wh such forces are produced the two kinds of electricity are either displaced rel tively to each other or are constrained to move through the body in opposi directions. This displacement or motion is always opposed by forces set within the body itself. The opposing forces are of two kinds, (1) a for analogous to the opposing force set up in an elastic body when it is stretched compressed, and (2) a force analogous to the resisting force due to mechanic friction produced when one body moves over another.

6. When the electricity in a body is acted upon by an external force, bu cannot escape from that body to another, this force is transmitted to the bo itself.

7. Electricity possesses inertia, just as ordinary matter possesses inertia; i.e., force is required to change the motion of a charge of electricity just as a force required to change the motion of a portion of matter. The "effective" inert of a given quantity of electricity depends upon the path over which it caused to move and upon the nature of the surrounding bodies (*see Electr Theory*).

Unit of Charge or Quantity of Electricity. — The unit of electr charge or quantity of electricity in the practical system of units is called t coulomb. For the relation between the coulomb, statcoulomb, abcoulom and other units of quantity see *Units and Conversion Factors*.

ELECTRIC FIELDS OF FORCE. — In any portion of a substance which the electricity is acted upon by a force tending to move it, there is sa to be an "electric field of force," or briefly an "electric field." An electric fie is also said to exist in any region of free space where a charge, if placed the would have a force exerted upon it tending to move it.

Intensity of an Electric Field (F). — The "intensity" of an electric fie at any point is defined as the force per unit positive charge exerted on a char at this point by the agent or agents producing the field i.e., by the agent agents tending to move the charge. The direction of the field intensity, or t direction of the field, is defined as the direction of the force acting on a *positi* charge at this point. A positive charge then moves or tends to move in t direction of the field and a negative charge moves or tends to move in t opposite direction.

Units of Electric Field Intensity. — The unit of electric field intens has not been given any special name, but since it is of the same nature electromotive force per unit distance, the intensity at any point may be co veniently expressed as so many volts, abvolts or statvolts *per centimeter* or *inch;* see *Units and Conversion Factors*. Hence electric field intensity is f quently called the potential, or voltage, "gradient."

Lines of Electric Force. — Lines of Electric Intensity. — A line dra in an electric field in such a manner that its direction at each point coinci

ith the direction of the field at that point is called a "line of electric force." line of force is usually a curved line, though in certain special cases it may straight. Any number of such lines may be drawn in an electric field, but two of these lines can intersect. The density of these lines, i.e., the num- drawn through unit area perpendicular to their direction, may be chosen rbitrarily to represent the value of the field intensity at this area, and when drawn are preferably called "lines of electric intensity," as distinguished om flux lines and stream lines defined below. The term "lines of force," owever, is frequently used to designate any one of these three sets of lines, but s loose use of the term is liable at times to lead to much confusion. The rm "line of electric force" will be used in this article to designate merely the irection of the field at any point; in any statement involving the *density* of ese lines the proper one of the other terms will be employed.

Electric Equipotential Surfaces. — A surface drawn in an electric field in uch a manner that it is perpendicular at each point to the line of force through ch point is called an "electric equipotential surface." The electric in- nsity has no component along such a surface, and therefore no work is re- ired to move a charge from one point to another over any path in such a rface.

ELECTROMOTIVE FORCE (E). — The work done by the field intensity moving unit positive charge around any *closed* path or circuit (Fig. 1) in electric field is defined as the "electromotive force," breviated "e.m.f.," acting around this path. Elec- motive force is not a force in the mechanical sense t is *work per unit charge*. The relation between elec- motive force E and field intensity F is analogous to at between work and mechanical force viz.,

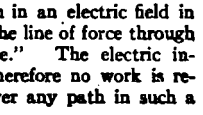


Fig. 1.

$$E = \int (F \cos \theta)\, dl, \qquad (1)$$

here dl represents an elementary length of the path, $(F \cos \theta)$ the *component* the field intensity along dl and $\int$ represents the integral around this closed th. When the field intensity has the same value F at every point of a path d coincides in direction with the path at every point, the electromotive force ting around the closed loop is

$$E = Fl \qquad (1a)$$

here l is the total length of the path.

Units of Electromotive Force. — The practical unit of electromotive rce is the volt; see *Units, Practical Electrical*. See also *Units and Con- rsion Factors* for the other units and their interrelations.

Sources of Electromotive Force. — The primary sources of e.m.f. are (1) two dissimilar bodies in contact (*see Batteries; Electrochemistry, Principles* f) and (2) a varying magnetic flux linking the circuit (*see the articles on nerators; Transformers, etc.*). The e.m.f. is said to be "located" at the rface of contact in the case of a "contact" e.m.f., or in that portion of the rcuit which is linked by the varying magnetic flux in the case of an "induced" m.f., for experience shows that the value of the work integral, equation (1), ound any circuit passing through a given surface of contact or linking a given rying flux is always the same, irrespective of the shape of the circuit and of e nature of substance through which the path passes, provided there are no her sources of e.m.f. in this path. Contact e.m.f.'s are usually extremely

small (of the order of 0.001 volt) except in the case of metallic subst contact with electrolytes, in which case they may amount to several v *Batteries; Electrochemistry, Principles of.* E.m.f.'s of 500,000 volts or n be produced by a varying magnetic flux.

Direction of an Electromotive Force. — The direction of the e.m.f portion of a circuit is taken as the direction in which a positive charg be forced *around* a circuit containing only this one source of e.m.f. A circuit may contain several sources of e.m.f.; in this case the resultan acting around in the circuit is the *algebraic* sum of all these e.m.f's, the acting around the circuit in one direction being taken as positive and th ing around the circuit in the opposite direction being taken as negative. e.m.f.'s which act in the opposite direction to the resultant e.m.f. ar "back" or "counter" e.m.f.'s.

A convenient symbol for a source of constant e.m.f. is shown in Fig. long light line represents the positive terminal and the short heavy



Fig. 2.

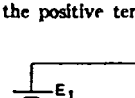


Fig. 3.

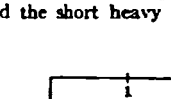


Fig. 4.

negative terminal. Fig. 3 shows two e.m.f.'s acting around a circuit in t direction, and Fig. 4 shows two e.m.f.'s acting around the circuit in directions. In the first case the resultant e.m.f. is $E_1 + E_2$ and the two are said to be "in series," and in the second case the resultant e.m.f. actin right-handed direction around the circuit is $E_1 - E_2$ and the two e.m said to be "in opposition." When E_2 is less than E_1 then E_2 is a counter e.m.f.

DIFFERENCE OF ELECTRIC POTENTIAL (V). — Consider tion of a path A between any two points 1 and 2 in an electric field (The total work done on unit charge, *by the e.m.f.'s external to this portio path* when unit charge moves from 1 to 2, is called the "drop of electri tial" from 1 to 2. The term "difference" of electric potential is also co used to designate this quantity; the term "drop" is preferable since it the direction of the difference. Electric potential drop is of the same na electromotive force and is expressed in the same units. It is frequently viated "p.d." Potential drop may be due either (1) to a "back" electr force, analogous to the back pressure of a pump, or (2) to an opposin analogous to that due to the resistance of a pipe to the flow of water.

Let the path from 1 to 2 be in the direction of the line of force from let E_{12} be an e.m.f. whose source is between 1 and 2 and whose direction 1 to 2, then the general expression for the potential drop from 1 to 2 is

$$V_{12} = \int_1^2 F\,dl - E_{12}.$$

The first term represents the "resistance" drop and $-E_{12} = E_{21}$ represe "back" pressure. If the field intensity along the path from 1 to 2 is neg then $V_{12} = -E_{12}$; hence an e.m.f. in a given direction is equivalent to a n drop of potential, i.e., is equivalent to an actual *rise* of potential. Con

) with equation (1) it is evident that the total drop of potential around a *closed* rcuit is always zero. This relation is conveniently expressed by the formula

$$\Sigma V = 0 \qquad (3)$$

hich holds for every closed path or circuit. This is one way of stating Kirchoff's second "law."

Voltage and Voltage Gradient. — The term "voltage" is commonly used r either an e.m.f. or a potential difference, particularly when these quantities re expressed in volts. Since from equation (2) the field intensity F is equal in ids to the drop in voltage per unit length, the electric field intensity is also requently called the voltage "gradient."

Positive and Negative Terminals. — That terminal of a device which is at he higher potential is called the positive terminal, the other terminal being alled the negative terminal. The drop of potential is *always* from the positive o the negative terminal, irrespective of the direction of flow of electricity hrough the device.

FLOW OF ELECTRICITY. — Whenever an electric field is set up in a ubstance by any means whatever a displacement of the electricity in that ubstance always takes place, the nature of the displacement depending upon he nature of the substance. In every case the positive electricity within the ubstance is displaced in the direction of the field intensity and the negative lectricity in the opposite direction, until an opposing force of some kind is set up which just balances the forces due to the impressed field.

Conductors and Insulators or Dielectrics. — A substance in which a onstant electric field is always accompanied by a *continuous* displacement or *low* of electricity through the substance is called an "electric conductor;" hen there is no flow of electricity through a conductor the field within the conuctor is *always* zero. Every substance is a conductor of electricity, at least to a slight extent, but some substances are far better conductors than others. A ubstance in which a constant electric field produces only a relatively small ontinuous flow of electricity is called an "electric insulator" or "dielectric." A *perfect* dielectric may be defined as a substance through which it is impossible to set up a continuous flow of electricity; no such substance exists, but very poor onductors are approximately such. Free space may be considered a perfect dielectric, but free space differs from a substance in that it does not contain electricity.

Metals are the best conductors, carbon and most moist substances are fair onductors; dry non-metallic bodies such as air and other gases (at normal pressure), porcelain, glass, rubber, and dry paper are very good insulators.

A wire covered with an insulating substance or supported on insulating substances is said to be "insulated," even though its ends are connected to a source of e.m.f.

Electric Current (I). — The displacement of the electricity within a substance cannot be measured directly, but only in terms of some effect produced thereby. Two effects which always occur when a displacement of electricity is produced are (1) a magnetic field is established around the path along which the displacement takes place (but disappears when the electricity comes to rest) and (2) heat is developed in the path of the displacement. The magnetic field produced by a displacement or flow of electricity is usually taken as the measure of the *rate* of flow, i.e., of the quantity of electricity displaced per unit time through a surface perpendicular to the direction of the displacement. This rate of flow is called the "intensity" of the electric current, or simply the "electric current," and is usually represented by the symbol I.

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Direction of the Electric Current. — A flow of positive electric one direction is equivalent magnetically to a flow of an equal amount of ne electricity in the opposite direction; hence the total flow along a given p the sum of the positive electricity displaced per unit time in one direction point in this path plus the negative electricity displaced per unit time pas point in the opposite direction. The "direction" of the electric current is as the direction in which the positive electricity is displaced, and is, the the same as the direction of the field intensity.

Current due to Varying Electric Field. — When the electric fi any substance is *varying*, the total magnetic effect produced is found to d not only upon the rate of displacement of the electricity within the subs but also upon the *rate of change* of the electric field. In fact, a magneti is produced around a path in *free space* along which the intensity of the el field is varying, see *Waves, Electromagnetic*. In dealing with varying el fields it is found convenient to consider the variation of the field intens equivalent to an actual flow of electricity, and to take as the total *equ* electric current the flow of electricity which would produce the same ma field as that actually observed; the *actual* flow of electricity is then in g less than this equivalent current, but the difference is negligible except i stances which are good insulators.

Units of Electric Current. — The practical unit of electric current ampere; see *Units, Practical Electrical*. For the relation between this un the statampere and abampere see *Units and Conversion Factors*.

Continuity of an Electric Current. — When a varying electric fi considered as equivalent to an electric current, it is found that the total e lent current coming up to any point or surface in any network of circuits, no matter how complicated, is *always* equal to the total current leaving that point or surface, irrespective of the nature of the substances through which the currents are established and irrespective of whether the currents are constant or are varying. For example, in Fig. 5,

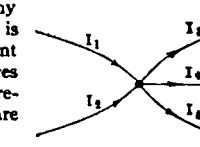


Fig. 5.

$$I_1 + I_2 = I_3 + I_4 + I_5. \qquad (4)$$

Or, calling the currents coming up to any point positive, and the currents le that point negative, the *algebraic* sum of all the currents at any point in work of circuits is always zero. This fundamental principle is conven expressed by the formula

$$\Sigma I = 0$$

which holds at every junction point both for variable and for continuous cur This is Kirchhoff's first "law."

Stream Lines of Electric Current. — Current Density (σ). — consequence of the continuity of an electric current, the total current i substance of any size or shape may be looked upon as made up of a numb small streams of electricity flowing side by side, the strength (quanti electricity per second) of each stream being constant throughout its length the cross-section of each stream at any point is so chosen that each st represents unit current (unit quantity per second), then the number of streams crossing unit area of a surface perpendicular to their direction w equal to the current per unit area of this surface, or to the "current density this surface. Each such stream may be represented graphically by a line ciding with its axis; such lines are called "stream lines." When the st lines are drawn as described their direction at any point gives the directi

current at this point and the number of these lines per unit area perpendicu- to their direction is equal to the current density at this point.

In the case of an insulated wire the stream lines are parallel to the axis of the e, except in the immediate vicinity of its ends; this non-uniformity at the ls in the case of a long wire is negligible. The stream lines in an ordinary e may also, in most practical cases, be considered as all coinciding, and the e may, therefore, be treated as a geometrical line as regards *external* effects. wever, in the case of a short rod or strip (such as an ammeter shunt) con- ted in the circuit by wires attached to its ends, the stream lines are not in eral parallel but diverge from one terminal and converge toward the other.

Continuous, Direct, Pulsating, Alternating and Oscillatory Currents.— "continuous" electric current is defined as a current which does not vary th time. A "direct" current is a current which is always in the same direc- n but may vary or pulsate in value. The term "direct current" is ordi- rily used to designate either a continuous current or a current which varies pulsates only by an inappreciable amount, such as the current from a battery direct-current generator (q.v.). A "pulsating" current is a direct current hich pulsates by an appreciable amount, such as the current from a rectifier (q.v.). An "alternating" current is a current which reverses in direction, being st positive and then negative, but alternates between *constant* maximum sitive and negative values; see article on *Alternating Currents*. An "oscilla- ry" current is a current which reverses in direction, oscillating between positive d negative values which either decrease or increase with time.

Conduction Current and Displacement Current. — Experience shows at when an electric field is established in any substance, the total equivalent lectric current set up depends (1) upon the value of the field intensity, (2) upon le rate of change of the field intensity, and (3) upon the nature of the substance which the field is established. The current density σ at any point at any stant may in general be expressed by the relation

$$\sigma = \gamma F + \frac{1}{4\pi}\frac{d}{dt}(kF), \tag{6}$$

here F is the field intensity, γ and k are coefficients depending upon the chemi- l nature and physical condition of the substance at the point in question, and

$\frac{d}{dt}$ means the rate of change with respect to time, the factor 4π arising from the

istorical definition of the quantity k, see below. The total current may then e considered as the sum of two components having respectively the densities

$$\sigma_1 = \gamma F \qquad \text{and} \qquad \sigma_2 = \frac{1}{4\pi}\frac{d}{dt}(kF). \tag{6a}$$

The first of these components (σ_1) is called the "conduction" current, and the second (σ_2) is commonly called the "displacement" current. The term "displacement" current, however, is somewhat a misnomer, for both com- ponents of the total current are probably due, in part at least, to a displace- ment of electricity; whereas a displacement current is set up by a varying electric field in a *free space*, although there is probably no electricity in free space to be displaced. The conduction current is the only appreciable com- ponent in substances usually classed as conductors, and the displacement cur- rent is appreciable only in substances ordinarily classed as dielectrics. The conduction current in a dielectric is usually small, though measurable; it is frequently called the "leakage" current. When the electric field in a dielectric is rapidly varying the displacement current may be many times greater than the conduction or leakage current through the dielectric.

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Conductivity (γ) and Resistivity (ρ). — The quotient of the density σ the conduction current by the field intensity F, i.e., the coefficient γ in expression $\sigma_1 = \gamma F$ is called the "conductivity" of the substance at the po in question. Since in an ordinary conductor the displacement current is appreciable, the conductivity of an ordinary conductor is also equal to density of the total current divided by the field intensity, i.e., for a conduc

$$\sigma = \gamma F,$$

where σ represents the density of the total current. Experience shows that a given conductor at constant temperature (and also at constant pressure case of a gas) this coefficient γ is a constant irrespective of the strength, d tribution or time variation of the current. The value of γ for a dielectr however, is not in general a constant but depends upon the time variation the field intensity; see below under *Capacity and Condensers*.

The above relation between σ and F may also be written

$$F = \rho\sigma, \qquad (7$$

where ρ is the reciprocal of the conductivity γ. The constant ρ is called t "resistivity" or "specific resistance" of the substance. Values of γ and ρ f various conductors are given in the article on *Resistance and Conductance*, an also the methods of measuring these quantities. The values of γ and ρ f some of the more common insulating materials are given in the article on *I sulating Materials, Properties of*. For the units of conductivity and resistivi see *Units and Conversion Factors* and also the next two paragraphs.

Conductance (g) and Resistance (r). — To cause a *continuous* current I flow through a given conductor in which there is no source of e.m.f. a differen of potential must be established by some external agent between the ends of th conductor. Let V be the potential drop established through the conducto from any point 1 to any other point 2, then the quotient

$$g = \frac{I}{V} \qquad (8$$

is defined as the "conductance*" from 1 to 2, and the quotient

$$r = \frac{V}{I} \qquad (8a$$

is defined as the "resistance*" from 1 to 2. Conductance is the reciprocal o resistance and vice versa. The practical unit of resistance is called the ohm and the practical unit of conductance is called the mho; see *Units and Con version Factors*.

It should be carefully noted that the definitions expressed by equations (8, and (8a) hold only when there is no e.m.f. in the portion of the circuit unde consideration; this condition is realized only when the current remains con stant in value (i.e., a *continuous* current) and the conductor is of uniform material and at constant temperature throughout. Also, the definition is mean ingless unless the same current flows through each cross-section of the conducto and the drop of potential is the same between all points in the two end surfaces; i.e., the end surfaces must be equipotential surfaces.

Factors Upon Which Conductance and Resistance Depend. — The re sistance or conductance of a given portion of a conductor included between

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equipotential surfaces and bounded laterally by a surface through which tream line passes, depends upon (*a*) the conductivity of the conductor he dimensions of this portion of the conductor, and (*c*) the distribution e stream lines over each cross-section perpendicular to them. Consider ase of a straight wire or bar over the cross-section of which the current is mly distributed. Let l be the length of the bar, A its cross-section and resistivity. Then from equation (2) the drop of potential along the length $V = Fl$; from equation (7a) $F = \rho\sigma$; therefore $V = \rho\sigma l$. The total current σA; whence the resistance and conductance are

$$r = \rho \frac{l}{A} \quad \text{and} \quad g = \gamma \frac{A}{l}. \tag{9}$$

ence, the conductivity of a substance is equal to the conductance, and the tivity is equal to the resistance, of a unit cube of this substance when the ent through this cube is parallel to four edges of the cube and is uniformly ibuted over the section at right angles to these four edges. Hence conduc- ty is frequently expressed as mhos per centimeter cube or inch cube; see *tance and Conductance; Units and Conversion Factors.*

quation (9) is applicable only to a conductor in which the stream lines are formly distributed and parallel to each other, such as in insulated wires carry- continuous or comparatively slowly varying currents. When the stream es are not parallel to each other, let dl represent an elementary length along stream line and σ the current density at dl; then taking the integral along stream line from one end surface to the other, the resistance is

$$r = \frac{\rho \int \sigma \, dl}{I} \tag{9a}$$

re I is the total current. The calculation of the value of σ at each point g the line from one surface to the other is difficult except in certain special s of symmetry; see however, equation (22) below.

hm's Law and Resistance Drop. — From the relations noted above it is ent that, in a conductor (*a*) which remains at constant temperature, (*b*) in ch there is no internal e.m.f., and (*c*) in which the distribution of stream lines ains unaltered, *the quotient of the voltage by the current is a constant.* This tion is known as Ohm's Law; it holds only when the three conditions specified ve are fulfilled.

he above relation may also be written $V = rI$ which is merely another form equation (2); i.e., if r is the resistance between any two points 1 and 2 n electric circuit in which the current is I, then the integral of the electric l intensity along the path from 1 to 2 is equal to rI. This drop of poten- l due solely to resistance between 1 and 2 is called the "resistance drop" m 1 to 2, and is always in the direction of the current. When there is an f. in the circuit between 1 and 2 and the distribution of current remains same,* the total drop from 1 to 2, from equation (2), is

$$V_{12} = rI_{12} - E_{12}, \tag{10}$$

subscripts indicating the directions of the various quantities. Equation (10) metimes referred to as the "modified" Ohm's law.

In general, the distribution of current depends upon the time variation of the volt- see article on *Skin Effect.*

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Terminal and Impressed Voltages. — The application of this eq
best shown by considering a simple circuit containing a generator and
or other receiving device, Fig. 6. Let I be the current in this circuit,
the internal resistance of the generator, R_m the internal resistance of the motor and R_l the total resistance of the "line" or connecting wires, let E_g be the e.m.f. developed by the generator and E_m the back e.m.f. developed by the motor, and let V_g be the terminal voltage of the generator and V_m the terminal voltage of the motor. Through the generator the current flows from the − to the + terminal, the e.m.f. is from the − to the + terminal, and the drop of potential the + to the − terminal. Hence

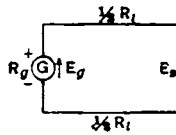


Fig. 6.

$$V_g = E_g - R_g I,$$

i.e., the terminal voltage is less than the generator e.m.f. by an amou
to the resistance drop in the armature. Through the motor the curr
from the + to the − terminal, the e.m.f. is from the − to the + termi
the drop of potential is from the + to the − terminal. Hence

$$V_m = E_m + R_m I,$$

i.e., the terminal voltage is greater than the back e.m.f. of the mot
amount equal to the resistance drop through the motor.

The terminal voltage of the motor is less than that of the generat
amount equal to the resistance drop in the line, i.e.,

$$V_m = V_g - R_l I.$$

The expression "impressed" electromotive force is also used to desig
rise of potential from the negative to the positive terminal of any
device, whether it be a motor, bank of lamps, or any "straight" resistan
resistance containing no source of electromotive force.

Series Circuits. — When several conductors are connected end to
that the *same current* flows through each of them (Fig. 7), they are said to be connected "in series." Let I_{12} be the current in each conductor in the direction from 1 to 2, let R', R'', R''', etc., be the resistances of the various conductors and E'_{12}, E''_{12}, E'''_{12}, etc., be the e.m.f.'s in the circuit between 1 and 2 in the direction from 1 to 2. Then the potential drop from 1 to 2 is

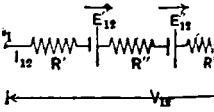


Fig. 7.

$$V_{12} = R'I_{12} - E'_{12} + R''I_{12} - E''_{12} + R'''I_{12} - E'''_{12}, \text{ etc.}$$

Therefore, the resistances between the points 1 and 2 are equivalent to resistance

$$R = R' + R'' + R''', \text{ etc.,}$$

and the e.m.f.'s between the points 1 and 2 are equivalent to a single e

$$E_{12} = E'_{12} + E''_{12} + E'''_{12}, \text{ etc.}$$

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equivalent conductance of several conductances G', G'', G''', etc., in series *there are no e.m.f.'s in the path*, is G where

$$\frac{1}{G} = \frac{1}{G'} + \frac{1}{G''} + \frac{1}{G'''} + \ldots \qquad (11b)$$

allel Circuits. — When several conductors are connected to two common ints so that the *same potential drop* tablished through each (Fig. 8), they are to be "in parallel." Let the currents, e.m.f.'s resistances be as designated in the figure. n from equation (5)

$$I_{12} = I'_{12} + I''_{12} + I'''_{12} + \text{etc.}$$

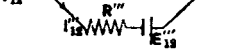


Fig. 8.

from equation (10a)

$$V_{12} = R'I'_{12} - E'_{12} = R''I''_{12} - E''_{12} = R'''I'''_{12} - E'''_{12} = \text{etc.},$$

which relations the currents in the individual branches may be calculated. ere *there are no e.m.f.'s* in the various branches, the combined resistance of veral branches from 1 to 2 is R where

$$\frac{1}{R} = \frac{1}{R'} + \frac{1}{R''} + \frac{1}{R'''} + \ldots, \qquad (12a)$$

the combined conductance is

$$G = G' + G'' + G''' + \ldots, \qquad (12a)$$

re G_1, G_2, G_3, etc., are the individual conductances.

wo Parallel Circuits. — In the special case of two conductors in parallel, no e.m.f. in either, the combined resistance is

$$R = \frac{R_1 R_2}{R_1 + R_2}. \qquad (12b)$$

eries-parallel Circuits. — When a circuit is made up of several conductors e of which are in series and some in parallel, it is called a "series-parallel" it. The total resistance or conductance of such a circuit can be calculated the constants of the several branches by applying successively the formulas eries and for parallel circuits.

Kirchhoff's Network Laws. — The relations given above for conductors in es and in parallel are special cases of two general laws already stated, namely:

The algebraic sum of the currents coming up to any junction in a network conductors is always zero (equation 5).

The algebraic sum of the potential drops around any closed loop in a net- k of conductors is always zero (equation 3).

ese two laws are known as Kirchhoff's Laws, from the name of the scien- who first clearly enunciated them. By making use of them one can always termine (*a*) the current in each branch of a network when the resistance ch branch and the e.m.f. in each branch are known, or (*b*) the e.m.f. in each ch when the current in each branch and the resistance of each branch are wn.

should be carefully borne in mind in applying these laws that a current ing a point is equivalent to a negative current *entering* that point, and that

an e.m.f. in any chosen direction is equivalent to a *rise* of potent direction. In working out any problem concerning a network of ci convenient to make a diagram of the network and to place on each this diagram a number or symbol to represent the value of the curr branch and an arrow or subscripts to indicate the direction of the cur sented by this number or symbol, and wherever there is an e.m.f. number or symbol to represent the value of this e.m.f. and an arrow o to indicate its direction. Then at any junction point those currents r by arrows pointing toward the point are to be considered positive (say represented by arrows pointing away from the point are to be consid tive; and for any closed loop those currents and e.m.f.'s represented pointing around the loop in the clockwise direction (say) are to be positive and those pointing around the loop in the counter-clockwis are to be considered negative. With this understanding, these la written

$$\Sigma I = 0 \text{ at every point,}$$

$$\Sigma E = \Sigma rI \text{ for every closed loop,}$$

where I, r and E represent the current, the resistance and the e.m.f. r in each branch of the loop, and the symbol Σ indicates the algebraic quantities following it.

These equations enable one to write down a set of simultaneous eq the given network, but it will be found that at least one of the curren may be derived directly from the other current equations, and that a of the potential equations may be derived from the other potential That is, the number of independent equations of each form will be on the number which it is possible to write down. It should also be no is frequently unnecessary to write down formally all the possible in equations; many of the simpler problems can be solved by writing independent expressions for the potential drop between each pair of equating these two expressions.*

When the currents and e.m.f.'s are *varying*, the first law applies t current (conduction and displacement current), but the second law i given in (13b) applies only to closed loops of conduction current; in the instantaneous values of the currents and e.m.f.'s must be taken quantities are varying.

ELECTRIC ENERGY AND POWER. — From the definition o drop it follows that the total work done by the external agents in forci of electricity from any point 1 in a circuit to any point 2 is $W = V$ the definition of electric current the quantity of electricity carried fr when the current I is established from 1 to 2 is $Q = It$, where t is the ti which the current exists. Hence when a current I is established th device for a time t by an impressed voltage V, the energy input to thi

$$W = VIt$$

and the power input, i.e., energy input per unit time, is

$$P = VI.$$

When V and I are expressed in volts and amperes respectively the po is in watts; if t is in seconds, the energy input is in joules or watt-second V and I are in statvolts and statamperes respectively, or in abvolts a

* The application of these laws to the solution of complicated network p given in detail in Del Mar's *Electric Power Conductors*, New York, 1913.

s respectively, the power input is in ergs per second, if t is in seconds the gy input is in ergs. See *Units and Conversion Factors*.

pplying the above relations to the simple circuit shown in Fig. 6 containing nerator and a motor (armature windings only are considered), the power ut to the motor armature is

$$P_i = E_m I + R_m I^2, \tag{15a}$$

power *output* of the generator armature is

$$P_0 = E_g I - R_g I^2 \tag{15b}$$

l the power lost in the line is

$$P_l = R_l I^2.$$

e term $R_g I^2$ represents the power lost in heating the armature winding of the erator due to its resistance, and the term $R_m I^2$ represents the power dis-ted as heat in the armature winding of the motor. The net electric input the generator armature is $E_g I$ and the gross mechanical output of the motor nature is $E_m I$. The gross mechanical input to the generator is greater than I and the net mechanical output of the motor is less than $E_m I$ by an amount e to the friction and "core-loss" in the respective machines; see *Generators d Motors*.

Joule's Law. — That portion of the power input to any device which is equal the product of the resistance of the conductors forming the winding of the ice by the square of the current through this winding is always converted into t. That is, when a current I flows through a resistance r heat is always ipated" in this resistance, and the rate of dissipation is

$$P_h = rI^2. \tag{15c}$$

is experimental fact is known as "Joule's Law." This law applies directly y to continuous or non-varying currents. The relation $P_h = rI^2$ is, however, o as the basis for defining the "effective" resistance of a conductor to an rnating current (q.v.).

DIELECTRIC FLUX (ψ) AND DIELECTRIC FLUX DENSITY). — As noted above the displacement current through a dielectric at any nt depends upon the rate of change of the electric field intensity and upon the ture of the dielectric, and the density of this displacement current at any point y be expressed by the relation

$$\sigma_2 = \frac{1}{4\pi}\frac{d}{dt}(kF), \tag{16}$$

ere F is the field intensity and k a coefficient depending upon the nature of e dielectric. The coefficient k in this expression is the so-called dielectric co-ient or dielectric constant.

The quantity kF, whose rate of change is equal to 4π times the density of the placement current, is called the "dielectric flux density," and may be repre-ted by the symbol D. Then

$$D = kF. \tag{17}$$

e direction of the dielectric flux density is arbitrarily chosen to be the same that of the electric field intensity F. Through any surface of area A at each nt of which the dielectric flux density has a constant value D and is perpen-ular to that surface, there is said to exist a "dielectric flux" equal to DA. he total dielectric flux through a surface may be represented by the symbol ψ.

In general, the total dielectric flux through any surface perpendicular at point to the direction of the field intensity at that point (i.e., through an potential surface) is

$$\psi = \int D\, ds,$$

where ds represents any elementary area of this surface and D the flux de per unit area at ds, and $\int$ represents the sum of all the products $D\,ds$ for surface. The total displacement current through this surface is then

$$i = \frac{1}{4\pi}\frac{d\psi}{dt}.$$

Lines of Dielectric Flux. — The electrostatic flux through any surface be represented by lines drawn in the same direction as the lines of electric in sity, but of such a density that *their number per unit area* perpendicular to direction at any point *is equal* to the *dielectric flux density* at this point. number of these lines cutting any surface is then equal to the total dielec flux through this surface. The ratio of the number of flux lines through surface to the number of lines of electric intensity through that surface is e to the dielectric coefficient of the substance in which the field exists.

ELECTRIC CHARGE (Q) AND DIELECTRIC FLUX (ψ). — Wi any substance of uniform structure throughout the dielectric flux lines are tinuous lines, i.e., the number of these lines coming up to one side of a sur *within* such a substance is equal to the number of these lines leaving the o side of that surface. Experience shows that it is impossible to produce appreciable dielectric flux in those substances ordinarily classed as conduct *hence dielectric flux lines cannot pass through a good conductor*, but terminat its surface. Every dielectric is a conductor to at least a slight extent, on account of this fact the dielectric flux lines coming up through one di tric to the surface of contact between this dielectric and another do not pass through the second dielectric, but some of them terminate at this surf

Experience shows that to establish an electric field in the dielectric arou conductor, electricity must be *conducted through the conductor* to the surfac contact between the conductor and the dielectric. For example, conside good conductor in contact with a perfect dielectric, Fig. 9; a momentary conduction current must flow through the conductor along the stream lines of the conduction current, represented by the dotted lines. While the field is being established (and therefore varying) a displacement current is set up in the dielectric requiring an equal conduction current in

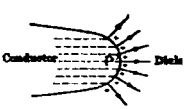


Fig. 9.

the conductor, and consequently $\frac{1}{4\pi}$ times the rate of change of the dielec flux (ψ) established in the dielectric must be equal to the conduction current flowing up to this surface through the conductor, i.e.,

$$\frac{1}{4\pi}\frac{d\psi}{dt} = i,$$

or

$$\psi = 4\pi \int i\, dt = 4\pi Q,$$

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: Q is the quantity of electricity (current multiplied by time) conducted gh the conductor to this surface.

is relation is a general one, viz., the total dielectric flux from any area A t surface of a *conductor* is equal to 4π times the total charge on this area. e every flux line originates at a positively charged conducting surface and inates at a negatively charged conducting surface, 4π of these lines con- g each unit positive charge to each unit negative charge.

e quantity of electricity conducted through a conductor when a momen- current is established through it can be readily measured by means of a ic galvanometer (*see Galvanometers*) and consequently the dielectric flux al to $4\pi Q$) may be readily determined.

its of Dielectric Flux. — Dielectric flux may be expressed in the same as electric charge, viz., coulombs, statcoulcombs or abcoulombs; see *Units Conversion Factors*.

rface Density of Charge (σ_c) and Dielectric Flux Density (D). — When e is no current in a conductor there can be no electric field within it, see ion (7), and therefore *the surface of a conductor in which no current is flow- is always an equipotential surface.* Hence the lines of electrostatic intensity, e surrounding dielectric, and therefore the dielectric flux lines also, must t at enter this surface in a direction perpendicular to it. The dielectric x density in the dielectric just outside a conducting surface in which there is ectric current is perpendicular to this surface and is

$$D = 4\pi\sigma_c, \tag{20a}$$

re σ_c is the charge per unit area of the surface at this point, or the "surface sity" of the charge.

Dielectric Flux Density Due to a Number of Charged Conductors. — an be shown that when any number of charged conductors are surrounded a *uniform* dielectric, the dielectric flux density at any point in the field may expressed by considering each elementary surface having a charge q as pro- ing at any point P at a distance r from q a flux density equal to q/r^2, in direction of the line from q to P when q is positive and in the direction of line from P to q when q is negative. The total flux density at P due to the charges is then the *vector summation*

$$D = \sum \frac{q}{r^2}. \tag{20b}$$

Dielectric Flux Density at any Point due to a Uniformly Charged ire of Circular Cross Section and Infinite Length. — Let q be the charge r unit length, K the dielectric coefficient of the surrounding dielectric, as- ed uniform, and r the perpendicular distance from the center of the wire any point P, then the dielectric flux density at P due to this wire is

$$D = \frac{2q}{r} \tag{20c}$$

e resultant dielectric flux density at any point due to any number of *uni- ly* charged wires is the vector sum of the flux densities due to each sepa- ely. However, when two or more wires are close together the distribution charge on them is not uniform,* but when the wires are more than 10

* The distribution can be calculated readily in the case of two parallel wires; see nder and Osborne, *Elec. World*, 1910, *Vol.* 56, *p.* 667.

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diameters apart the error introduced by the assumption of uniform c practically negligible.

ELECTROSTATIC CAPACITY (C) AND CONDENSERS. — T lish a given dielectric flux ψ through a given dielectric a certain diffe electric potential is always required. Consider any portion of an electric field (Fig. 10) between the two equipotential surfaces S and S_1 bounded laterally by a surface tangent at each point to the flux line through that point. Let V be the drop of potential from S to S_1, and let ψ be the dielectric flux through this region. When there is no source of e.m.f. between S and S_1 the quotient



Fig.

$$C = \frac{\psi}{4\pi V} \qquad (21)$$

is defined as the "electrostatic capacity" of this portion of the field. pare with the definition of conductance, equation (8).

When the equipotential surfaces S and S_1 are the surfaces of two con the two conductors and the dielectric between them are said to form a tric condenser." Practical forms of condensers are described in the a *Condensers, Electric*. When all the flux lines from one conductor end second conductor (e.g., when they are given equal and opposite charges necting them respectively to the two terminals of a source of e.m.f.), flux from one to the other is equal to $4\pi Q$ where Q is the numerical valu total charge on either conductor. The capacity of the condenser may written

$$C = \frac{Q}{V}.$$

When there are several charged conductors in the field the total fl one conductor does not in general all end on another single conduct some of the flux lines from No. 1, say, may run to No. 2, some to No Let ψ_{12} be *that portion* of the flux from any conductor 1 which ends other conductor 2, and let V_{12} be the drop of potential from 1 to 2, t capacity between conductor No. 1 and conductor No. 2 is

$$C_{12} = \frac{\psi_{12}}{4\pi V_{12}}.$$

Or, calling Q_{12} that portion of the charge on No. 1 which is balanced by and opposite charge on No. 2, the capacity between 1 and 2 is

$$C_{12} = \frac{Q_{12}}{V_{12}}.$$

Units of Capacity. — The unit of capacity in the practical system is the farad (*see Units, Practical Electric*), but as this is a very large unit equal to one-millionth of a farad, called the microfarad, is usua ployed. The c.g.s. electrostatic unit may be called the statfarad a c.g.s. electromagnetic unit the abfarad. See *Units and Conversion Fact*

Factors Upon Which Capacity Depends. — The capacity of a giv tion of a dielectric depends upon (*a*) the dielectric coefficient k of t lectric, (*b*) the length of the dielectric flux lines through it; (*c*) the cross of the dielectric at right angles to the flux lines, and (*d*) upon the distribu the flux lines over this cross-section. Compare with electric conductan

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of a dielectric bounded laterally by flux lines surfaces (Fig. 10) can be expressed by the

$$= \frac{k\psi}{4\pi \int D\,dl}, \qquad (21d)$$

ψ the total dielectric flux through the given tary length along one of the flux lines and D oint, the integral being taken along the flux her. When the end surfaces are conductors respectively, then

$$C = \frac{KQ}{\int D\,dl}. \qquad (21e)$$

la the capacity of various practical forms of the article on *Capacity and Charging Cur-* oted that the capacity of a condenser depends ric flux (k being assumed constant), but not ix; i.e., for a given dielectric and given dis- constant. In general, when any conductor inductive capacity is placed in the electric of a condenser, the distribution of the flux, ondenser, is altered.

ce and Capacity. — Comparing equations t when the dielectric flux lines and the cur- distribution in any given region, the ratio o the capacity of this region is $4\pi\gamma/k$ where he conductivity of the material in this region. y and conductance of the dielectric between ondenser differ only by a constant coefficient. condenser, then

$$g = \frac{4\pi\gamma}{k} \cdot C \qquad (22)$$

between its plates. Values of C for various *apacity and Charging Current.*

Condenser. — To charge a condenser a dif- e established between its plates. This may cting the two plates of the condenser respec- source of e.m.f., see Fig. 11. If the dielectric source of e.m.f. t set up in this difference of po- ished across the il a charge equal e "negative" to

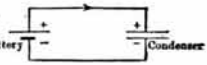


Fig. 11.

nser. The establishment of the electric flux nser may be looked upon as setting up in the analogous to the opposing force set up in a hen the opposing force just balances the im- ned, just as the compressing of a spring ceases

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when the force producing the compression is just balanced by the
force due to the elasticity of the spring.

When a condenser has thus been charged, the wires connecting it to th
of e.m.f. may be removed and the condenser remains charged for a lengt
depending upon the resistance of the dielectric separating the plates; th
this resistance the longer the time that the condenser remains charge
plates may also be moved apart and they still retain their charges, o
a positive charge and the other a negative charge, but the distribution
charges on the plates will in general become altered. Experience show
mechanical force is required to separate the charged plates irrespe
whether or not they are connected to the source of e.m.f.

When the two charged plates are "short-circuited" by a wire, as s
Fig. 12, a momentary current is established through the wire and the
field between the plates and the charges disappear. The quantity of el
discharged through the wires is equal to the quantity of charge origi
either plate. A charged condenser, therefore, acts like a
source of e.m.f., the direction of this e.m.f. *around* the circuit
containing the condenser being in the direction *through* the
condenser from its negative to its positive plate. A condenser
when it is being charged may also be looked upon as produc-
ing a back e.m.f., that is, an e.m.f. opposing the e.m.f. which
charges it. When a condenser is considered from this point of view
conducting portion of the circuit is to be considered in applying Kirchhof
When the condenser has an appreciable leakage its resistance must be co
to be in *parallel* with its e.m.f.

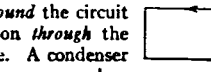


Fig.

Charging or Capacity Current and Leakage Current. — The
ment current through the dielectric of a condenser is frequently ca
"charging" or "capacity" current. The conduction current through
electric is called the "leakage" current. Let C be the capacity of the co
g the conductance of the dielectric, and v the voltage across the condens
the total current through the condenser is

$$i = gv + C\frac{dv}{dt},$$

where $\frac{dv}{dt}$ represents the rate of change of v with time. The compone
this current is the leakage current and the component $C\frac{dv}{dt}$ is the cha
capacity current.

Capacities in Series. — When several capacities* are connected en
so that the *same dielectric flux* passes through each of them, they are sa
"in series." The total capacity of any number of individual capacitie
C_1, etc., connected in series is C where

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ \cdots$$

Compare with conductances in series, equation (11b).

Capacities in Parallel. — When several capacities* are connected
the same pair of equipotential surfaces so that the *same potential drop* i
lished through each, they are said to be "in parallel." *When there are no*

* Either condensers, or dielectrics of different kinds, sizes or shapes in cont
equipotential surfaces.

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two equipotential surfaces the total equivalent
es C_1, C_2, C_3, etc., connected in parallel is

$$+ C_2 + C_3 \ldots \qquad (25)$$

rallel, equation (12a).

CAPACITY (K) AND DIELECTRIC

uation (21d) it is evident that when the capa-
d (1) when a dielectric A is between the plates
B is between these plates, then the ratio of
the ratio of the dielectric coefficients of the
luctive" capacity of any dielectric is defined
ndenser having this substance as its dielectric
lenser when air forms the dielectric between
e capacity is, therefore, independent of the

units is based on the arbitrary choice of unity
ence, in the c.g.s. electrostatic system of units
he dielectric coefficient are numerically equal.
n of units the dielectric coefficient of air is not

cal of the square of the velocity of light in air).

when the centimeter is taken as the unit of

air is $\frac{1}{9 \times 10^{11}}$. Hence, calling K the specific
ic referred to air as unity, and k its dielectric

tem	$k = K$,
system	$k = \frac{K}{9 \times 10^{20}}$,
as unit of length)	$k = \frac{K}{9 \times 10^{11}}$.

e capacity of various insulating materials are
Materials, Properties of.

dual Charge. — The value of the dielectric
is not strictly a constant unless the dielectric
e case of such nonhomogeneous substances as
tc., the dielectric coefficient is found to depend
e., upon the length of time that the voltage is
h the time of electrification (*see Insulating*
nomenon is sometimes described as "electric
the charge from the plates of the condenser
ncrease in the dielectric coefficient for a given
quantity of electricity conducted to the plates.
e experimental fact that when such a condenser
t with a wire, Fig. 12, the wire then being re-
rs on the plates after a lapse of a few seconds.
phenomenon closely associated with electric
he electric field in a heterogeneous dielectric is
t of heat is dissipated in the dielectric greatly
ounted for in terms of its leakage resistance as
measurements. This may be due in part to

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an actual increase in the resistance of the dielectric with the speed of of the field, or may be due to a phenomenon analogous to magnetic i.e., to a lag of the dielectric flux density behind the electric field int *Magnetic Materials, Properties of*). Whatever may be the cause of loss of power for rapidly varying fields, it is generally described as th to "dielectric hysteresis." The heat developed is in many cases quit able. See also the article on *Condensers, Electric.*

DIELECTRIC STRENGTH. — ELECTRIC SPARK AND EL CORONA. — Experience shows that when an electric field is esta a dielectric and the intensity of this field is increased, a point is reache the dielectric loses its insulating property and becomes a conduct condition of affairs is usually accompanied by a spark which burns a ho the dielectric, i.e., the dielectric is "punctured." Under other cond breakdown may not be permanent, but may result in the acquisition conductivity by the dielectric only while the voltage gradient is m above the critical value, the dielectric regaining its insulating property field is reduced below this critical value. This latter condition is us scribed as the formation of an electric "corona" in the dielectric; in t air the formation of corona manifests itself by a bluish light in the a the conductors between which the field is established. Whether the b produced by a given voltage is of the nature of a puncture or results i mation of a corona depends chiefly upon the *distribution* of the diel produced in the dielectric (*see Corona, Electric*).

The critical field intensity or voltage gradient at which breakdown called the "dielectric strength" of the dielectric. The dielectric depends upon the nature of the dielectric, its value for the various ordinarily employed in practice depending decidedly upon their che physical nature (*see Insulating Materials, Properties of*). It is also f for a given dielectric the critical voltage *gradient* at which breakdo depends in general upon (*a*) the distribution of the dielectric flux jus breakdown and (*b*) upon the thickness of the dielectric. It is natur expected that the *voltage* (total potential difference) required to produc down would depend upon the distribution of the dielectric flux and the of the dielectric, for the voltage gradient at all voltages depends u factors (*see above under Capacity*), but there is as yet no satisfactory ex of the dependence of the *critical gradient* upon these factors.

In fact, but little is known regarding the nature of an electric breakd even the values of the dielectric strength are known only approximatel instances, for in many of the tests made to determine its value the di of the electric flux was not known. The values of the dielectric stren in the article on *Insulating Materials, Properties of*, must, therefore, be c only as rough approximations except for conditions identical with th which the tests were made.

ELECTROSTATIC ENERGY. — From the general relations by equations (15) and (23) it is evident that when the potential between the plates of a condenser is increased from 0 to V the ene is

$$\int_0^t gv^2\,dt + \int_0^V Cv\,dv.$$

The energy represented by the first term on the right-hand side of this is dissipated as heat in the dielectric, but the energy represented by th term, which, when C is constant, may be written

$$W = \tfrac{1}{2}CV^2,$$

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heat; this is a fact of experience. More-
ged, by short-circuiting its plates with a
; CV^2 is transferred to the wire. Hence,
said to be stored in the condenser, or pref-
nser, for the electric force F exists only in
s called the "electrostatic" energy. It is
spring when the latter is compressed or
be written

$$\frac{1}{2}QV = \frac{1}{8\pi}\psi V. \qquad (26a)$$

me of an electric field may be written

$$= \frac{kF^2}{8\pi} = \frac{D^2}{8\pi k}, \qquad (26b)$$

the electric field intensity or potential drop
ic flux density or flux per unit area perpen-

(26) to (26b) are based on the assumption
the value of F. When this condition does
blish the field is $\int_0^V Cv\,dv$, the evaluation of
tween C and v.

AN ELECTROSTATIC FIELD. —
onductors or insulators) in an electric field
forces upon one another tending to produce
ease the energy of the field. Let f be the
nove any body in the field in a given direc-
he energy of the field due to displacing the
then

$$= -\frac{dW}{dx}, \qquad (27)$$

ause a change in the existing electric charges
s general relation it can be shown that every
ulsion on every other surface charged with
force of attraction on every surface charged

onductors forming a condenser the force of
on the other is

$$= -\frac{V^2}{2}\frac{dC}{dx}, \qquad (27a)$$

enser, C the capacity of the condenser, and
pacity of the condenser when one conductor
other. This relation results from the sub-
ple, the capacity of a parallel plate condenser

$$C = \frac{kA}{4\pi x},$$

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where k is the dielectric coefficient, A the area of the smaller plate, an distance between the plates. Hence the force of *attraction* is

$$f = \frac{V^2 kA}{8\pi x^2}.$$

Principle of the Electrometer. — This relation suggests a method of m ing potential difference, for, by transposing,

$$V = x\sqrt{\frac{8\pi f}{kA}}.$$

If the force acting on the upper plate is measured by means of a balance, a and x are also measured, and the dielectric between them is air ($k = 1$ electrostatic system, by definition), then all the data necessary for the c tion of V is at hand. The above formula for V is approximate only, sin capacity formula is approximate, due to the assumption of a uniform flu sity in the dielectric between the plates. As a matter of fact the flux d near the edges of the plate is not uniform, but it is possible to correct f non-uniformity; see article on *Electrometers*.

MAGNETS AND MAGNETIC SUBSTANCES. — A magnet m defined as any body which possesses the property of attracting pieces of i steel * and which when freely suspended takes up a definite position with r to the geographical meridian. A magnetic substance is any body which ac this property when it is placed near a magnet or near a conductor carryi electric current. A body which is given this property is said to be " netized." A magnetic needle is a magnetized needle of iron or steel; the seeking end of such a needle is called its north pole and the south seeking e south pole. When such a needle is freely † suspended near a magnet conductor carrying an electric current a couple is bound to be exerted u which causes it to take up a definite direction. The nee · is said to "p in the direction of a line drawn through it from its south to its north pole.

MAGNETIC FIELD OF FORCE. — Any region in which a magnetic stance (e.g., a piece of soft iron), when placed therein, becomes magneti said to be a "magnetic field." A magnetic field exists in and around magnetized substance and around every stream line of electric current. direction of the magnetic field at any point P is arbitrarily chosen as the tion in which a small magnetic needle point would point when placed at P out disturbing appreciably the existing conditions.

Magnetic Flux (ϕ). — Consider a small closed turn of wire, Fig. 13, placed in a magnetic field with its plane perpendicular to the direction of the field. Experience shows that when such a turn of wire is removed from the field in any manner whatever (the coil remaining short-circuited on itself or forming part of a closed circuit), or when the magnetic field is caused to disappear in any manner whatever, a momentary electromotive force is set up or "induced" in this coil, which in turn causes a momentary electric current to flow th the coil. This e.m.f. exists only while the coil is *moving across* the field or the field through the coil is *varying*.

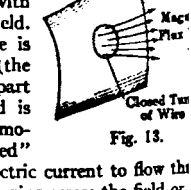


Fig. 13.

* With a force in excess of the gravitational force, which latter is extremely small

† A needle is said to be freely suspended when there is no controlling force exerted it through its suspension tending to make it take up any definite position.

time integral of the induced e.m.f. when the coil is removed entirely the magnetic field is taken as the measure of the "magnetic flux" through the coil when in its original position. That is, calling e the induced in the coil at any instant due to its motion through the field, the time during which the e.m.f. exists in the coil, then the magnetic flux the coil when in its original position is

$$\phi = \int_0^t e\,dt. \tag{28}$$

antity is readily measured by means of a ballistic galvanometer; see *Testing*.

of Magnetic Flux. — The unit of magnetic flux in the c.g.s. electrostatic system is frequently called a "maxwell" or simply a "line." The flux in the practical system of units is sometimes called a "weber"; see *Conversion Factors*.

netic Flux Density (B). — Experience shows that the magnetic flux any closed loop, such as the turn of wire described above, depends upon the inclosed by this loop. The magnetic flux per unit area through any perpendicular to the direction of the field is defined as the "magnetic density" at this surface, and is usually represented by the symbol B. By density at any *point* is meant the flux density at an infinitely small drawn perpendicular to the field at this point. The direction of the flux density at any point is the same as that in which a magnetic would point if placed at this point; i.e., the direction of the flux density the direction of the magnetic field are the same. When the flux density same value B at every point of a surface of area A and is perpendicular surface, then the total flux through this surface is

$$\phi = BA. \tag{29}$$

otal magnetic flux across any surface S may in general be expressed matically by the surface integral

$$\phi = \int (B \cos \alpha)\,ds, \tag{29a}$$

ds represents any elementary area of this surface and $(B \cos \alpha)$ the component of the flux density perpendicular to ds.

its of Magnetic Flux Density. — The unit of magnetic flux density in the c.g.s. electromagnetic system is called the "gauss"; no name has been given the corresponding practical unit.

gnetic Flux Lines. — Continuity of Magnetic Flux. — Magnetic flux is represented by lines drawn in the field in such a direction that their tion coincides at each point with the direction of the field at that point, of such a number that their density at each point (number per unit area perpendicular to their direction) is equal to the magnetic flux density at that t. Such lines are called "magnetic flux lines." Experience shows that lines drawn in a magnetic field always form *closed* loops, i.e., a magnetic flux has no ends. As a consequence of this fact the total magnetic flux coming any surface in a magnetic field is always equal to the total flux leaving surface. (Compare with stream lines of electric current.) When the flux

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leaving a surface is considered as equivalent to a negative flux cou
that surface, this relation may be expressed by the formula

$$\Sigma\phi = 0$$

at every surface, the summation being an algebraic one. This is an
Kirchhoff's first law for electric circuits.



Fig.

Magnetic Fields Due to Electric Currents. — Experience shows that every stream line of electric current is always accompanied by a magnetic field the flux lines of which *link* the stream line of current. That is, the flux lines thread the loops formed by the stream lines and the stream lines thread the loops formed by the flux lines; see Fig. 14.

Right-handed Screw Law. — The direction of the curre
around any electric circuit and the direction in which the flux lines c
current thread this circuit are related to each other in the same man
direction of motion of a point on the edge of the head of a right-han
placed at the center of the circuit and the direction of advance of
Or, if one faces the electric circuit looking in the direction of the flux li
ing it, the current producing these lines is in the clockwise direction
circuit. The relative direction of the current and its magnetic flu
briefly described by saying that the current is in the right-handed scre
with respect to the flux which it produces.

MAGNETICALLY INDUCED ELECTROMOTIVE FORC
measure of magnetic flux is based on the experimental fact that wh
magnetic field threading an electric circuit changes, an electromoti
induced in that circuit. When the circuit is formed by a single tu
this induced e.m.f. is, from the definition above, equal to the rate of
this flux with respect to time, i.e., $e = \frac{d\phi}{dt}$. When the circuit is in t
a coil each turn of which links the flux, the e.m.f. induced in *each* tu
to $\frac{d\phi}{dt}$ where ϕ is the flux which links that particular turn. When
links the *same number of flux lines*, then the total induced e.m.f. in
turns is

$$e = N\frac{d\phi}{dt}.$$

When the change in flux is due to a motion of a circuit or part
through a magnetic field the induced e.m.f. in any conductor is als
the number of flux lines which *cut across* this conductor.

Magnetic Linkages (λ). — The condition that each turn be link
same flux ϕ is seldom the case; some of the flux lines link only p
turns, see Fig. 14. In general, the total e.m.f. is

$$e = \frac{d}{dt}(\phi_1 + \phi_2 + \ldots \phi_n),$$

where ϕ_1, ϕ_2, etc., represent the fluxes linking the various turns.
$(\phi_1 + \phi_2 + \ldots \phi_n)$ may be called the total number of "magnetic
and may be conveniently represented by the symbol λ, viz.,

$$\lambda = \phi_1 + \phi_2 + \ldots \phi_n.$$

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ay then be written

$$e = \frac{d\lambda}{dt}. \qquad (31a)$$

ame flux, ϕ, then $\lambda = N\phi$.

E.M.F. — The direction of this induced e.m.f. be in the *left-handed* screw direction with respect f one faces the circuit looking in the direction of ced e.m.f. is in the counter-clockwise direction. set up by this e.m.f., however, would produce a right-handed screw direction. Hence a change h an electric circuit always sets up an e.m.f. rent around this circuit in such a direction as to fact may be expressed mathematically by writing

tion (31), i.e., by putting

$$e = -N\frac{d\phi}{dt}. \qquad (31b)$$

en the e.m.f. induced in the circuit in the right- espect to the increase of flux. Or stated in other e *rise* of electric potential and $N\frac{d\phi}{dt}$ represents the circuit in the right-handed screw direction with

ARYING MAGNETIC FLUX. — Consider a wire, and let each of these N turns be linked by a agent, e.g., another current is flowing. to B be increasing $\frac{\phi}{t}$ in the *left-handed* to the current I in ere is induced in A the direction of I

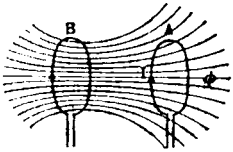


Fig. 15.

erefore, the electric instant is $ei = NI\frac{d\phi}{dt}$. This power is transmitted he varying flux through it; hence the power

$$p = NI\frac{d\phi}{dt} \qquad (32)$$

magnetic power input, this power being converted ower.

Current. — The varying flux established by B pon as the means whereby this energy is trans- ield, just as an electric current may be looked upon y is transferred from one point to another in an

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electric circuit. Hence the varying flux may be looked upon as a "
displacement current."

Magnetomotive Force ($\mathfrak{F}$). — The above expression for the rate of
of energy by a varying magnetic field may be compared with the rate of
of energy, or power input $P = EI$, corresponding to an electric current
in a circuit in which there is *back* electromotive force E. The strengt
"magnetic displacement current" may be chosen arbitrarily* as

$$\text{Magnetic displacement current} = \frac{1}{4\pi}\frac{d\phi}{dt},$$

just as the strength of the electric displacement current is taken as $\frac{1}{4\pi}\frac{d}{4\pi d}$

ψ is the total electrostatic flux. Then the quantity correspondin
electromotive force must be chosen numerically equal to

$$\mathfrak{F} = 4\pi NI$$

and may be called the "magnetomotive force," abbreviated "m.m.
magnetic power input may then be written

$$p = \mathfrak{F} \times (\text{Magnetic displacement current}).$$

where $\mathfrak{F}$ is the *back* magnetomotive force.

Direction of the Magnetomotive Force. — The closed path of
netic flux lines through a magnetic field is called a "magnetic circuit,
the path of the stream lines of an electric current is called an electri
In general, a magnetomotive force is produced in every magnetic circuit
it is linked by an electric circuit, equal in numerical value to $4\pi NI$,
is the number of times the current I links this circuit. The magne
force is taken as positive when the current links the flux lines in t
handed screw direction, for then an increase in the flux corresponds to a
power output. When the current links the flux lines in the left-hand
direction the magnetomotive force is taken as negative, i.e., a "back"
motive force, for in this case an increase in flux corresponds to a magnet
input; see the special case considered above.

Units of Magnetomotive Force. — Ampere-Turns. — The pro
in the expression for the magnetomotive force, equation (33), is c
"current-turns"; when I is expressed in amperes it is called the "amper
The magnetomotive force as above defined differs from this product o
constant numerical factor; hence the ampere-turns of a coil may be ta
measure of the magnetomotive force produced by it. This unit of
motive force, namely, one ampere-turn, is the unit commonly employe
practical calculation of magnetic circuits. The c.g.s. electromagneti
called the gilbert; 1 ampere-turn = 1.2566 gilberts. See *Units and C
Factors*.

MAGNETIZING FORCE OR MAGNETIC FIELD INTENSI
— Experience shows that the magnetic flux density produced at any
a given magnetomotive force depends (*a*) upon the position of the p
respect to the source of the m.m.f. and (*b*) upon the nature of the su
through which this m.m.f. produces the magnetic flux. Compare
electric current density or dielectric flux density produced at a given

* The factor 4π arises from the manner in which the conceptions of the mag
were originally developed.

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These facts lead to the conception of the magnetic field as being due to a "magnetizing magnetizing force H depending solely upon the the field and the *distribution of the flux lines*, as nsity B which depends not only upon these two *of the medium at the point in question.*

lation between electromotive force and electric ng force (also called the "magnetic field inten- ong any closed path in a *magnetic* field may be s line integral around such a path is equal to the ing around this path, viz.,

$$4\pi NI = \int (H \cos\theta) dl, \qquad (34)$$

ntary length of this path, see Fig. 16, ($H \cos\theta$) f the magnetizing force at dl in the direction of of current turns linked by the t such a definition leads to a n a quantitative manner the xperimental facts. Magnetiz- ed as the force in dynes which ic pole," see p. 412. direction with the magnetizing (34) may be written

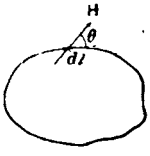


Fig. 16.

$$= \int H dl. \qquad (34a)$$

ormula see the articles on *Magnetic Properties of*

izing Force. — Experience shows that except for agnet the magnetizing force H and the flux den- direction. For points inside a permanent magnet field intensity H, due solely to the magnet itself, f the flux lines, i.e., a permanent magnet produces itself.

orce. — The magnetizing force at any point in a ented by lines drawn in the field in such a direction with the direction of the magnetizing force at each per unit area perpendicular to their direction that gives the value of the magnetizing force at that "lines of magnetizing force" or "lines of magnetic the lines of magnetizing force and the magnetic n (except within the substance of permanent mag- *different*. Only in non-magnetic substances do nagnetizing force coincide. The simple expression used to designate either the flux lines or the lines t is evident that such a loose use of this term is when speaking of the magnetic field within a mag-

orce. — Magnetizing force is of the nature of mag- ngth, just as electric field intensity is of the nature

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of electric potential difference per unit length. Hence the c.g.s. electro unit of magnetizing force may be called the "gilbert per centimeter"; with volts per centimeter. When the magnetomotive force is exp ampere-turns, the magnetizing force is expressed in ampere-turns p meter or per inch; see *Units and Conversion Factors*.

Values of the Magnetizing Force in a Uniform Medium. — V medium surrounding the stream lines of an electric current is of a *unif netic nature throughout*, the magnetizing force at any point may be c from the shape and distribution of the stream lines of the current, irr of whether the medium be non-magnetic or highly magnetic, e.g., i *Units and Conversion Factors* for numerical multipliers to change t practical units.

Magnetizing Force at any Point Due to an Element of a Stream Line (Fig. 17). — Consider any closed stream line of electri and let the surrounding *medium be uniform* in its magnetic properties throughout the region in which the magnetic field produced by this stream line exists. It can be shown that each elementary length dl of this stream line may be considered as contributing to the magnetizing force H at any point P in this region an amount

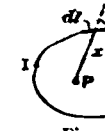
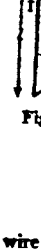


Fig.

$$dH = \frac{(I \sin\theta)\, dl}{x^2}, \qquad (35)$$

where I is the current flowing along this stream line, x the distance fr dx, and θ the angle between x and dl. The direction of dH is perpend the plane determined by x and dl. The total magnetizing force at P the *vector sum* or *vector integral* of dH for all the elementary lengths in the stream line is divided.

Magnetizing Force Due to a Straight Wire (Fig. 18). — A equation (35) to the case of a straight wire of circular cross-section carrying a current I, the magnetizing force at any point P due to a length l of this wire is



Fi

$$H = \frac{I}{x}(\sin\theta_1 + \sin\theta_2), \qquad (35a)$$

where x is the perpendicular distance from P to the wire and θ_1 and θ_2 the angles designated in Fig. 18.

When the wire is very long compared with x, this becomes

$$H = \frac{2I}{x}.$$

This formula also holds approximately for any point outside a wire shaped cross-section, provided x is large compared with the maximum d of this section. For a point *inside a long wire of circular cross-section* o *a* the magnetizing force is also given by (35b) when I is taken to repres *part of the current inside the circle through P* concentric with the axis of t When the current density is uniform over the cross-section, as is usually (*see, however, the article on Skin Effect*), the magnetizing force inside the

$$H_i = \frac{2xI}{a^2}.$$

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Magnetizing Force on the Axis of a Circular Coil of N Turns. — t I be the current, r the mean radius of the coil, and x the distance of the ict from the center of the circle; then

$$H = \frac{2\pi NIr^2}{(r^2 + x^2)^{3/2}} \tag{35d}$$

Magnetizing Force due to a Solenoid. — A solenoid is a helical coil f wire, each turn having the same radius. Let N = total number of turns, = current in abamperes, r = mean radius of the helix in centimeters, l = length helix in centimeters. Then at any point on the axis of the helix (inside or tside) at a distance of x centimeters from its center, the magnetizing force gilberts per centimeter is

$$H = \frac{2\pi NI}{l}\left[\frac{0.5\,l + x}{\sqrt{r^2 + (0.5\,l + x)^2}} + \frac{0.5\,l - x}{\sqrt{r^2 + (0.5\,l - x)^2}}\right] \tag{35e}$$

his formula holds only when the thickness of the winding is small compared ith the mean radius r. When l is large compared with r this reduces to

$$H = \frac{4\pi NI}{l}. \tag{35f}$$

r all points inside the solenoid (whether on the axis or not) at a distance from s ends large compared with r, that is, inside the central portion of a long lenoid, the field is uniform over the cross-section of the solenoid and its value given by (35f). An exact formula for field intensity at any point inside a sole- id is given by O. Billieux in *Rev. Gen. d'El.* 6, *p. 827, Dec. 13, 1919.*

Magnetizing Force Inside a Toroid (Fig. 19). — A toroid is a cylinder nt into the form of a closed ring, making a shape like a doughnut. When ch a ring is *uniformly* wound with an insulated wire so that the turns of the re are close together and cover the entire surface f the toroid, the magnetic field is confined entirely ithin the space inclosed by these turns, and there- re, when the core on which the wire is wound is of ni form magnetic material throughout, both the lines f magnetizing force and the flux lines must be circles ncentric with the hole in the "doughnut." The agnetizing force will have the *same* value at every int on the circumference of any *one* of these circles, d, therefore, from equation (34a) the value of H at any point P within the re is

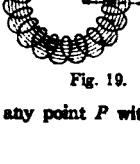


Fig. 19.

$$H = \frac{4\pi NI}{l}, \tag{35g}$$

here N is the total number of turns on the core, I the current in each turn d l the length of the circumference through P. Unless the hole in the "dough- t has a large radius compared with the radius of the cross-section of the core ill not be uniform over this section, since l for the various points in the cross- tion will differ considerably.

It should be noted that the value of H is independent of the material of the re provided only that the core be of uniform material throughout. That is,

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equation (35g) applies to an iron core as well as to an air or wood core, provi the iron is uniform throughout and there is no air gap across the path of the f lines. Even a mechanically perfect contact between two pieces of iron of same kind, however, is sufficient to vitiate the above formula.

MAGNETIC PERMEABILITY (μ). — PARAMAGNETIC AND DI MAGNETIC SUBSTANCES. — The quotient of the magnetic flux dens B at any point by the magnetizing force H at that point is defined as "magnetic permeability" μ of the substance as medium at that point, viz.,

$$\mu = \frac{B}{H}. \qquad (\text{C}$$

Compare with the definition of dielectric coefficient, equation (17.) The c.g electromagnetic system of units is based on the arbitrary assumption of un as the value of the magnetic permeability of air. Any substance which has magnetic permeability greater than that of air is called a "paramagnetic su stance," and any substance which has a permeability less than that of air called a "diamagnetic substance." The only substances which are strong paramagnetic, i.e., which have a permeability considerably greater than th of air, are iron, steel, nickel and cobalt, and certain alloys of non-magne elements. The only substance which is appreciably diamagnetic is bismu which has a permeability of about 0.9998. All other elements are practica non-magnetic, i.e., their permeabilities differ from unity by less than 1 per ce

The permeability of a given sample of any highly magnetic substance is n a constant, but depends upon the value of the magnetizing force; see the curv in the article on *Magnetic Properties of Iron*. The permeability also depen very largely upon the previous heat treatment and the exact composition of t material, and also upon its previous magnetic history; these relations are al discussed in detail in that article. The methods of measuring permeability a described in the article on *Magnetic Testing*.

North and South Poles. — That portion of the surface of any magnetiz body from which the flux lines pass out into the air (or into any substance lower permeability) is said to be a north magnetic pole, and that portion of t surface at which the flux lines enter the body is said to be a south magnetic po A "unit north pole" is a pole from which 4π flux lines emerge into the su rounding air. When a magnetic needle is placed near the surface of a ma netized body its north seeking end points away from this surface when th surface is a north pole and toward the surface when this surface is a south po

Difference of Magnetic Potential (U). — Consider any two points 1 a 2 in a magnetic field (Fig. 20) and let the path between them from 1 to 2 pass through an electric circuit producing a magnetomotive force in the direction from 1 to 2, then from analogy with the electric circuit, equation (2), the expression

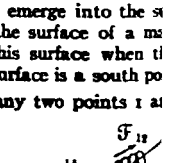


Fig. 20.

$$U_{12} = \int_1^2 (H \cos\theta)\, dl - \mathcal{F}_{12} \qquad (37)$$

is called the "drop of magnetic potential" from 1 to 2. From the definiti of magnetizing force, equation (34), it follows that around any *closed* circuit th drop of magnetic potential is always zero. A magnetomotive force $\mathcal{F}_{12}$ therefore, equivalent to a rise of magnetic potential from 1 to 2.

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When there is no source of m.m.f. between 1 and 2 and the path coincides with ne of magnetizing force, the drop of magnetic potential is

$$U_{12} = \int_1^2 H\, dl. \tag{37a}$$

Magnetic potential difference is of the same nature as magnetomotive force and ay, therefore, be expressed in the same units, viz., gilberts or ampere turns.

Magnetic Equipotential Surfaces. — A surface drawn in a magnetic field such a manner that this surface is perpendicular at each point to the magtizing force at this point (i.e., to the line of magnetizing force through this int) is called a "magnetic equipotential surface," compare with *electric equiential surface*.

Magnetic Reluctance ($\mathcal{R}$). — To establish a magnetic flux ϕ through a given rtion of a substance which is *not itself linked by a source of m.m.f.* a difference agnetic potential must always be established between the end surfaces of is substance. Let U be the magnetic potential drop established from one face to the other, then the quotient

$$\mathcal{R} = \frac{U}{\phi} \tag{38}$$

defined as the magnetic reluctance of the given portion of the substance. ompare with electric resistance. The c.g.s. electromagnetic unit of reluctance called the oersted. It should be noted that the above definition is meaningless except when applied to a portion of a substance of which the end surfaces e magnetic equipotential surfaces and through every cross-section of which e same flux passes.

Factors upon Which Reluctance Depends. — The magnetic reluctance a given portion of a substance included between two equipotential surfaces nd bounded laterally by a surface through which no flux line passes depends on 1. the magnetic permeability of the substance, 2. the dimensions of this rtion of the substance and 3. upon the distribution of the flux lines over each ss-section perpendicular to them. The relations are identical with those ich determine the electrical resistance of a conductor, the magnetic permeility taking the place of the electric conductivity. For example, *for a straight r of constant cross-section A and length l, through which the flux lines are straight, rallel and uniformly distributed, the reluctance is*

$$\mathcal{R} = \frac{l}{\mu A}. \tag{38a}$$

Note particularly that this formula for reluctance is applicable only under e special conditions just stated. Formulas for other cases are much more mplex; see Douglas, J. F. H., *Reluctance of Irregular Magnetic Fields*, A.I.E.E., ec., 34, May, 1915.

Magnetic reluctance is not a constant quantity even for a given material and ven flux distribution, unless this material is non-magnetic. For all highly agnetic materials μ depends upon the magnetizing force and therefore also on the flux density. It should also be noted that the magnetic reluctance es not represent a "resistance" in the sense of something which causes a ssipation of energy.

Magnetic Permeance ($\mathcal{P}$). — The reciprocal of magnetic reluctance is called magnetic permeance." The permeance of a straight bar under the conditions ecified above is

$$\mathcal{P} = \frac{\mu A}{l} \tag{39}$$

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The permeability of a substance is, therefore, equal to the permeanc cube of this substance when the flux through the cube is parallel to of the cube and is uniformly distributed over the section at right angl four edges.

Magnetic permeance is analogous to electric conductance, except not a factor which affects the *dissipation* of energy in a substance. however, enter into the expression for the energy *stored* in a magnet the same way that the electrostatic capacity of a dielectric is a d factor in the expression for the energy stored in the electric field.

Kirchhoff's Laws for the Magnetic Circuit. — As already noted (30), the total magnetic flux coming up to any surface in a magnet always zero, provided a flux leaving a surface is considered as a *ne* coming up to that surface. This fact may be represented by the for

$$\Sigma\phi = 0$$

for every surface in the field. Similarly, from the definition of magne tial drop, it follows that the *total* magnetic potential drop around a circuit is zero, or that the total magnetomotive force acting around a circuit is equal to the sum of the reluctance drops around that circuit, w be represented by the formula

$$\Sigma\mathfrak{F} = \Sigma\mathfrak{R}\phi.$$

These two equations are identical in form with those representi hoff's laws for the electric circuit, equation (13). They are, howev easy to use for practical calculations, for the magnetic flux is not c approximately geometrical lines like the currents in a network of wires, but in general fills all space surrounding the coils which est magnetomotive forces; also, when there is iron or other magnetic m the circuit, the permeability depends on the flux density and the history of the iron. (The distribution of magnetic flux in and aroun circuit is analogous to the distribution of current in and around an ur mass of copper of the same shape as the iron circuit immersed in a liqu a conductivity about equal to that of carbon.) Only in the special uniformly wound circular ring or toroid are the lines of induction *entirely* to an iron circuit; in general a certain number also exist in th in whatever other substances are in the vicinity of the iron circuit.

SELF AND MUTUAL INDUCTION. — When the current in electric circuit varies with time the magnetic flux accompanying thi also varies with time, and, since this flux links the current which pr an e.m.f. is induced in each turn of the circuit equal to the rate at whic through this turn is varying, and in such a direction as to *oppose* the the current. That is, an *increasing* electric current is always accompa *back* e.m.f. due to the increase in the magnetic flux which accompanie crease of current. Or, viewed from another point of view, an increa velocity of a stream of electricity develops a back pressure, just as velocity of a stream of water is increasing it develops a back pr "velocity head" due to the inertia of the water. The magnetic field acc ing an electric current may, therefore, be looked upon as a result of its magnetic inertia," or "electromagnetic mass"; see also the article on *Theory*.

Again, when an electric current *decreases* its accompanying flux and an e.m.f. is set up in the circuit tending to oppose this decrease, i.e.

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sing. This is again analogous to the effect of matter.

on or Inductance (L). — In general, the co- change of the current $\left(\frac{di}{dt}\right)$ in any circuit must luced electromotive force e is called the "coeffi- ly the "inductance" of the electric circuit. In e.m.f. in an electric circuit is

$$e = L\frac{di}{dt}, \tag{41}$$

electric circuit and $\frac{di}{dt}$ represents the change in

since $e = \frac{d\lambda}{dt}$, see equation (31a), where λ is the ween the electric circuit and the flux established e may also be defined by the relation

$$L = \frac{d\lambda}{di}. \tag{42}$$

to the increase in the number of linkages per unit the permeability of the magnetic circuit is *con-* onstant equal to the linkages per unit current. by every stream line of electric current, and the etic circuit is constant, then

$$L = \frac{4\pi N^2}{\mathfrak{R}}, \tag{42a}$$

ns forming the electric circuit and $\mathfrak{R}$ is the etic circuit.

f various electric circuits are given in the article *ctance*.

practical unit of inductance is called the henry; nry and the abhenry and millihenry see *Units*

duction. — Mutual Inductance (M). — In which the rate of change of the current $\left(\frac{di_a}{dt}\right)$ lied to give the electromotive force e induced it B, is called the "coefficient of mutual induc- ductance" between A and B; see Fig. 15. In in any circuit B by a varying current i_a in any

$$e_b = M_{ab}\frac{di_a}{dt}, \tag{43}$$

nce between A and B.

ciple of the conservation of energy that the mu- ith respect to a second circuit B must be equal

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to the mutual inductance of B with respect to A, that is, $M_{ab} = M_{ba}$. the e.m.f. induced in A when the current in B increases by an amount

$$e_a = M_{ab} \frac{di_b}{dt}.$$

Since $e_b = \frac{d\lambda_{ab}}{dt}$, where λ_{ab} is the number of linkages between the and the flux through B due to the current i_a, the mutual inductance be defined by the relation

$$M_{ab} = \frac{d\lambda_{ab}}{di_a}.$$

That is, the *mutual inductance between two circuits A and B is equal crease in the number of magnetic linkages of the circuit B per unit increa current in A*, and vice versa. When the permeability of the magnetic *constant*, the mutual inductance is also a constant equal to the linkages unit current in A, and vice versa. When every flux line linking *both* is linked by every turn in A and every turn in B, then

$$M_{ab} = \frac{4\pi N_a N_b}{\mathcal{R}_{ab}},$$

where N_a and N_b are the number of turns forming the circuits A and ively and $\mathcal{R}_{ab}$ is the reluctance of that *part* of the magnetic circuit which the flux from A to B passes when there is current *in one coil only*

The units of mutual inductance are the same as those of self-in see *Units and Conversion Factors*.

Formulas for mutual inductance for a few special cases are given in t on *Inductance, and Inductive Reactance*.

Instantaneous Potential Drop Through a Coil. — Consider a co which has a resistance r and an inductance L. Then when this coil co other source of e.m.f. than its own self-induced e.m.f., the expression f stantaneous potential drop through the coil is

$$v = ri + L\frac{di}{dt},$$

where i is the instantaneous value of the current and $\frac{di}{dt}$ the increa current per unit of time. Compare with the equation

$$i = gv + C\frac{dv}{dt},$$

for the instantaneous current through a condenser, where g is the con of the dielectric in the condenser, v the potential drop across it, and crease in the potential drop per unit of time.

When there is another coil near the first coil, and the two coils ha ances r_1 and r_2 and self-inductances L_1 and L_2 respectively, and a m ductance M, then the potential drops through them are respectively

$$\left.\begin{aligned} v_1 &= r_1 i_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \\ v_2 &= r_2 i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} \end{aligned}\right\}$$

where i_1 and i_2 are the currents in the two coils in the *same* direction.

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Effective or "Total" Inductance. — In certain cases of symmetry, when the algebraic sum of all the currents in the field is zero, the voltage drop along any *portion* of a circuit may be represented by an expression of the form

$$v = ri + L\frac{di}{dt},$$

although there may be several electric circuits in the vicinity in which electric currents are flowing. An example of this is the case of the wires of a three-phase transmission line arranged so that they form the three edges of an equilateral prism; see *Inductance and Inductive Reactance*. The coefficient L in this case is called the "effective self-inductance" of this particular portion of the circuit; it really takes into account not only the self-induction of the particular part of the circuit under consideration but also the mutual induction of the rest of the circuit or circuits with respect to this particular portion. Similarly, when the voltage drop in any portion of a circuit involves not only the current i_1 in this circuit but also a current i_2 in some part of this circuit or in some other circuit, the coefficient M_{12} in the expression

$$v_1 = r_1 i_1 + L_1\frac{di_1}{dt} + M_{12}\frac{di_2}{dt}$$

is called the effective mutual inductance of the part 2 with respect to 1 although it may also be due in part to circuit 2.

Leakage Inductance. — In discussing the action of a transformer (q.v.), which is merely two electric circuits linking the same iron core, it is more convenient to deal with the *resultant* flux due to the currents in *both* electric circuits in windings instead of considering the fluxes due to the two windings separately. Referring to Fig. 21, let ϕ_r represent that portion of the resultant flux due to the currents i_1 and i_2 in the two windings 1 and 2, and let ϕ_1 represent that part of the total flux which links 1 only and ϕ_2 that part of the total flux which links 2 only. Let λ_1 be the linkages between ϕ_1 and circuit 1 and λ_2 be the linkages between ϕ_2 and circuit 2. Then

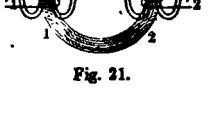


Fig. 21.

$$L_1' = \frac{\lambda_1}{i_1} \quad \text{and} \quad L_2' = \frac{\lambda_2}{i_2},$$

are called the "leakage inductances" of the two windings respectively; the reluctance of the paths of ϕ_1 and ϕ_2 are practically constant since the air portion of these paths forms a greater part of the reluctance in each case.

Let i_1 be the current in winding 1 and i_2 be the current in winding 2 in the *opposite* direction to i_1 (this is the actual relation in a transformer during most of the time) and let e_1 be the impressed e.m.f. across the terminals of the first or primary winding and e_2 the terminal e.m.f. at the terminals of the second or secondary winding when the current i_2 is flowing. Then

$$\left.\begin{aligned} e_1 &= r_1 i_1 + L_1'\frac{di_1}{dt} + N_1\frac{d\phi_r}{dt} \\ e_2 &= N_2\frac{d\phi_r}{dt} - r_2 i_2 - L_2'\frac{di_2}{dt} \end{aligned}\right\} \qquad (47)$$

where r_1 and r_2 are the resistances of the two windings and N_1 and N_2 are the number of turns in the two windings respectively.

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Comparing equation (47) with (46) and noting that $e_1 = v_1$ and $e_2 =$ i_2 in (47) is taken in the opposite direction from i_2 in (46), it may be sho

$$L_1' = L_1 - \frac{N_1}{N_2} M,$$

$$L_2' = L_2 - \frac{N_2}{N_1} M.$$

Whence the leakage inductance of each winding is very much less total self-inductance of that winding.

Fundamental Equations of the Transformer. — Comparing (47) and (46) it may also be seen that *

$$\phi_r = \frac{M}{N_2}\left(i_1 - \frac{N_2}{N_1} i_2\right).$$

Put $i_2' = \frac{N_2}{N_1} i_2$, that is, i_2' is the current which would be produced in th ary if it had the same number of turns as the primary. The differenc

$$i_m = i_1 - i_2'$$

is called the "magnetizing current," and the quantity $L_m = \frac{M}{N_2}$ may the magnetizing inductance. Then

$$\phi_r = L_m i_m.$$

In the above deduction no account is taken of the eddy-current and l loss in the iron core; these losses (the eddy-current loss in particular looked upon as due to a third current i_3 flowing in a single turn short on itself and having a resistance r_3 and negligible inductance. The for this tertiary circuit is then

$$0 = \frac{d\phi_r}{dt} - r_3 i_3.$$

Whence the corresponding current in the primary winding is $i_3' = \frac{i_3}{N}$ may also be written

$$i_3' = g N_1 \frac{d\phi_r}{dt},$$

where $g = \frac{1}{r_3 N_1^2}$ is called the "leakage conductance" of the transform total primary current is then

$$i_1 = i_2' + i_m + i_3'.$$

From equation (47) and the relations given in the last two paragr complete theory of the transformer may be developed.

ENERGY OF THE MAGNETIC FIELD. — Energy is required lish a flow of electricity just as energy is required to set a column of motion, this "energy of motion" of electricity being analogous to th energy of a moving body. This energy of motion is most conveni

* In this equation i_1 and i_2 are taken in the opposite direction.

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field which accompanies the flow of electricity
ıtical expression for it may be put into various

Electric Circuit, Permeability Constant. —
ectric circuit and the magnetic field which is
hen the current in it increases from zero to a
urrent has the value i and number of magnetic
its own flux at this instant is λ, then when the
kages increase by an amount $d\lambda$ in the right-
pect to the current and therefore the *electric*
change is, from equation (31a), $id\lambda$, which is
input into the magnetic circuit which it links.
o the magnetic circuit or magnetic field is

$$\int_0^I id\lambda = \int_0^I Li\,di,$$

equation (42). When the permeability is con-
for constant permeability

$$W = \frac{1}{2} LI^2. \tag{48}$$

$$I = \frac{1}{8\pi}\frac{\mathfrak{F}^2}{\mathfrak{R}} = \frac{1}{8\pi}\mathfrak{R}\phi^2 \tag{48a}$$

orce ($= 4\pi NI$ when the coil has N turns in a
e reluctance of the magnetic circuit and ϕ the

unit length of a magnetic flux line is equal to
e flux per unit area perpendicular to this flux
B, the *energy per unit volume* of the magnetic

$$\frac{HB}{8\pi} = \frac{\mu H^2}{8\pi} = \frac{B^2}{8\pi\mu}. \tag{48b}$$

e compared with the corresponding formulas,
ergy.

or More Electric Circuits, Permeability adily shown that the total energy required to several electric circuits linking one or more ctance is

$$= \tfrac{1}{2} L_1 I_1^2 + \tfrac{1}{2} L_2 I_2^2 + \ldots + M_{12} I_1 I_2 + M_{13} I_1 I_3 + \ldots \tag{49}$$

the self and mutual inductances respectively.

$$W = \frac{1}{2}\Sigma\phi I, \tag{49a}$$

ic one and includes every complete *turn* of the nt in this turn and ϕ the magnetic flux linking w direction with respect to the current.

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The energy per unit volume at any point in the magnetic field du number of electric circuits is represented by equation (48b), where H are taken as the resultant magnetizing force and flux density respec this point.

When the permeability is not constant the *energy transferred to un* of the magnetic field due to any number of currents is

$$w = \frac{1}{4\pi}\int_0^B H\,dB$$

provided the magnetizing force H and the flux density B are either in the directly opposite directions, as, for example, in the case of a uniformly ma iron toroid. To integrate this expression requires a knowledge of the between B and H. Note also that, due to the phenomenon of hysteresis, part of the energy required to establish a magnetic field i other magnetic substance is dissipated as heat and is not recoverable field disappears; therefore, only part of the energy represented by mula is "stored" in the field in a recoverable form. See article on *Properties of Iron*.

MECHANICAL FORCES IN THE MAGNETIC FIELD. (*article on Electromagnets.*) — Experience shows that all bodies in which a current exists, and all bodies in which a magnetic flux exists, exert i mutual mechanical forces upon one another tending to produce such motion of these bodies as will *increase* the energy of the magnetic fiel be the component of the force tending to move any body in the field i direction and let dW be the increase in the energy of the field due to the body a distance dx in this direction, then

$$f = \frac{dW}{dx},$$

provided this displacement does not alter the existing magnetomotive the field.

Similarly, calling T the component of the torque tending to turn an the field about a given axis, and dW the *increase* in the magnetic ener the turning of the body through an angle of $d\alpha$ radians about this axi

$$T = \frac{dW}{d\alpha},$$

provided this displacement does not alter the existing magnetomotive the field.

Equations (51) and (51a) also give the actual force and torque re during a change in position which *does* cause a change in the magn forces in the field, provided dW is taken to represent the net increa energy of the field. This force and torque may differ greatly from t state force and torque; see article on *Electromagnets*.

Force Produced by a Magnetic Field on a Coil Carrying a Cu From equation (32) the energy *output* of an electric circuit, when the flux threading it in the right-handed screw direction with respect to th in it increases by an amount $d\phi$, is $dW = NI\,d\phi$, where N is the n turns linked by this increase in flux and I is the current in each turn the energy *input* into the magnetic field. Whence if an increase in

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duced through the coil when it moves a distance dx, the force acting on e coil in the direction of dx is

$$f = NI\frac{d\phi}{dx}; \qquad (52)$$

represents the increase in the flux linking the coil in the *right-handed* screw ection with respect to the current in it or the number of flux lines which cut e coil as the result of its motion. Similarly, when the coil is so mounted that it can move only about a fixed axis, then the value of the torque tending to rn it about this axis is

$$T = NI\frac{d\phi}{d\alpha}, \qquad (52a)$$

here $d\phi$ represents the increase in the flux linking the coil in the right-handed rew direction with respect to the current in it when the coil turns through an ngle α (in radians).

From these relations it follows that a coil carrying an electric current, when n the magnetic field due to any other agent (current or permanent magnet), ways tends to take up that position in which it will embrace the maximum ssible flux linking the coil in the right-handed screw direction with respect the current in it. This accounts for the attraction of two parallel coils when ey carry currents in the same direction, and the repulsion of two such coils ien they carry currents in opposite directions. This principle is useful in termining the direction of motion of the moving element in such devices as e electric motor, galvanometer, current balance, electrodynamometer (q.v.).

Torque on the Coil When its Plane is Parallel to the Magnetic Field. — When the coil is placed with its plane parallel to the flux lines due to me other agent (e.g., a permanent magnet or another coil carrying a current), the flux linking the coil due to this agent is zero; see Fig. 22. Let e two circles represent sections of the two sides of the coil its plane being perpendicular to the page, and let e dot in the left-hand circle indicate that the current is up through this side of the coil and the cross in the ther circle that it is down through the other side. Let B be the flux density of the field constant for each point along the flux line since the flux lines are parallel, and let A be the area of the coil and let $\phi = BA$, that is, ϕ represents the total flux which *would be produced* through the coil by a uniform field of flux density B at *right angles* to it. Then the torque on the coil when its plane is *parallel* to the field is

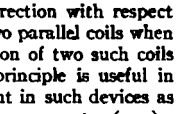


Fig. 22.

$$T = N\phi I. \qquad (53)$$

This relation is useful in calculating the torque on the moving element of a galvanometer, ammeter, electrodynamometer, wattmeter, etc.

Average Torque on a Coil Rotating in a Magnetic Field. — Consider a coil which is rotating with an angular velocity ω about a fixed axis n a magnetic field due to some other agent (e.g., an armature coil rotating in the magnetic field produced by the current in the field coils). Let the current in this coil be constant and in the same direction with respect to the coil while the coil turns from the position in which it embraces the maximum flux ϕ in the left-handed screw direction to the position (a half revolution in a 2-pole machine) when it embraces this same maximum flux ϕ in the right-handed

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screw direction. The total change in the flux while the coil turns thro angle, π radians in the case of a 2-pole machine, is 2ϕ, whence the torque turning the coil through this half revolution is

$$T = \frac{2N}{\pi} I\phi \cdot$$

That is, the average torque is proportional to the product of the current total flux per pole. When a commutator is provided to change the d of the current every half turn, then the torque is in the same directio complete turn. See *Motors*.

When the coil is mounted in a slotted iron core which rotates with as in an ordinary motor, this torque is exerted partly on the wire and pa the teeth of the core.

Force on a Wire in a Magnetic Field. — Consider a wire of l forming part of a closed circuit, Fig. 23. Let B be the value of the flux at the wire, I be the current in the direction indicated, and let the lines representing the flux be perpendicular to the wire in the direction from the eye to the page. When this wire moves a distance dx to the left the flux threading the closed loop formed by the circuit is increased by an amount $d\phi = Bldx$, whence the force acting on the wire is, from equation (51),



Fig. 2

$$f = BlI.$$

Left-hand Rule. — The relative directions of this force, the flux B and the current I may be conveniently determined by pointing the fo of the left hand in the direction of the flux and the middle finger in the d of the current (I), then if the thumb is held perpendicular to these two it will point in the direction in which the force tends to move the wire. pare with the right-handed rule for e.m.f.

Force between Two Current-Carrying Conductors. — The force between any two electric circuits carrying currents i_1 and i_2, due magnetic field of these currents, may be readily found by combining eq (49) and (51). This gives for the component of this force in any direct value

$$f_x = i_1 i_2 \frac{dM}{dx}$$

where dM is the increase in the mutual inductance between the two when one circuit is displaced a distance dx with respect to the other, tance dx being measured in the direction in which it is wished to find t ponent of the force. In this formula i_1 and i_2 are both to be consid positive when they link the mutual flux in the same direction. Fr relation follows the well known fact that two coils, or conductors, c currents which are in the *same* direction *attract* each other, since when is moved *toward* the other their mutual inductance *increases*.

The mutual inductance of two long parallel wires when these are fa relative to their diameters is

$$M = 2l \log_e \frac{2l}{D},$$

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and l their length, both in centimeters (*see Reactance*). Hence, from equation (56) the l wires on the other is

dynes per centimeter (56a)

d in the plane formed by two. This formula llel conductors of any cross-section, provided e greatest dimension of their cross-section. , e.g., in the case of parallel bus-bars close to ce is much more complex (*see Dwight, H. B., , Elec. World, 70, p. 522, Sept. 15, 1917*).

in a Magnetic Field. — In general the re- flux set up by a given magnetomotive force s of the various magnetic bodies in the field with respect to the electric circuit producing body in the field is displaced the total reluc- ue chiefly to the change in the dimensions of om equations (48a) and (51) it can be shown netic body in the field is in the direction of the value

$$-\frac{1}{8\pi}\phi^2\frac{d\mathfrak{R}}{dx}, \qquad (57)$$

e remains constant; where ϕ represents the $d\mathfrak{R}$ represents the *increase* in the reluctance ing to a displacement dx of the body in the inus sign in this formula indicates that the which a motion of the body would *decrease* deducing this expression it is assumed that the field is constant. It can also be shown he same formula holds for actual magnetic y is not a constant.

or the attraction of one magnet for another er each other than their like poles, and the ir like poles are nearer than their unlike poles. a of iron or other paramagnetic substance by r "face" of an electric circuit, and the repul- by either pole of a magnet cuit; see article on *Electro-*

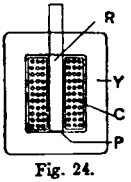


Fig. 24.

equation (56) consider the which is one form of "per- of iron the flat end P of yoke Y. This rod passes yoke. C is a magnetizing od are uniformly distributed yoke at the joint P. Let rod and let B be the flux density at this area. e dx, so that an air gap of length dx is formed ce of the magnetic circuit is produced due to

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the formation of an air gap at P, and a decrease in reluctance is pro
the shortening of the iron part of the circuit, i.e., by the reluctance of
dx of the rod. Due to the high permeability of the iron compared
of the air, the decrease in the reluctance of the iron part of the circu
neglected in comparison with the increase in reluctance due to the for
the air gap. The net increase in reluctance may then be taken as the
of this air gap of length dx, that is $d\mathcal{R} = dx/A$, since the permeabilit
unity. Whence, from equation (56), the force required to raise the ro

$$f = \frac{1}{8\pi}\frac{\phi^2}{A} = \frac{B^2A}{8\pi}.$$

That is, the tractive force per unit area between the rod and the yo
portional to the square of the flux density in the rod.

HYPOTHESIS REGARDING THE NATURE OF MAGNE

The peculiar properties possessed by a magnetic needle or other magn
accounted for by assuming that at least some of the molecular ch
magnetic substance have an orbital motion without friction, forming
"molecular solar system." The magnetization of such a substance is
to the setting of the molecular currents in planes more or less paral
plane of the magnetizing current. In the case of a permanent mag
molecular currents retain their parallel or "polarized" condition even
magnetizing current is removed. For example, when a needle is m
by a current in a coil placed around it, the molecular currents are s
angles to the axis of the needle. A magnetic needle placed in a magn
therefore, tends to set itself so that each molecular current embraces
flux and hence "points" in the direction of this flux.

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ECTROCHEMICAL PROCESSES, INDUSTRIAL. — (*See also* trochemistry, *Principles of; Furnaces, Electric.*) The principal industrial trochemical processes are the following :

Electroplating,
Galvanoplasty, including electrotyping,
Electrolytic refining of metals,
Electrolytic winning of metals,
Electrolytic oxidation and reduction,
Electrolysis of sodium and potassium in chloride solutions,
Electrolysis of water,
Electric-furnace processes (*see Furnaces, Electric*),
Production of ozone.

Some of the more important of these various processes are briefly described low.

ELECTROPLATING. — Electroplating consists in covering a conducting face (usually metallic) with a thin, smooth, compact, well-adhering layer of tal by depositing this metal electrolytically from an aqueous solution of one its salts. The anode of the electroplating vat consists of rods or plates of the e metal as that of the salt in solution and is connected to the positive ter- nal of the source of electricity. The object to be plated forms the cathode, ich is connected to the negative terminal. The anode dissolves approximately the same extent that the cathode gains, so that the amount of the metal ions the bath remains nearly constant.

Suspension of Objects to be Plated. — The cathodes are always sus- ded in the bath between two rows of anodes, so that they will be plated iformly on both sides. When the cathode is of irregular shape, or very large, must be turned frequently during the plating in order to get a uniform de- sit. The cathodes and anodes are suspended by copper wires from hori- ntal metallic tubes, the ends of which rest on the edge of the plating vat. e metallic tubes are permanently connected to the source of the electricity, that as soon as the cathodes are suspended in the bath, electrolysis begins. mall objects, such as tacks, pins and screws, are suspended in the vat in a ire basket, which is, of course, plated simultaneously. To get a uniform ished surface the objects should be well shaken during electrolysis. The odes are removed from the bath only when they are nearly used up and have be replaced.

Construction of Vats. — Large plating vats are made of wood lined with me specially prepared substance resembling pitch, or with lead. Small tanks silver or gold plating are usually porcelain lined.

Voltage and Current Density. — Electroplating tanks are always connected parallel, so that they will be electrically independent of each other.

Low-voltage generators of from 5 to 6 volts are, therefore, used in plating, d each tank must be connected directly to the generator through a regulating ostat in order to regulate the voltage.

The proper current density in any plating process is that density at which a od deposit is formed. This may vary within certain limits for a given solu- on and temperature; it is a function of the temperature and the nature of the lution.

Washing and Pickling. — In order to make the metal adhere well to the rface to be plated, the surface must be smooth and perfectly clean. It is first olished, and the grease is then removed by dipping it into a hot alkaline bath ntaining 10 per cent, by weight, of sodium carbonate or sodium hydrate.

After washing off the alkali, the object is dipped into a bath called a ' the purpose of which is to remove any oxide that may have been proc the alkali, and to give a bright surface. The pickle is then washed off wi and the object is suspended immediately in the electroplating vat.

Pickling Solutions. — The pickle varies with the nature of t treated. Cast iron and wrought iron are pickled in a solution cons 15 parts, by weight, of water to 1 part of concentrated sulphuric acid. able pickle for zinc is dilute sulphuric or hydrochloric acid. Coppe bronze and German silver are pickled first in a bath consisting of 200 weight, of nitric acid of specific gravity 1.33, 1 part of common salt ar of lampblack. The lampblack is intended to form some nitrous acid nitric acid. The object is then washed in boiling water and is imme "bright dipping bath," to give a bright surface. This bath consists of by weight, of nitric acid of specific gravity 1.38, 100 parts of concentr phuric acid and 1 part of common salt.

After the plating is finished, the object is removed from the plati washed in hot water and placed in warm sawdust to dry.

Plating by Dipping. — A thin film of metal may be deposited on a dipping it into a solution of a salt of a metal which is electronegative *trochemistry, Principles of*) with respect to the metal to be plated, e.g. ping iron into a copper-sulphate solution. A small amount of iron and an equivalent amount of copper is deposited on the remaining course, only a thin film can be produced in this way, for, as soon as t covered with copper, the action ceases. No external electric current in this process.

Plating by Contact. — When the metal to be plated is electronega respect to the metal to be deposited on it, the electro-deposition ca tained by connecting the former to a zinc rod. In this case, the solut be of a complex salt, in order to reduce the deposition of the metal in on the zinc itself. For example, silver may be deposited on copper by ing a zinc rod or plate to the copper object by a wire and dipping bo potassium-silver-cyanide solution; the zinc dissolves and silver is dep the copper, while some silver is also deposited on the zinc. No externa is needed in this process.

Nickel Plating. — The solution ordinarily used consists of 50 parts, b of the double nickel-ammonium sulphate, $NiSO_4 \cdot (NH_4)_2SO_4 \cdot 6\,H_2O$ w 25 to 50 parts of ammonium sulphate to 1000 parts of water. The an nickel. The solution is made acid enough to redden litmus slightly, addition of a small amount of sulphuric acid or one-half per cent of ci The proper current density on the cathode is about 0.6 ampere per squ meter (5.5 amperes per square foot) of exposed surface, which requires volts. The surface should be perceptibly coated with nickel in two minutes, and a few bubbles of hydrogen are liberated continuously. current is too weak, the surface becomes discolored, and if too strong h is evolved more rapidly and the surface turns dark.

Iron is sometimes copper plated before it is nickel plated, but thi necessary, for nickel adheres to iron perfectly well if the surface has been cleaned.

A nickel-chloride solution gives good results in plating any metal exc Iron always eventually rusts if plated in a chloride bath.

Copper Plating. — The metals on which copper is usually plated, zinc, iron and tin, are more electropositive than copper. On dipping these metals into an acid copper-sulphate bath, they would become with a layer of copper, which in some cases is spongy and does not

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elocity with which this reaction takes place a
of copper and potassium, $KCu(CN)_2$, is used.
cuprous cyanide in potassium cyanide to form
an excess of 0.2 per cent of potassium cyanide.
50° to 60° C. The proper current density at
e per square decimeter (4.6 amperes per square
s at room temperature. For further details, see
rds, No. 52.

eived a thin coating of copper in a cyanide bath
cid copper-sulphate bath. The cyanide must
the sulphate bath. A sulphate bath may be
f copper sulphate $CuSO_4 \cdot 5\ H_2O$ and 50 grams
1 liter of water. The proper current density
decimeter (6.5 amperes per square foot) which

weakened by copper plating in a cyanide bath,
ile suspended, slightly stretched, in the bath
e to absorbed hydrogen. See *Met. and Chem.*
s. *Am. Electrochem. Soc.*, Vol. 32, p. 247, 1917;

lly deposited zinc is of a dull color and is not
vers obtained by dipping in melted zinc, but
to protect iron better for a given thickness of
melted zinc. (*Burgess, Electrochem. and Met.*
uitable solution consists of 200 grams of zinc
as of sodium sulphate, $Na_2SO_4 \cdot 10H_2O$ and 10
slightly acidified with sulphuric acid. The
s from 0.5 to 2 amperes per square decimeter
ot) which requires from about 1 to 2.5 volts.
more zinc is dissolved than is deposited, due to
replaced as it is used up. The resistance may
to 40° or 45° C.

solution of zinc and of copper sulphates were
e deposited. In a cyanide solution of zinc and
e deposited simultaneously in the form of an
hemie, Vol. 11, p. 367, 1905.) The copper is
nc, so that at a low current density, 0.1 ampere
e per square foot), only a small amount of zinc
per square decimeter (2.8 amperes per square
80 per cent of copper. Increasing the current
of the deposit only slightly.

g is made by substituting zinc cyanide for half of
given above for plating. Brass anodes are used.
found to give good deposits are the following:

dried,
ried,
potassium and copper,
ate,
potassium and zinc,

e.

tance contains *n* parts, by weight, of that substance
on.

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With the electrodes 15 centimeters apart, current density 0.3 ampere p decimeter (2.78 amperes per square foot) about 3 volts are required.

1 liter water,
15 grams double cyanide of potassium and copper, crystallized,
16.5 grams double cyanide of potassium and zinc,
25.0 grams sodium sulphite,
2.0 grams potassium cyanide, 98 per cent.

Current density 0.3 ampere per square decimeter (2.78 amperes per squ requiring 3 volts when the electrodes are 10 centimeters apart. (*Galvanostegie, 1. Teil, p. 238, 1910.*)

Silver Plating. — The double cyanide of potassium and silver is u used for silver plating on account of the smooth deposit obtained solution. The deposit from a nitrate comes down in the form of isolated which do not cover the surface completely. The solution contains f 5 per cent silver as potassium-silver cyanide, $KAg(CN)_2$, with 0.5 per ce potassium cyanide. Too much or too little free cyanide gives a bad co deposit. A good silver plating bath may be made up as follows:

20 grams potassium silver cyanide,
10–12 grams potassium cyanide, 99 per cent,
1 liter water.

The current density is 0.3 ampere per square decimeter, at abou (*Schlötter, Galvanostegie, 1. Teil. p. 149, 1910.*) The anodes are silver Silver is deposited only on a surface of copper or copper alloy. Oth must be copper plated before silvering. In order to make the silver ad the copper surface must be amalgamated by dipping the cleaned sur "quicking bath," consisting of a solution of 30 grams of potassium cyanide, $KHg(CN)_2$, and 30 grams of potassium cyanide in 1 liter On removal from the quicking bath, articles are washed and placed ately in the silvering bath.

Gold Plating. — The solution used in gold plating contains from per cent of gold as the double cyanide of gold and potassium, $KAu(C$ twice as much free potassium cyanide. The current density on the c about 0.2 ampere per square decimeter (1.9 amperes per square foo requires about 1.5 volts. The anodes are pure gold. The solution ma hot or cold. The deposit from a hot solution is more dense, more uni of a richer color. The color of the gold deposit may be influenced l taneously depositing some other metal. Green gilding may be obt adding a little silver cyanide to the bath, until the desired tint is obtain solution should be cold. To give the deposit a red tint, a little coppe is added to the solution.

Other Plating Processes. — Plating with the following metals is s carried out: platinum, tin, lead, iron, antimony, and arsenic.

Plating on Aluminum frequently does not wear well, on account of culty in getting a perfectly clean aluminum surface on which to plate. due to the rapidity with which a thin invisible film of oxide or hydroxi on aluminum when exposed to the air or to any solution. One method coming this difficulty is to immerse the aluminum in a solution of p hydrate until hydrogen is evolved, and then dip without previous was potassium-silver-cyanide solution. The aluminum is immediately cov a layer of silver. It is still better to amalgamate by dipping into a 0.5 solution of mercuric chloride immediately after treating with hydra chloride is rinsed off, and the object again treated with potassium hyd

ten immediately suspended in the silvering bath. (*Langbein, Electrodeposition of Metals, 4th ed., p. 409, 1902.*)

Burgess (*Electrochem. Ind., Vol. 2, p. 85, 1904*) recommends cleaning first with dilute hydrofluoric acid, then with a mixture of 100 parts of sulphuric acid and 5 parts of nitric acid, both concentrated. After rinsing with water the surface is immediately plated with zinc, as this metal is found to adhere better than many others. Starting with the zinc surface, other metals are readily deposited.

GALVANOPLASTY. — Galvanoplasty is the art of reproducing by electrolysis articles of various kinds, or of making finished products, such as set-up type, copper tubes, etc.

Electrotyping. — The object is to make a copper plate which shall be an exact duplicate of type which has been set up ready for printing. First an impression of the type is made in wax, which is then covered with a thin layer of graphite, by dusting the fine powder over the wax surface with soft brushes. A thin layer of copper is then formed by sprinkling the surface with iron filings and pouring over the surface a solution of copper sulphate. The iron goes into solution, depositing copper on itself and on the graphite. The wax plate is then washed in water and suspended in an acid bath of copper sulphate, where copper is deposited electrolytically until a thin sheet that can be stripped from the wax has been formed. After removing the copper sheet from the wax plate, a melted lead-antimony alloy is poured on its reverse side, making a plate approximately 0.5 inch thick. This is then used for printing in place of the original type. The economy of this procedure comes in the saving of wear on the type, and the relatively small amount of type which has to be kept in stock.

The current density ranges from 1 to 2 amperes per square decimeter (0.9 to 1.8 amperes per square foot) and the volts per cell from 0.75 to 1.5.

Copper tubes are made by the Elmore process by depositing copper on a conducting cylinder which rotates in an acid copper-sulphate bath. The surface must be conducting, but the copper must not stick so firmly that the cylinder cannot be slipped out of the tube when finished. In order to keep the outer surface of the tube smooth, it is frequently polished during the deposition of copper. Copper sheets may be made by making tubes of large diameter and cutting them open.

Metallic foil may be made by the electrolytic deposition of a thin metallic layer on a surface from which it can be removed.

Parabolic mirrors are made by depositing copper electrolytically on a parabolic glass surface that has been silvered, and separating the metal from the glass by warming. (*Cowper-Coules, Electrolytisches Verfahren zur Herstellung parabolischer Spiegel, 1904.*)

ELECTROLYTIC REFINING. — The method of refining metals electrolytically is as follows. The impure metal is made the anode of an electrolytic bath, the electrolyte of which is, at the start, a solution of a pure salt of the metal to be refined, and the cathode is a sheet of the refined metal. On passing the current, metal dissolves, along with certain of the impurities. The impurities which are electronegative with respect to the principal metal dissolve; those electropositive with respect to the principal metal remain adhering to the anode. When the latter finally drop from the anode they may be dissolved by the free acid, in which case they would be precipitated again on coming in contact with the anode or the cathode. Some metals are precipitated as an insoluble salt as soon as they dissolve, and are thus removed from the further action of the current.

When it goes into solution, the principal metal is, therefore, separated from those metals which are electronegative with respect to it. When it is deposited

on the cathode, it is separated from those metals which are electropositi respect to it. The bath thus becomes contaminated with certain of the ties in the anode, and these would eventually be deposited on the cathod bath is not purified from time to time.

Anode Mud. — The metals which do not dissolve drop to the of the tank forming the "anode mud." It is from this mud that the pla gold and silver are recovered in copper refining. For methods of work anode mud, see Kern, *Met. and Chem. Eng.*, Vol. 9, p. 417, 1911.

Copper Refining. — The object in refining copper electrolytically obtain as pure copper as possible for electric conductors and to obt precious metals contained in the crude copper. A representative comp of crude copper anodes for American refineries is the following:

Copper	98–99.5 per cent.
Silver	0–300 oz. per ton.
Gold	0–40 oz. per ton.
Arsenic	0–2 per cent.

The refined copper is about 99.95 per cent copper. The electrolyte is tion of $CuSO_4$ and H_2SO_4 containing from 4 to 10 per cent of free acid an 12 to 20 per cent of $CuSO_4$. The current density ranges from 0.43 to 4.8 a per square decimeter (4 to 45 amperes per square foot) of cathode surfa the volts per cell range from 0.1 to 0.3. (*Ulke, Die Elektrolytische Raf des Kupfers, p. 42, 1904.*) The electrolyte circulates slowly from tank t The cathodes, called *starting sheets*, are thin sheets of refined copper.

Multiple and Series Systems of Arranging the Electrodes. tanks for holding the solution and electrodes are made of wood and a quently lined with lead. There are two methods of arranging the elec In the "multiple system" all the cathodes of one tank are connecte likewise the anodes, the cathodes having an anode on each side, as sh Fig. 1.

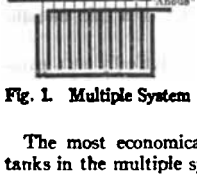


Fig. 1. Multiple System

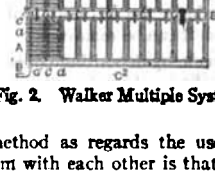


Fig. 2. Walker Multiple System

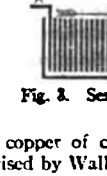


Fig. 3. Series

The most economical method as regards the use of copper of conn tanks in the multiple system with each other is that devised by Walker *Pat. 687, 800, 1901*). In this system the current flows from tank to tank out being collected in a single bus bar in this passage. The *cathodes* first tank rest on a conducting bar G (Fig. 2) on which the *anodes* of the tank also rest. The figure shows two series of tanks with a leading in bus bus bar B' connecting the two series, and leading out bus bar B^2. A more improvement is to have the cathodes of a tank make direct contact wi anodes of the adjacent tank.

In the Hayden or "series system," the electrodes are arranged as sh Fig. 3. The impure copper plates are suspended in the solution at equal dis apart, only the end ones being connected to the dynamo. The current at the electrode A, which dissolves, and on flowing through the tank through the intermediate plates. Pure copper is deposited on the sides plates facing A, and dissolved from the opposite surfaces facing B.

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ducting preparation is painted over the sides of the intermediate electrodes ng *A*, so that the copper deposited can be separated from the impure copper. en a certain amount of the impure copper has been dissolved, the electrodes emoved, the pure copper is separated from the impure, and the latter is ted and cast into new electrodes. This method is in use at the large plant the Nichols Copper Company, Laurel Hill, New York, and at the Baltimore pper Smelting & Rolling Co., Canton, Md. All others use the multiple system.

Comparison of the Two Systems. — The energy required in the series tem is about 70 per cent of that required in the multiple system. Contacts e more trouble in the multiple than in the series system. The electrodes in series system cost more to prepare than in the multiple system. The estment in a series plant of given capacity is less than in a multiple plant. re lead-lined tanks cannot be used in the series system, the maintenance pense of a series plant is greater than that of a multiple plant.

Nickel Refining. — Nickel may be refined by using a weakly acid solution of kel chloride or nickel sulphate. To get thick deposits the solution must be ted to from 50° to 90° C. Nickel and copper may be separated by the David Brown process, in which nickel is separated from an alloy of nickel and copper depositing the nickel electrolytically. Very pure nickel required for special poses is refined electrolytically by the Orford Copper Company, by a secret ess. Foerster obtained good results with a current density of 0.5 to 2.5 peres per square decimeter (4.5 to 23 amperes per square foot) between 50° C. 60° C. The neutral nickel-sulphate solution contained 30 grams of nickel r liter. Günther obtained good deposits at 60° to 65° C., with 4 to 5 amperes square decimeter (37 to 45 amperes per square foot) at 3.5 to 4 volts, with kel sulphate baths.

Silver Refining. — Two cases arise, (1) the separation of silver from copper an alloy consisting mainly of these two metals, and (2) the separation of silver m relatively small amounts of gold and platinum.

Dietzel Process. — One method of separating silver and copper is the etzel process. This consists in dissolving both of the metals as anode in a ghly acid solution of copper nitrate. The solution is then transferred to other vessel and the silver is precipitated by metallic copper, following which copper is deposited electrolytically.

The current density is about 1.5 amperes per square decimeter (14 amperes r square foot) of cathode surface, and the voltage per cell from 2.5 to 3.5 volts.

Moebius Process. — Silver is separated from small amounts of other tals by the Moebius process. In this process the anodes consist of the impure er, the cathodes of thin sheet silver, and the electrolyte is a slightly acid ate silver-nitrate solution. In the earlier type of apparatus the cathodes re stationary; in the later type the cathode is a rotating sheet of silver. In th the pure silver is scraped off as crystals.

The current density is about 3 amperes per square decimeter (28 amperes per are foot) of cathode surface, and the voltage per cell from 1.4 to 1.5 volts other type is the Balbach-Thum cell (*Met. and Chem. Eng., Vol. 9, p. 444,* 911).

Gold refining is carried out in a slightly acid solution of gold chloride. Gold ks do not dissolve in a solution of gold chloride $AuCl_3$, or of chloroauric d, $HAuCl_4$, but the chlorine liberated comes off in the gaseous form. If some e alkali chloride or hydrochloric acid is present, the gold dissolves. The sulting gold is never less than 999.8 fine, and frequently is 1000 fine.

The baths contain about 3 per cent of free hydrochloric acid with 30 to 40 rams of gold as chloroauric acid per liter. The bath is heated to 60° or 70° C.,

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and the current density is about 10 amperes per square decimeter (93 amp per square foot) at about 1 volt.

Lead refining is carried out by the Betts process. The electrolyte solution of lead fluosilicate ($PbSiF_6$) containing 60 to 70 grams of lead 120 to 130 grams of SiF_6 per liter, and 0.1 per cent of glue. The objec refining lead is to recover the copper, antimony, bismuth, gold and silver. cannot be separated from the lead electrolytically, on account of its proxi to lead in the electrolytic series.

The current density ranges from 1.3 to 1.7 amperes per square decimeter to 16 amperes per square foot) of cathode surface, and the voltage per cell f 0.30 to 0.38 volt.

According to Duisberg (*Journ. of Ind. and Eng. Chem. for 1912, p. 752*) is now refined electrolytically by the firm Langbein-Pfanhauser & Co., Leip It has valuable magnetic properties, and is used in electromotors. The trolysis is carried out at 100° to 120° C. See also Guillet, *J. Iron and Steel* Vol. 90, pp. 66–80, 1914, and Story, *Tr. Am. Electrochem. Soc.*, Vol. 29, pp. 3 367, 1916.

Refining of Other Metals. — A number of other metals may be refi electrolytically, such as mercury, tin, bismuth, and antimony, but these relatively unimportant.

ELECTROLYTIC WINNING OF METALS. — The attempts that h been made to win metals directly from their ores or from matter are based the same principle as that underlying metal refining. These attempts h not been successful until recently, however, on account of the large amount impurity that gets into the bath and on account of mechanical difficulties. best known of such attempts, are the following.

Marchese Process. — In the Marchese process it was attempted to tain pure copper from a matte containing principally copper, lead, iron sulphur, by electrolyzing this matte as an anode in a sulphate bath. process seemed a success at first, but finally failed.

Siemens and Halske Process. — The Siemens and Halske process for tracting copper consists in electrolyzing a solution of iron sulphate and cop sulphate in a cell in which the anode and cathode are separated by a linen phragm. The anode was carbon; the cathode pure copper. In the cath compartment the solution loses copper by deposition on the cathode. solution then circulates to the anode compartment, where the ferrous sulph is oxidized to ferric sulphate. See below, under *Electrolytic Oxidation*. Fr here the solution circulates to another vat where fresh ore, consisting of cop pyrites ($Cu_2SFe_2S_3$) that has been roasted so as to change the iron sulphide oxide, is treated. The ferric sulphate dissolves the cuprous sulphide as follo

$$Cu_2S + 2\,Fe_2(SO_4)_3 = 2\,CuSO_4 + 4\,FeSO_4 + S.$$

This solution, enriched in copper, is then conveyed to the cathode compartme and the cycle is completed. This process also failed when tried on a commerc scale.

Hoepfner Process. — In the Hoepfner process the copper ore, consisti of copper sulphide, is dissolved in a cupric chloride solution containing a re tively large amount of sodium chloride. The reaction is as follows:

$$Cu_2S + 2\,CuCl_2 = 4CuCl + S.$$

The cuprous chloride, insoluble in water, is held in solution by the sodium ch ride. The anode and cathode of the electrolytic cell are separated by a di phragm. The solution first circulates to the cathode compartment, where pa

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le copper is deposited, and then to the anode, where the cuprous chloride idized to cupric chloride. The solution from the anode then circulates to ore.

pper Hydrometallurgy at Chuquicamata. — A process is now being ted by the Chile Exploration Company for winning copper directly from e of the Chuquicamata copper mine, in Chile. The ore is dissolved in dilute uric acid in leaching tanks. The solution is then conducted to the electro- tanks where the copper is deposited, using insoluble anodes and copper starting sheets. Originally fused magnetite anodes were used, but were later replaced by *duriron* (ferro-silicon containing 12 per cent silicon). electrolytic refinery will have a capacity of 335,000 pounds of copper per (*E. A. Cappelen Smith, Met. and Chem. Eng., 1914, Vol. 12, pp. 291–294.*

lsom Process. — Lead was at one time extracted from galena (PbS) by Salom process, consisting in electrolyzing the powdered galena as cathode sphuric acid. The hydrogen deposited on the galena combines with the ur, forming hydrogen sulphide and leaving the lead as lead sponge. This ss was given up, partly at least, on account of the poisonous action of the gen sulphide. (*Trans Am. Electroch. Soc. Vol. 1, p. 87, 1902; Vol. 4, 1903.*)

ctrolytic Zinc. — Within recent years a large quantity of high grade lytic zinc has been produced in the United States and Canada, by a process r to that used for copper at Chuquicamata. Sulphate solutions are used, lead anodes and aluminum cathodes, from which the zinc is stripped in sheets. The solution must be free from impurities in order to get good sits. See Hansen, *Bull Am. Inst. Mining Eng.*, Vol. 135, p. 615, 1919; French, *Trans. Am. Electroch. Soc.*, Vol. 32, pp. 321–328, 1917; *Met. and m Eng.*, Vol. 18, pp. 549–550, 1918.

Detinning Tin Scrap and Old Cans. — The two principal methods of overing tin from tin scrap and old tin cans are due to Goldschmidt. The consists in electrolytically dissolving the tin and depositing it in the metallic te; the second method, which however is not electrolytic, converts the tin o tin tetrachloride by treating with dry chlorine.

In the electrolytic method the solution consists of a sodium hydrate solution, taining a certain amount of carbonate, absorbed from the air, and sodium nnate. The best concentrations are: 10 to 12 per cent alkalinity, not over er cent free alkali; carbonate not over 3 per cent; stannate not over 5 per nt. Temperature, 60° to 70° C. About one-tenth of the solution must be laced every week.

The tin scrap is suspended in the solution in baskets (39 by 35 by 18 inches) perforated sheet iron, containing 100 to 130 pounds of scrap. Old cans are ached, compressed and then cut up. The cathodes are sheet iron 39 by 35 hes. The tin dissolves from the anode and is deposited as spongy tin on the thode. The scrap is left in the bath for three hours. The spongy tin is com- ssed by a hydraulic press into cylinders weighing six pounds; these are sub- quently melted in a furnace with sealed tubes. This sponge contains 50 per nt tin and 50 per cent ash. The ash is subsequently reduced with carbon in open-hearth furnace, yielding 70 per cent of the tin.

Very careful working is necessary to remove the tin so completely that the n can be sold to open-hearth plants. Even then the iron contains 0.1 to 0.5 r cent tin.

The cathode current density is never over 0.75 ampere per square decimeter amperes per square foot), at 2 to 3 volts per cell. (*Electrochem. and Met. Ind., l. 7, p. 79, 1909; Met. and Chem. Eng., Vol. 10, p. 202, 1912.*)

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ELECTROLYTIC OXIDATION AND REDUCTION is frequ
ried out on substances in solution. One of the advantages of the e
method is that no other substance has to be added to the solution. I
out an electrolytic oxidation or reduction a porous diaphragm is used t
the anode and cathode compartments. The substance to be reduced
in the cathode compartment, where the whole or a part of the hydr
would be evolved by the current while in the nascent state, acts on
stance in question. The intensity of the reduction may be varied b
the potential difference between the solution and the cathode. This
plished either by increasing the current density on the cathode, or b
the cathode of different metals on which the overvoltage (*see Electro
Principles of*) is different. It frequently happens that the metal comp
cathode has a marked accelerating effect on the velocity of the
Thus the reduction may be much more complete on one metal than on
though the potential difference between the metals and the soluti
same in both cases. The same considerations apply to oxidation
anode.

Typical Reduction and Oxidation Processes. — Examples w
trolytic reduction has been found useful are: in the manufacture of
by corroding a lead anode in a suitable solvent, e.g., the Luckow proce
preparation of the lower salts of vanadium, molybdenum and titanium.
where electrolytic oxidation has been employed are: in the oxidati
lower cerium sulphate, $Ce(SO_4)$, to $Ce(SO_4)_2$, the latter being useful
dizing agent; in oxydizing potassium manganate, K_2MnO_4, to perm
$KMnO_4$; in the oxidation of potassium ferrocyanide, $K_4Fe(CN)_6$, to
cyanide, $K_3Fe(CN)_6$; and of chromium sulphate to a chromate.

Sodium permanganate has been made on a semi-commercial scale by
zing ferro-manganese anodes in sodium carbonate or hydrate solution
Am. Electrochem. Soc., Vol. 35, pp. 371–384, 1919). Potassium perm
has been made in the same way (*Chem. and Met. Eng., Vol. 21, pp. 680–6*

ELECTROLYSIS OF SODIUM OR POTASSIUM CHLOR
The electrolysis of sodium or potassium chloride may yield several
products, depending on the kind of cell employed. In the followin
sion the reactions for sodium choride are given; these reactions also
potassium chloride when K is substituted for Na.

Production of Electrolytic Bleach. — If there is no diaphragm
solution is kept cool, the chlorine and hydrate react on each other
principally sodium hypochlorite or "electrolytic bleach," according
equation

$$2\,NaOH + Cl_2 = NaOCl + NaCl + H_2O.$$

As soon as hypochlorite is formed, it begins to change to chlorate, bu
not as rapidly as it is formed. As the concentration of the hypochl
creases, a larger and larger proportion changes to chlorate, until fi
concentration of the hypochlorite reaches a limit, which depends on
perature, original salt concentration, current density, and other facto
hypochlorite then changes to chlorate as rapidly as it is formed.

The reactions by which hypochlorite changes to chlorate are two;
action of the discharged ClO ion on water:

$$6\,ClO + 3\,H_2O = 2\,HClO_3 + 4\,HCl + 1\tfrac{1}{2}\,O_2,$$

and (2) in a slightly acid solution:

$$2\,HOCl + NaOCl = NaClO_3 + 2\,HCl.$$

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e solution is warmed to about 50° C. the conditions are so changed that the ing concentration of hypochlorite is much lower than when cold. Sodium potassium hypochlorites are used only in solution, but the chlorates are allized out.

further electrolysis of a cooled sodium (or potassium) chlorate solution, rcrate, $NaClO_4$, is produced by the action of the liberated ClO_3 ion on r:

$$2\,ClO_3 + H_2O = HClO_4 + HClO_2$$

$$HClO_4 + NaOH = NaClO_4 + H_2O.$$

most of the cells used for producing hypochlorite, a vessel is divided into mber of narrow compartments by bipolar or intermediate electrodes, con- of carbon plates (Hass and Oettel) or platinum-iridium wire wound on plates (the Kellner cell). The solution is cooled by circulation. There essential difference between a hypochlorite and a chlorate cell, except the latter is used at a higher temperature. (*See numerous volumes in the ardt Monographs.*)

Production of Chlorine and Caustic. — If the anode and cathode are ated by a diaphragm of some kind, sodium hydrate is produced at the e by the action of the alkali metal on water:

$$2\,Na + 2\,H_2O = 2\,NaOH + H_2,$$

e at the anode chlorine is set free, which may be used to make bleaching der.

Various devices are used to separate the hydrate and chlorine in cells intended these products. In the McDonald cell (*Electrochem. Ind., Vol. 1, page 387,* and others a porous diaphragm is used. In the Hargreaves-Bird cell *S. Pat. 655,343, 1900; 596,157, 1897*), the porous diaphragm is supported a heavy copper gauge cathode, which is wetted only by the solution percolat- through the diaphragm. In the Townsend cell (*Electrochem. and Met. Ind., 5, page 209, 1907*) the cathode compartment is filled with kerosene oil. ing electrolysis the solution in the anode compartment percolates through porous diaphragm and the perforated cathode, and on coming in contact with oil forms drops and sinks to the bottom of the cathode compartment where is collected. In the "bell process" the anode is inside an inverted non- ducting, nonporous bell, and the cathode is a conducting ring outside. Two portant diaphragm cells are the Allen-Moore cell and the Nelson cell (*Trans. Electrochem. Soc., Vol. 35, pp. 239–249, 1919*).

In the Castner cell the compartments are separated by a mercury diaphragm, ing as an intermediate electrode; and in the Solvay and the Whiting cells rcury cathode is used, which, when charged with sodium in the electro- cell, is decomposed by water in a different compartment. The sodium lgam reacts with water like metallic sodium. (*See the Engelhardt Mono- hs.*)

ELECTROLYSIS OF WATER. — The electrolysis of water is carried out commercial scale for the production of hydrogen and oxygen. The elec- lyte is usually a 15-per cent sodium hydrate solution. A diaphragm of is used to separate the hydrogen and oxygen in the Flamand cell, now e by the International Oxygen Company at Newark, N. J. The vessel aining the electrolyte is cast iron and acts as the cathode; the anode is el. In the Siemens and Halske apparatus the gases are separated by a tallic gauze while bubbling to the surface of the solution; the Garuti and

Pompelli apparatus is based on a similar principle. (*See Viktor E Die Elektrolyse des Wassers, 1902.*)

ELECTROTHERMAL PROCESSES. — Some of the more i industrial electrothermal processes and products and the various types furnaces are described in the article on *Furnaces, Electric.*

OZONE (O_3) is made by the silent discharge of electricity throug The electrodes are water cooled, and protected to prevent the passage From 8000 to 50,000 volts alternating are applied, this voltage being from a small step-up transformer. For the Siemens and Halske ozo concentration of the ozone is about 2 or 3 grams per cubic meter of the passes through it, and the yield is from 18 to 37 grams per kilowatt ho *trochem. Ind., Vol. 2, p. 67, 1904.*) Milk has been sterilized by hig discharges; one process being the Shelmerdine process (*Electrical Time pp. 502–505, 1914*).

BIBLIOGRAPHY. — In addition to the references given above, t ing books should be consulted for further information regarding electrochemical processes:

Arens, *Handbuch der Elektrochemie;* Askenasy, editor, *Einfahrun Technische Elektrochemie, Vol. 1, Elektrothermie;* Blount, *Practica chemistry;* Engelhardt, editor *Monographien über angewandte Elek* Foerster, *Elektrochemie Wasseriger Lösungen;* Haber, *Grundriss der Te Elektrochemie;* Pring, *Some Electrochemical Centres;* Richards, *Me Calculations;* Rodenhauser and Schoenawa, *Electric Furnaces in the Steel Industry* (translated by C. H. Von Baur); Billiter, *Die elektroc Verfahren der chemischen Gross-Industrie;* Thompson, *Applied Electro* Allmand, *Applied Electrochemistry.* See also the volumes of the *Me and Chemical Engineering; Transactions of the American Electrochemica Zeitschrift für Elektrochemie; Transactions of the Faraday Society.* Bibliography in *Electrochemistry, Principles of.*

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CTROCHEMISTRY, PRINCIPLES OF. —(*See also Electricity Magnetism, Principles of; Elements, Chemical; Electrochemical Processes, rial; Furnaces, Electric.*) Electrochemistry is the science which deals the phenomena resulting from the direct transformation of electrical into cal energy or the converse transformation of chemical into electrical . By general usage the term, especially as applied to industrial processes, ne to include also those thermochemical phenomena which occur at tem- re produced in electric furnaces, although in such processes electrical frequently plays no other rôle than that of generating heat.

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FINITIONS. — The following terms are commonly used:

ment. — An element is a substance which cannot be decomposed into er substances by any known means of chemical analysis. (*See Table of rochemical Equivalents below, and article on Elements, Chemical.*)

oms and Atomic Weights. — An atom is the smallest mass of an element can enter into chemical combination with another element or itself. The ic weight of an element is a number which is proportional to the smallest n combining mass of the element, that of oxygen being chosen as the stand- and taken as 16. The relative proportions, by mass, of the elements form- any substance are simple multiples of these numbers. For table of the ic weights of the more common elements see below, and for a complete t see article on *Elements, Chemical*. On the atomic theory the atomic ht is proportional to the mass of the atom.

lecules and Molecular Weight. — A molecule is the smallest mass of stance which can exist and preserve its chemical properties. The molec- weight of an element or of a chemical compound is equal to the sum of the ic weights of the atoms contained in the molecule, and may readily be ulated from the atomic weights when the molecular symbol of the com- d is known. Thus the molecular weight of oxygen, O_2, is $2 \times 16.00 = 32.00$ there are two atoms in the molecule. The molecular weight of silver ite, $AgNO_2$, is $107.88 + 14.01 + 3 \times 16.00 = 169.89$.

adical. — A radical is a combination of two or more elements which per- as a group in chemical reactions, e.g., the SO_4 in H_2SO_4 is a radical, as plified by the reaction $H_2SO_4 + Zn = ZnSO_4 + H_2$.

ormula Weight. — The formula weight of an atom, radical or molecule is sum of the atomic weights of the elements of which it is formed. For mple, the formula weight of an oxygen atom, O, is 16; the formula weight

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of an oxygen molecule, O_2, is 32; the formula weight of the radical $14.01 + 3 \times 16.00 = 62.01$.

Valency. — An adequate consideration of valency would involve a dis beyond the limits of this article. As a simple definition, the valency acid or acid radical may be taken as the number of replaceable hy atoms which the acid molecule contains, the valency of the hydrogen atom always equal to unity. Thus hydrochloric acid, HCl, and nitric acid, HN are univalent acids and the elements H and Cl and the radical NO_3 ar valent; sulphuric acid, $H_2(SO_4)$, is a bivalent acid and SO_4 a bivalent r $H_3(PO_4)$ is a trivalent acid and PO_4 a trivalent radical, etc. Similarly, in like sodium chloride, NaCl, sodium is a univalent metal, since one at sodium replaces one atom of hydrogen in the corresponding acid. I barium chloride, $BaCl_2$, barium is a bivalent metal, as it replaces the hy of two molecules of hydrochloric acid to form the salt. To completely de the valency of a salt it is therefore necessary to stipulate the valency basic and acid constituents; thus sodium chloride, NaCl, is a uni-uni salt; sodium sulphate, Na_2SO_4, is a uni-bivalent salt, the basic constituent univalent and the acid constituent bivalent. Barium sulphate, $BaSO_4$, other hand, is a bi-bivalent salt. The valency of a number of elements according to the compound of which the element forms a part, e.g., cop bivalent in cupric salts like $CuSO_4$ but univalent in cuprous salts as CuCl is bivalent or trivalent according as it is a constituent of a ferrous or ferr respectively.

Bonds or Affinities. — An atom or radical is sometimes said to pos number of "bonds" or "affinities" equal to its valency in the compou which it forms a part.

Equivalent Weight — Chemical Equivalent. — The equivalent weight atom, ion or radical is defined as its formula weight divided by its va The equivalent weight of an element or compound is also referred to "chemical equivalent." The equivalent weight of an acid, base or salt molecular formula weight divided by the highest valency of either of its As hydrogen exhibits no other valency than unity its equivalent weigh atomic weight are identical. Similarly, the equivalent weight and mol weight of hydrochloric acid, HCl, are each 36.47. Copper in copper sulp $Cu(SO_4)$, and in cupric chloride, $CuCl_2$, has a valency of 2, hence equiv weights of these salts are one half their molecular weights respectively.

In computations of electrochemical reactions it is frequently convenie take as the unit of mass (or weight) of a substance, a mass in grams equ the number expressing the atomic weight, ionic weight, molecular weig equivalent weight of the substance. The following names have been given units.

Gram-Atom or Gram-atomic Weight. — A number of grams of an ele equal to its atomic weight, e.g., one gram-atom of oxygen is 16 grams.

Gram-Molecule or Mol. — A number of grams of a substance equal molecular weight, e.g., one mol of silver nitrate, $AgNO_3$, is 169.89 grams.

Gram-Equivalent. — A number of grams of an atom, radical or mol equal to its equivalent weight, i.e., to its formula weight divided by its val For example, a gram-equivalent of sulphuric acid is $98.09/2 = 49.04$ gr A gram-equivalent is usually represented by the chemical formula divide the valency, e.g., a gram-equivalent of sulphuric acid is denoted by $\frac{1}{2} H_2S$

Electrolyte — Electrolysis. — When an electric current is passed thr certain substances a chemical reaction takes place at the places where current enters or leaves the substance. Such substances are called "ele

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s;" if the current effects a decomposition or chemical change in the elec-
te the process is called "electrolysis."

lectrodes — Anode and Cathode. — Electrodes are the conductors by
ch the current enters and leaves the electrolyte. The electrode at which the
ent enters the electrolyte is called the "anode," and that by which the cur-
leaves the electrolyte is called the "cathode." The anode is therefore that
ode which is connected to the positive terminal of the generator; the
ode that connected to the negative terminal.

ons — **Anions and Cations.** — The constituents of an electrolyte which are
ually liberated or deposited from an electrolyte at the electrodes are called
ns. The term also applies to the constituents of an electrolyte which con-
the current. (*See sections below on Dissociation Theory and Theory of Elec-
ic Conduction.*) The ions liberated at the anode are called "anions," while
e liberated at the cathode are called "cations." For example, when a
ent enters and leaves an aqueous solution of copper sulphate, $CuSO_4$, at
latinum electrodes, the $CuSO_4$ is decomposed, the copper Cu being liberated
the solution and deposited on the cathode, and the SO_4 being liberated
the anode where it reacts with the water to form oxygen gas and sulphuric
d. The copper in the sulphate solution is therefore a cation and the SO_4 an
n. In general the metal atoms in salts and bases and the replaceable
drogen atom in acids are cations, while the acid radicals (e.g., SO_4) and the
adicals (e.g. OH in KOH) are anions.

The terms anion and cation are also used to designate specifically the negative
positive constituents of an electrolyte. For example, in dilute aqueous solu-
a molecule of hydrochloric acid, HCl, is looked upon as consisting of one hy-
gen cation and one chlorine anion; sulphuric acid, H_2SO_4, of two hydrogen
ons and one SO_4 anion. There is much evidence to indicate that a nega-
e charge of fixed amount is associated with each anion and a positive charge
deficit of negative electricity) of equal amount is associated with each cation,
espective of the chemical nature of the ion, except that the charges carried
any ion are directly proportional to its valency. The charge carried by each
dividual univalent ion as determined by Millikan, is $4.774 \pm 0.005 \times 10^{-10}$
ctrostatic units, the charge carried by every bivalent ion is twice this amount,
$4.774 \pm 0.005 \times 10^{-10}$ electrostatic units of negative electricity being the
rge of an electron. Hence on the basis of the electron theory, a univalent
on as Cl has associated with it one free electron, a divalent anion as SO_4 two
electrons, while a univalent cation as H has a deficit of one electron, a divalent
ion as Cu has a deficit of two electrons, etc. See *Electron Theory.*

To distinguish cations and anions from neutral atoms or molecules, small
s or minus signs are often written over the symbol, the number of such signs
ng equal to the valance of the ion. Thus

$\overset{+}{Na}$, $\overset{++}{Cu}$, $\overset{+++}{Fe}$ (ferric iron) represent cations; $\overset{-}{Cl}$, $\overset{-}{NO_3}$, $\overset{--}{SO_4}$, $\overset{---}{PO_4}$ anions, etc.

Ionic Weight. — The formula weight of an ion is called its ionic weight.

Gram-Ion. — A number of grams of an ion equal to its ionic weight, e.g.,
gram-ion of hydrogen is 1.008 grams, and one gram-ion of SO_4 is 96.07 grams.

Electrochemical Equivalent. — The electrochemical equivalent of an ion is
mass in grams of the ion liberated or deposited by one coulomb of electricity.

Electrochemical Constant or "Faraday." — The electrochemical constant,
noted by F, and called the "Faraday," is the number of coulombs required
liberate one gram-equivalent of any ion. It is a constant for all ions, and
value, as adopted by the International Congress of Applied Chemistry in
03, is $F = 96{,}540$ coulombs. (*See also page 452.*)

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Solvent, Solute and Solution. — When a substance A "dissolves" substance B, the substance A which dissolves is called the "solute substance B is called the "solvent." The two substances togeth "solution."

Osmotic Pressure. — The osmotic pressure of a solution may b as the force in virtue of which a solute tends to diffuse from region to regions of lower concentration. It can be measured by separatin tion and solvent by means of a diaphragm which is permeable to the s not to the solute. (See section below on *Theory of Solutions*.)

Specific Conductance (κ). — The specific conductance of a solu reciprocal of its specific resistance, i.e., it is the conductance of a liquid one centimeter long and one square centimeter cross section. pressed in reciprocal ohms, or mhos, and is denoted by κ.

Concentration (c). — The concentration (c) of a solution is the q the solute contained in unit volume of the solution. Thus it may be as grams per cubic centimeter or grams per liter, etc.

Equivalent Concentration (η). — The equivalent concentration of is the number of gram-equivalents of solute contained in one cubic of the solution; it is denoted by η. Calling w the equivalent weig solute, $\eta = c/w$.

Dilution (ϕ). — The dilution of a solution is the reciprocal of its tion, i.e., it is the number of cubic centimeters of solution in which equivalent of solute is dissolved. It is denoted by ϕ. Hence, ϕ $\eta = 1/\phi$.

Normal Solution. — A normal solution is a solution containing equivalent of solute per liter. For such a solution $\eta = 10^{-3}$ or $\phi =$

Equivalent Conductance (Λ). — The equivalent conductance of at the dilution ϕ is the conductance which a volume (in cu. cm.) of th containing one gram-equivalent of the solute would have, if placed parallel plate electrodes one centimeter apart. It is denoted by Λ_ϕ or Λ ing as the dilution or concentration of the solution is given. Hence or $\Lambda_\eta = \kappa/\eta$.

The dilution or concentration of a solution should always be stat nection with its equivalent conductance, otherwise the expression is in

Heat of Reaction. — The heat of reaction is the heat energy giv absorbed in a chemical reaction. It is usually expressed in calories; *and Heat Effects*. Ostwald recommends the use of a calorie equal to the mean gram-calorie for expressing thermochemical data and th adopted in the present discussion. It will be denoted in this article

Exothermic Reactions. — Reactions in which heat is given out t rounding bodies.

Endothermic Reactions. — Reactions in which heat is absorbed surrounding bodies.

NOTATION. — The notation used in this article is, in most insta proposed by the Bunsen Gesellschaft and adopted by the Fifth Int Congress of Applied Chemistry in Berlin, 1903. For convenience of the symbols most frequently used are tabulated below.

κ = specific conductance in reciprocal ohms;

η = concentration, expressed as gram-equivalents of solute per cu meter solution;

ϕ = dilution, expressed as cubic centimeters of solution per gram-e solute;

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e at infinite dilution;

rence;

y International Congress]
e, taken positive in direction of rise of potential;*
sured against a normal hydrogen electrode;
sured against a normal calomel electrode;

oulombs per gram-equivalent
degrees centigrade.
[θ adopted by International Congress]

. — A chemical equation, such, for example, as
of zinc in a dilute hydrochloric acid solution

$$HClAq = ZnCl_2Aq + H_2,$$

one gram-atom (65.37 grams) of zinc reacting
grams) of hydrochloric acid in aqueous solu-
$2 \times 35.46 = 136.3$ grams) of zinc chloride in
$= 2.016$ grams) of hydrogen gas. Since atomic
y unit of weight, as the pound or kilogram, may
tatement.

o express not only the chemical change which
y change involved, the "heat of the reaction"

$$q = ZnCl_2Aq + H_2 + 342 \text{ cal.}$$

equation signifies that the intrinsic energy rep-
onsisting of 65.37 grams of zinc and 72.94 grams
enough water to form a dilute solution, is 342
0° to 100° C.) greater than that represented by
136.3 grams of zinc chloride dissolved in water
as; in other words when the substances in the
e substances in the final system, an amount of
o 342 cals. When energy is given up by a
othermic reactions), as in the above illustra-
If a reaction is accompanied by an absorption
actions), i.e., if the system takes up heat and
ndings, the sign of the heat of the reaction is

first quantitative relations between the magni-
its chemical effect were discovered by Faraday
lay's Laws. They may be stated as follows:

of an electrolyte decomposed by an electric
o the total quantity of electricity which passes
the rate of chemical decomposition is directly
ne amount of decomposition is independent of
e current, size of electrodes and concentration
otal *quantity* of electricity flowing through the

rmonize the notation in this article with that used
Congress recommends the use of the symbol ϵ for a
in the direction of the *drop* of potential. See also
Sci. XXXIII, 79, 1918; *Committee Reports on Signs*
3.

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the voltage and intensity of the current, size of electrodes and con of electrolyte, so long as the total *quantity* of electricity flowing th circuit remains constant. (These factors, however, do affect the *ulti ucts* of an electrolysis.)

Second Law. — A given quantity of electricity always decomposes weights of different electrolytes irrespective of their nature. For e three electrolytic cells containing aqueous solutions of silver nitrat copper sulphate $CuSO_4$, and cuprous chloride CuCl (dissolved i chloride), respectively, be connected in series and the same quantit tricity passed through each, it will be found if a grams of silver are de the first cell, b grams of copper in the second and c grams of copp third, that the following proportion holds between these weights: $\frac{107.88}{1} : \frac{63.57}{2} : \frac{63.57}{1}$, where 107.88 and 63.57 are the atomic weight and copper respectively. In copper sulphate the valency of copper i in cuprous chloride its valency is 1; silver is always univalent and weights a, b, c are proportional not to the atomic weights but to the *weights* of the metals in the compounds from which they are electrol follows from this that a given current will deposit in a given time weight of metal from a salt in which it is combined with a valency of a salt in which it exists with a valency of 2. Thus, the same curren in a given time twice the weight of copper from a cuprous as from salt solution. In general, if the ion in a compound has a valen quantity of electricity required to liberate it will be n times as gre required to liberate the same ion from a compound in which it is univ

It is to be noted, since the numbers expressing the atomic weights ments, and hence their equivalent weights, are purely relative, that th weights of substances decomposed by a given quantity of electricit expressed in grams, kilograms, pounds or any other unit of weight. the above illustration the quantity of electricity which will deposit $\frac{63.5}{2}$ pounds of copper from a copper sulphate solution will deposit 107.88 silver.

Faraday's Laws are the expression of the results of direct experi have been tested to the limit of precision with which physical and measurements are capable of being carried out at the present time. dence indicates that they hold rigidly, i.e., that they are exact laws In cases where exceptions have seemed to exist these have been show from secondary causes. See Kraus, *Trans. Am. Elec. Chem. Soc.*, *21*, for special cases of electronic and ionic conduction.

Value of the Electrochemical Constant or Faraday. — The dete of the number of coulombs required to deposit one gram-equivalent i.e., the constant connecting the quantity of electricity and the mass stance liberated, involves two distinct investigations; first, the mea of the number of coulombs which pass through a given electrolytic second, the determination of the amount of the chemical decompositi importance of the constant has enlisted the skill of a number of t physicists, and its value is still being investigated at the present time.

The various methods which have been employed vary primarily in t adopted for measuring the current. A primary instrument the co which can be computed from its dimensions, is essential. Tangent g eters and various forms of current balances or dynamometers have structed for this purpose. The ultimate precision of the measurem these instruments is thus referred back to instrumental constants a

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racy with which the horizontal component of the earth's field, or the value he acceleration due to gravity, is known at the place where the research is ied out, respectively.

he amount of silver deposited from a silver nitrate solution has been adopted st universally for the chemical part of the research. The amount of silver osited depends to a slight extent upon whether or not the solution at the de is allowed to diffuse to the cathode. The following résumé of the determiions of the mass of silver in milligrams deposited by one coulomb is given he, *Bulletin of the Bureau of Standards, 1905, Vol. 1, p. 363*).

TABLE I. — ELECTROCHEMICAL EQUIVALENT OF SILVER IN MILLIGRAMS PER COULOMB

Observer	Year	Found	Electrochemical equivalent corrected by		
			Richards and Heimrod	Van Dijk	Guthe
		mg.	mg.	mg.	mg.
lucart	1884	1.1156	.....	1.1155	1.1153
l and W. Kohlrausch..	1884	1.1183	1.1173	1.1182	1.1177
ayleigh and Sidgwick..	1884	1.1179	1.1175	1.1178	1.1176
ray	1886	1.1183	.....	.....	1.1178
ocpael	1887	1.1174	.....	.....	1.1169
Blat and Potier	1890	1.1192	.....	1.1191	1.1189
tterson and Guthe	1898	1.1192	1.1175	1.1180	1.1177
Blat and Leduc	1903	1.1195	.....	1.1192	1.1190
n Dijk and Kunst	1904	1.1182	.....	1.1180	1.1178
				Mean	1.1176

If the atomic weight of silver be taken as 107.88 (latest corrected value) value of the Faraday from the average of Guthe's corrected values is

$$\frac{107.88}{0.001117 6} = 96{,}530 \text{ coulombs.}$$

This value agrees very closely with the ue $F = 96{,}540$ adopted by the International Congress of Applied Chemistry 1903 and based on the atomic weight of silver = 107.93, and on the definition the legal ampere as that current which in one second deposits 0.001118 gram silver. (*See Report of International Electrical Congress, 1893; Definition legalized the U. S. Government in 1894.*) In view of the above agreement it seems visable to adhere to the value 96,540 until by international agreement another ue shall be adopted. For a complete résumé of recent work on the value of raday the *Bull. Bureau of Standards, 13*, 479, 1916, should be consulted. The reau of standards gives 96,503 as the most probable value, and recommends ,500 as the best round value.

ELECTROCHEMICAL EQUIVALENTS OF THE ELEMENTS. — m the definitions of the electrochemical equivalent and the Faraday, it lows that the electrochemical equivalent of any ion, expressed in grams per ulomb (one ampere per second) is equal to

$$\frac{\text{gram-equivalent of the ion}}{96{,}540}.$$

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Table II contains the values of the electrochemical equivalents of common elements which may be found useful in certain calculati

TABLE II. — ELECTROCHEMICAL EQUIVALENTS OF THE IMPORTANT ELEMENTS

(Based on atomic weights of 1921, and $F = 96,540$ coulombs

Element	Symbol	Atomic weight	Valence	Milligrams deposited by one ampere in one second	d a c
Aluminum	Al	27.1	3	0.0935	
Antimony	Sb	120.2	3	0.4152	
Arsenic	As	74.96	3	0.2589	
Barium	Ba	137.37	2	0.7115	
Bismuth	Bi	208.0	4	0.5387	
Bromine	Br	79.92	1	0.8279	
Cadmium	Cd	112.40	2	0.5821	
Calcium	Ca	40.07	2	0.2076	
Carbon	C	12.005	4	.....	
Cerium	Ce	140.25	3	0.4843	
Chlorine	Cl	35.46	1	0.3673	
Chromium	Cr	52.0	2	0.2694	
Chromium	Cr	52.0	3	0.1795	
Cobalt	Co	58.97	2	0.3054	
Cobalt	Co	58.97	3	0.2036	
Copper	Cu	63.57	1	0.6586	
Copper	Cu	63.57	2	0.3293	
Fluorine	Fl	19.0	1	0.1968	
Gold	Au	197.2	1	2.043	
Gold	Au	197.2	3	0.6810	
Hydrogen	H	1.008	1	0.01043	
Iodine	I	126.92	1	1.313	
Iron	Fe	55.84	2	0.2894	
Iron	Fe	55.84	3	0.1929	
Lead	Pb	207.10	2	1.073	
Lithium	Li	6.94	1	0.0725	
Magnesium	Mg	24.32	2	0.1260	
Manganese	Mn	54.93	2	0.2845	
Manganese	Mn	54.93	3	0.1897	
Mercury	Hg	200.6	1	2.077	
Mercury	Hg	200.6	2	1.039	
Nickel	Ni	58.68	2	0.3039	
Nickel	Ni	58.68	3	0.2026	
Oxygen	O	16.00	2	0.08287	
Platinum	Pt	195.2	2	1.011	
Platinum	Pt	195.2	4	0.5055	
Potassium	K	39.10	1	0.4051	

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ABLE II. — *Continued*

ymbol	Atomic weight	Valence	Milligrams deposited by one ampere in one second	Grams deposited by one ampere in one hour
Ag	107.88	1	1.118	4.025
Na	23.00	1	0.2382	0.8576
Sr	87.63	2	0.4539	1.634
S	32.06	..	.....	.....
Tl	204.0	1	2.113	7.607
Tl	204.0	2	1.057	3.804
Sn	118.7	4	0.3076	1.107
Ti	48.1	4	0.1245	0.448
W	184.0	2	0.9550	3.431
Zn	65.37	2	0.3386	1.219

f any radical may be readily calculated from its ectrochemical equivalent of SO_4 is

96,540 = 0.0004975 gram or 0.4975milligram.

LECTROLYTES—Solutions. — (*See also article ce.*) The specific conductance of an electrolytic limits. It depends upon the nature of the sol- he temperature and on the concentration of the factors is discussed below. For numerical values *Leitvermögen der Electrolyte;* Landolt-Börnstein, *ternationales de Constantes.*

Most inorganic salts conduct electrolytically when temperature to cause them to pass into the liquid Faraday's, Ohm's, and Joule's Laws hold as they The conductance increases in general from 1 to 1½ An exhaustive résumé of all matters relating to nd in Lorenz's *Electrolyze der Geschmolzene Salze.* concentration (100 per cent) the specific conduct- y very high. This, together with the difficulty of hemically inert vessel of suitable shape to contain regulating high temperatures to a fraction of a ent of the conductivity of fused electrolytes far se of solutions. Fused silica and natural quartz y used for conductivity cell.. See Goodwin and 25, p. 469, 1907; Vol. 26, p. 28, 1908; Goodwin Vol. 28, p. 1, 1909; Arndt, *Zeit. far Electrochem.* 3, p. 509, 1907; Vol. 14, p. 662, 1908; Foot and 1909; *Trans. Am. Elec. Chem. Soc.*, 21, 105, 1912;

ROLYTIC CELLS. — When a cell formed by two ctrolytes gives out electric energy the cell is called ry chemical batteries are voltaic cells. If across

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the terminals of a cell an external electromotive force, greater than
tromotive force developed within the cell, is impressed, then a curren
through the cell in the opposite direction, and the cell will absor
energy. A cell which absorbs electric energy is usually referred
"electrolytic cell." The cells used in electrolytic refining and similar
are electrolytic cells. An electrolytic cell may or may not have a
motive force on open circuit, but may develop an electromotive force
of the chemical changes or changes in concentration which take pla
the current forced through it by some external source. A voltaic cel
an electrolytic cell when the electromotive force impressed across its
exceeds (and opposes) its own electromotive force.

POLARIZATION. — When an electric current passes through
voltaic or an electrolytic cell there is, in general, developed at the ele
the cell as a result of the chemical actions and changes in concentrati
take place, a *back* or *counter-electromotive* force, in addition to its op
electromotive force (if any), and an *increase in the resistance* of th
addition to the change in resistance due to the heating effect of the
Both of these effects cause a decrease in the strength of the current
the cell. These two phenomena are said to be due to "polarizat
"transition resistance" respectively.

Even in the case where the electrolyte, as a whole, suffers no chang
centration, as in the electrolysis of copper sulphate between copper e
a counter e.m.f. of polarization is produced in consequence of the
in concentration of the copper ions in the neighborhood of the anode and
Vigorous stirring of the electrolyte tends to reduce this concentration
and the resulting polarization, but, except for very low current de
cannot be completely eliminated. It is for this reason, in refining proce
energy is required to transfer the metal from anode to cathode in ac
that necessary to overcome the internal resistance of the cell.

A transition resistance results from the formation of a film of pc
ducting material over the electrode and may or may not be present
to the character of the electrolysis.

Measurement of E.M.F. of Polarization and Transition Resis
As both transition resistance and polarization tend to cut down th
flowing through the cell, they cannot be distinguished by this effe
The transition resistance may be determined by measuring the ohmic
of the cell before and after the passage of the current by the usual alt
current method. The existence of an e.m.f. of polarization in a c
normally has no open-circuit e.m.f. may be qualitatively demonst
short-circuiting the cell through a galvanometer immediately after
the primary circuit; if the cell be polarized, a current which diminish
will flow through it in the reverse direction. A voltmeter, or, better
trometer connected across the electrolytic cell, will indicate the po
voltage the instant after the current is broken. This voltage will di
the polarization disappears, the rate depending upon the current thr
voltmeter and the rate of diffusion of the electrolytic products ca
polarization. Owing to the rapidity with which the e.m.f. of polariza
off after the exciting cause is removed, special precautions must be
In its measurement. One of the best methods is to connect up th
containing the applied e.m.f., and electrolytic cell with a tuning-fork in
and electrometer so that at the instant the battery current is broke
vibration of the fork, the circuit containing the cell and electrometer
meter is closed, and vice versa. By this arrangement, the e.m.f. of po
is measured during the fraction of a second that the battery circuit

d before it has had time to sensibly diminish. The polarizing current may o be regarded as practically constant.

It is frequently of importance to know, not the polarization of the cell as a hole, but the polarization at each electrode. This is obtained by measuring e drop in potential at each electrode against a normal hydrogen or calomel ectrode while the impressed e.m.f. is acting on the electrolytic cell, or immeiately after the current through the cell is interrupted.

REVERSIBLE ELECTRODES — DEPOLARIZERS. — If the chemil and thermal actions which take place at a given electrode when a given uantity of electricity passes in one direction through a cell are exactly the verse of the actions which take place when the same quantity of electricity asses through it in the opposite direction, the electrode and the solution with hich it is in contact are said to form a "reversible electrode." Such an elecode does not polarize provided the concentration of the solution is kept conant.

There are two types of reversible metal-liquid electrodes, namely:

Electrodes of the First Type, consisting of a metal in contact with a olution of one of its own salts, e.g., copper in copper sulphate, zinc in zinc ulphate, etc. The two electrodes of a Daniell cell are of this type.

Electrodes of the Second Type, consisting of a metal in contact with a olution containing one of its difficultly soluble salts and a second soluble salt f some other metal, having the same anion. The difficultly soluble salt, called he "depolarizer," must be present in excess as solid. Such an electrode is ercury in contact with a solution of zinc sulphate containing mercurous sulhate in excess as solid; this is one of the electrodes of the Clark cell.

Reversible Gas Electrode. — An electrode consisting of "platinum black" aturated with an atmosphere of hydrogen gas and dipping partially into a olution containing hydrogen ions is also a reversible electrode. This is a pecial form of electrode of the first type in which a gas by being occluded in latinum is made to play the rôle of a metal.

Other "gas electrodes" e.g., chlorine, may be similarly prepared.

CONTACT POTENTIALS; ELECTROMOTIVE FORCE. — The lectromotive force of a voltaic cell, the back-electromotive force of an electrolytic ell, and the electromotive force of a thermocouple, are all due to differences of otential which always exist at the junction of dissimilar substances. These ingle potential differences are called "contact potentials," the word "differnce" being understood. For a general discussion of this subject see Langmuir, *Trans. Am. Elec. Chem. Soc.*, 29, 125, 1916.

Metal-metal Potentials. — The potential at the junction of two dissimilar etals may be measured either by the Peltier effect, i.e., by the heat developed r absorbed at the junction when a known quantity of electricity is forced across t, or by the thermoelectric force set up in a circuit formed by the two metals in uestion when the two junctions are kept at different temperatures. In the ormer case the potential may be calculated from the expression $e = H/nF$ hen H is the Peltier heat developed or absorbed at the junction by the passage f nF coulombs. In the latter case $e = T\frac{de}{dT}$, where $\frac{de}{dT}$ is the thermoelectric oefficient of the junction at the absolute temperature T. Both methods give esults which prove that the potential difference thus arising is of the order of magnitude of a few millivolts, except in the unusual combination of antimony nd bismuth where it amounts to about 0.03 volt. Table III taken from an rticle by Caswell, *Physical Review, 33, 401, 1911*, contains the values of the metal-metal potentials for the more common metals against copper at ordinary

temperatures. The columns headed *A* give the values as determined first method, columns headed *B* give the values as determined by the method. The plus sign (+) indicates that at a junction formed by t metal and copper the given metal is at the higher potential, the minus s that it is at a lower potential than the copper.

TABLE III. — CONTACT POTENTIALS BETWEEN COPPER AND METALS, IN MILLIVOLTS

(Temperature 15–25° C.)

Metal	LeRoux	Jahn		Edlund		Caswell		Oth Obse
Against Copper	*A*	*A*	*B*	*A*	*B*	*A*	*B*	*A*
Antimony	− 5.64	.....	.....	.....	.....	.....	.....	−3.06
Iron	− 2.93	−3.68	−3.07	− 2.96	− 3.08	.....	.....	.....
Cadmium	− 0.53	−0.72	−0.72	+ 0.16	+ 0.21	.....	.....	.....
Zinc	− 0.45	−0.68	−0.41	− 0.01	− 0.02	.....	.....	.....
Copper	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Silver	.....	−0.48	−0.58	+ 0.03	+ 0.04	+ 0.03	+ 0.06	.....
Gold	.....	.....	.....	+ 0.33	+ 0.50	.....	.....	.....
Lead	.....	.....	.....	+ 0.50	+ 0.57	.....	.....	.....
Tin	.....	.....	.....	+ 0.56	+ 0.82	.....	.....	.....
Aluminium	.....	.....	.....	+ 0.70	+ 0.89	+ 0.70	+ 0.89	.....
Platinum	.....	+0.37	+0.38	+ 1.02	+ 1.23	+ 0.85	+ 0.66	.....
Palladium	.....	.....	.....	+ 2.17	+ 2.43	.....	.....	.....
Nickel	.....	+5.07	+5.44	.....	.....	+ 6.0	+ 6.35	{+6.75 +8.04
Bismuth	+22.3	.....	.....	+17.7	+17.6	+16.1	+16.0	.....

The contact potential difference between any two of these metal *algebraic* difference between the potentials of the two metals against e.g., the contact potential difference between iron and platinum acco Jahn's measurements (*A*) is + 0.37 − (− 3.68) = 4.05 millivolts.

The contact potential difference between any two metals is a functio temperature, the sign of the potential for a given pair of metals so reversing as the temperature rises. Although of importance in ther pyrometry and radiometry, metal-metal potentials are of little signifi considerations of the voltaic cell.

Metal-gas Potentials. — The contact potential differences between two metals should be carefully distinguished from potential differences having their origin in the so-called "Volta effect," i.e., potential differences which are manifested when two dissimilar metals in metallic contact are separated by an air or other gaseous gap. The two phenomena are quite distinct, there being no known relation between them.

Zinc — air — lead .....
Lead — air — tin.....
Tin — air — iron.....
Iron — air — copper.....
Copper — air — platinum.....
Platinum — air — carbon.....

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difference across the air gap between combinations
on metals are given in the table at the bottom of
is a fall of potential from the zinc to the lead
e is taken from data by Ayrton and Perry, *Phil.*

. — When two dissimilar electrolytic solutions are
henomenon of diffusion takes place between them
ure results. At the same time a difference of
tween the solutions, the magnitude of which
of migration and the relative concentration of
he diffusion, the charge which they carry, the
the gas constant: Liquid junction potentials
are, in general, of small magnitude. Thus the
two solutions of potassium chloride, one solution
tion of the other, is only 0.0004 volt, and diminishes
ions approaches unity, being, in fact, proportional
o. Potassium chloride is often used as an inter-
s desired to reduce the liquid-liquid potentials of
inimum because of the small potential to which
ails of eliminating liquid-liquid contact potentials,
-Chemische Messungen, pages 448–449.
atest between acid or between alkali solutions.
loric acid solutions whose concentrations are in
rature of 18° C., there is a potential difference of
wo sodium-hydrate solutions under the same con-
ifference of 0.034 volt, these voltages also varying
entration ratio. For formulas, see page 482.

— From what has been said regarding the magni-
uid-liquid potentials, it follows by the process of
t of the electromotive force of a voltaic cell must
en metals and liquids. The *absolute* value of the
a metal and the solution with which it is in con-
ertain assumptions regarding the nature of surface
eferred to below. For practical purposes the value
as the e.m.f. of a cell constructed with two half
given metal and solution, and the other some form
trode. Two normal electrodes are in common use,
e and the hydrogen electrode.

ectrode. — The normal calomel electrode consists
normal solution of potassium chloride saturated
latter being present in excess as a solid.

Electrode. — The normal hydrogen electrode
coated with a thin deposit of platinum black and
t atmospheric pressure. The electrode is mounted
rogen gas and partially dipping into an acid solu-
n that it contains 1 gram-equivalent of hydrogen
id solution containing 2 gram-equivalents per liter
tion. Hydrogen gas is allowed to bubble through

lation of the International Congress of Applied
quid potentials should hereafter be given as directly
normal calomel or the hydrogen electrode, un-
potentials.

electrode to a normal calomel electrode there is

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a rise of potential through the electrolyte of 0.283 volt, hence, if from gen electrode to any metal electrode the rise of potential is e_h, and calomel electrode to any metal electrode the rise of potential is e_c, th

$$e_h = e_c + 0.283 \text{ volt.}$$

The difference between any two metal-liquid potentials remains the spective of the normal electrode to which they are referred.

Specific Electrode Potentials. — On the assumption that the e conductance ratio is a true measure of the degree of ionization of an el and that the gas laws hold for solutions up to normal concentration, it i to calculate from electrode potential measurements against a normal what the potential difference would be between an element and a solu taining ions of that element at a concentration of one gram formula w liter. Such potential differences (measured directly or calculated) specific electrode potentials. Much experimental work remains to before these fundamental constants are known with precision. For o metals are there known at present better than + 0.01 volt. The table contains values for some of the more typical electrochemical These values are all referred to the hydrogen electrode as standard. T thesis ( ) signifies one electronic change which is subtracted from or ad atom or ion. For a more complete table see the Monograph of Abe bach and Luther, *Abhandlungen Deutsch. Bunsen Gesellschaft*, Vol. (1911) and No. 8 (1915), or Washburn's *Principle of Physical Chemistr*

TABLE IV. — SPECIFIC ELECTRODE POTENTIALS

Elements (electrodes) in equilibrium with aqueous solutions contai gram formula weight of the indicated ions per liter. The electrode a charge against the solution of the sign and magnitude indicated.

Electrochemical reaction	Volts	Electrochemical reaction	
$Li - (-) = Li^+$	−3.03	$2H^+ + 2(-) =$	H_2
$K - (-) = K^+$	−2.93	$Cu^{++} + 2(-) =$	Cu
$Na - (-) = Na^+$	−2.72	$O_2 + 2H_2O + 4(-) =$	$4OH^-$
$Mg - 2(-) = Mg^{++}$	−1.55	$I_2 + 2(-) =$	$2I^-$
$Zn - 2(-) = Zn^{++}$	−0.76	$Fe^{+++} + (-) =$	Fe^{++}
$Fe - 2(-) = Fe^{++}$	−0.43	$Ag^+ + (-) =$	Ag
$Cd - 2(-) = Cd^{++}$	−0.40	$Hg^+ + (-) =$	Hg
$Co - 2(-) = Co^{++}$	−0.29	$Br_2 + 2(-) =$	$2Br^-$
$Ni - 2(-) = Ni^{++}$	−0.22	$Cl_2 + 2(-) =$	$2Cl^-$
$Pb - 2(-) = Pb^{++}$	−0.12	$Au^+ + (-) =$	Au
$Sn - 2(-) = Sn^{++}$	−0.10	$F_2 + 2(-) =$	$2F^-$
$Fe - 3(-) = Fe^{+++}$	−0.04		
$H_2 - 2(-) = 2H^+$	∓0.0		

Variation of Electrode Potentials with Concentration. — ing to Nernst's theory of electrode potentials (*see below*) the *change* in t of these potentials with concentration may be calculated by the following

$$e_1 - e_2 = \frac{0.000198\,T}{n} \log_{10} \frac{c_1}{c_2},$$

where e_1 is the potential at concentration c_1, and e_2 the potential at conc e_2, T is the absolute temperature, and n the valence of the metal in the

ɲ formula is also justified by experiment. For example, the electrode ɲtial of silver in a normal silver-nitrate solution at 25° C. is 0.80 referred the normal hydrogen electrode. If the concentration of the silver ions be ɲced to 1/1,000,000 its value in a normal solution, the electrode potential of ɲr will become

$$e_2 = 0.80 - \frac{0.000198 \times 298}{1} \log_{10}\left(\frac{1}{10^{-6}}\right)$$

$$= 0.80 - 0.0590 \times 6 \times 0.45 \text{ volt.}$$

Electrochemical Series — Nobility of the Elements. — The elements, as ɲged in Table IV, constitute the "Electrochemical Series." Those elements ɲ which e_h is negative are said to be less "noble" than hydrogen, while those ɲ which e_h is positive are said to be more "noble" than hydrogen. The alkali ɲals having the greatest tendency to form ions in water stand at one end, ɲke the "noble" metals, such as gold, platinum, palladium, having but a very ɲht tendency to form ions, are at the other end. The halogens which go into ɲution as negative instead of positive ions stand at the lower end of the series. ɲher series have been given which differ from the above in that the elements ɲ not compared under similar conditions in regard to the concentration of the ɲution with which they are in contact. Changing the electrolyte, e.g., to ɲssium cyanide, alters not only the numerical values of the potentials, but may ɲpletely change the order in which certain elements occur in the series.

ɲy metal if placed in a solution of a salt of a metal standing below it in the ɲies will tend to replace it; thus, zinc precipitates iron, copper, silver, etc., ɲm their solutions but will not displace the alkali metals from solutions of ɲir salts. Any metal standing above hydrogen will tend to displace it from ɲ acid solution with evolution of hydrogen. Metals below hydrogen in the ɲies will not dissolve in acid by a simple replacement of hydrogen. From ɲchemical standpoint the adoption of the hydrogen electrode as a standard ɲs the advantage over the calomel standard that it divides the metals into ɲo groups according to their behavior towards acids.

The approximate electromotive force of a battery consisting of two metals ɲpping into normal solutions of their respective salts may also be computed ɲ once from the table by taking the difference of the two corresponding elec- ɲode potentials. Thus a zinc-copper cell should have an electromotive force ɲual approximately to $E_{Zn-Cu} = (e_h)_{Zn} - (e_h)_{Cu} = -0.76 - 0.34 = 1.10$, the ɲe of potential being from the zinc to the copper in the cell. As a matter of ɲct, this combination, the Daniell cell, has an electromotive force of approxi- ɲately 1.10 volts. Other conclusions to be drawn from t. ' table will be pointed ɲut below.

ELECTROMOTIVE FORCE AND HEAT OF REACTION. — The ɲlectromotive force of a reversible cell maintained at constant temperature may ɲe readily calculated from the first and second law of thermodynamics (*see Thermodynamics*). By a "reversible" cell is meant a cell which does not polarize ɲnd which operates under conditions such that changes which take place within ɲhe cell constitute a thermodynamically reversible process. (*See Thermody- ɲamics, Principles of.*) The discussion given below also applies, with a rough ɲegree of approximation, to most commercial cells, which, as a rule, are not ɲstrictly reversible.

Gibbs-Helmholtz Equation. — In the case of a reversible cell, such, for ɲxample, as the Daniell cell,* shown in Fig. 1, the relation between the heat of ɲeaction (H) and the electromotive force (E) of the cell is calculated as follows.

* The special construction of this cell renders it reversible.

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From Faraday's Laws, the quantity of electricity which must flow the cell in order to deposit or liberate one gram-ion at either electrod coulombs, where n is the valency of the ion of highest valency involve chemical reaction and F is the electrochemical constant (*see above*). Hence, the external work done by the cell (when there is no other external work than electrical work) is nFE joules, where E is the e.m.f. of the cell. If the cell is kept at the same temperature (T degrees, absolute scale) as the surrounding bodies, then the external work nFE done by the cell is the maximum external work it can do at this temperature T (*see Thermodynamics, Principles of*). Hence, from equation (8) of the article on thermodynamics,

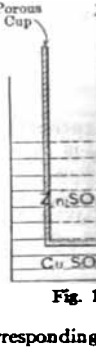


Fig. 1

$$nFE = H' + nFT\frac{dE}{dT},$$

or

$$E = \frac{H'}{nF} + T\frac{dE}{dT},$$

where H' = the heat of reaction, in joules per gram-ion, corresponding chemical change which takes place.* H' gives the change in intrinsic corresponding to the chemical changes which take place within the cell can be found by an independent calorimetric measurement, by caus reaction to take place under such conditions (*constant volume*) that hea only form of energy produced.

Temperature Coefficient of Electromotive Force. — Fro above equation it follows that the energy developed by the cell is equal heat energy of the chemical reaction taking place within it plus a certai quantity of energy equal to $nFT\,dE/dT$. This may be either positive o tive, according as the temperature coefficient of electromotive force dE plus or minus, i.e., according as the electromotive force of the cell incre decreases with the temperature. If the electromotive force on open increases with the temperature of the cell, then on closed circuit the c tend to cool, i.e., its temperature will fall, and its electromotive force w wise decrease, the energy $nFT\,dE/dT$ being derived from the heat within the cell (or surroundings). If the electromotive force on open decreases with increasing temperature of the cell, then on closed circuit will tend to heat up, i.e., its temperature will rise and its electromotiv will decrease. A cell for which dE/dT is other than zero can work at co temperature only by absorbing heat from or giving out heat to some sur ing body.

Only for the unique conditions that $dE/dT = 0$, or that $T = 0$, i.e. the electromotive force is independent of the temperature or the cell wo temperatures approaching absolute zero, is $E = H'/nF$. By a curious it happens that the first of these conditions practically obtains in the the Daniell cell considered above. The electromotive force of the cell is independent of the temperature. Its observed value is $E = 1.10$ volts, its value computed by the above equation, putting $dE/dT = 0$, is 1.09 v

Thomson's Rule. — In computing the electromotive force of a b from heats of reaction it is usually necessary to content oneself with

* Since 1 large mean calorie (Ostwald calorie) = 4 18.6 joules and $F = 96,54$ may be written, putting H = heat of reaction in large mean calories,

$$E = \frac{H}{2.035\,n} + T\frac{dE}{dT}.$$

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econd term in the above equation, since at
m which the value of dE/dT can, a priori, be
tion

$$\frac{H'}{nF} = \frac{H}{230.5\,n}$$

' is in joules, H in large mean calories.)
ately to most commercial cells, although these
ourse, the heat of reaction used must be that
cal changes which take place in the cell.

Theorem. — Nernst, by assuming that the
nd free energy of a system not only become
o that they approach equality asymptotically
press the electromotive force (E) of a cell ex-
roperties of the substances taking place in the
ula has been tested a satisfactory agreement
nd experiment. The principles involved are
are fully discussed in Nernst's *Silliman Lec-
mics to Chemistry*. See also Nernst's *Theoreti-*

commercial primary cells (*see Batteries*,
hey derive the major part of their energy from
within them. There is also a class of cells in
ped by the cells at constant temperature is de-
surroundings, i.e., cells in which $H = 0$, and,

$$E = T\frac{dE}{dT}.$$

ws that for such cells the electromotive force
temperature. Such cells are very simple of
ncentration cells. They are of considerable
int of view, and their electromotive force can
d by an application of Nernst's formula for
A pure concentration cell can be formed of any
hich the various parts tend to diffuse into each
sorption of heat, by constructing a cell in which
be it gaseous or liquid, is effected electrically.
e Blanc's *Electrochemistry*, English translation,
solutions forming a concentration cell when
nt of dilution" the general Gibbs-Helmholtz
al case is applicable.

problem of converting the energy liberated
arbon dioxide directly into electric energy ha:
The reaction, $C + O_2 = CO_2$, liberates a very
61 large calories per gram-atom of carbon con-
per cent is converted into electrical energy
gine and dynamo. The difficulties encountered
enerator are the following: (1) the velocity of
at high temperatures; (2) it is difficult to utilize
ugh the agency of a conducting medium which
k; (3) a satisfactory high-temperature electro-
in the presence of CO_2, is difficult to obtain;
rbon to form ions.

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ELECTROLYTIC DECOMPOSITION. — Faraday's laws en to determine the amount of the substances primarily liberated or dep the electrodes of any electrolytic cell, but they do not enable one to p nature of the secondary chemical actions which may take place. (S *on Secondary Reactions.*) The factors which determine what product formed in any given case are numerous. The chemical process occ the cathode is always of the nature of a reduction; at the anode, of an o these terms being used in their most general sense. It may be that trolyte, taken as a whole, undergoes no change, as is the case, for exam copper-sulphate solution when electrolyzed between copper electrode the chemical reaction at the cathode is the exact reverse of that at th Generally, however, this is not the case; different chemical prod usually formed at the two electrodes, and appear either in the form o as a solid precipitate, or remain dissolved in the electrolyte.

Decomposition Voltage of Electrolytes. — When a gradually in difference of potential is applied to the electrodes of an electrolytic trolysis does not in general begin at once but only after a certain electromotive force is reached, even though the cell has no open-circ It should be noted that this condition does not apply to the case electrodes are such that the electrolyte as a whole undergoes no cha result of electrolysis. Thus, in the electrolysis of a zinc-sulphate between zinc electrodes an exceedingly small electromotive force is to maintain a steady current through it indefinitely (assuming t centration changes at the electrodes are completely eliminated by Although, in this case, electrolysis starts at once, the electrolyte as a not decomposed, for as much zinc dissolves at the anode as is deposit cathode. If a platinum anode be substituted for the zinc anode so result of electrolysis zinc is separated at the cathode and oxygen gas is at the anode, an e.m.f. of 2.35 volts is required to start the electrolysis. if the electrolyte is an aqueous solution of sulphuric acid it requires a m voltage of 1.67 volts to liberate oxygen and hydrogen gas against smoo num electrodes. The minimum voltage necessary to decompose a co electrolytically is called its "decomposition voltage." It is influenc variety of factors and conditions which will now be considered.

Measurement of Decomposition Voltage. — Decomposition volta been experimentally determined in several ways. Certain investigat taken the value necessary to produce visible electrolysis as the criterion; others have followed the polarization at the electrodes until it became constant and assumed this value as that at which electrolysis begins. Results obtained by the so-called ammeter-voltmeter method must be accepted with caution. In this method the value of the electromotive force applied to the cell is gradually increased from zero and plotted as abscissas and the corresponding currents through the cell plotted as ordinates. The resulting curves have the general form shown in Fig. 2.

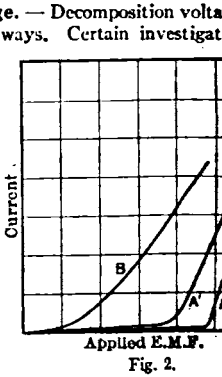


Fig. 2.

The slope of these current-voltage curves depends upon the internal resistance of the cell, the size and the distance apart of electrodes. The critical at which the current suddenly increases in value is, however, quite

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s, e.g., silver nitrate between platinum elec-
hich a metal is deposited. Below the critical
t passes through the cell and no visible decom-
parent. When the point *A* is reached, visible
ness of the bend in the curve and its course
ure upon the sensitiveness of the galvanometer
the size of electrodes and the tendency of the
o back into solution.

With a sensitive reflecting galvanometer, a steady
days without any apparent electrolysis when an
olt (far below the "decomposition voltage") is
dipping into acidulated water. It might seem
s here violated. These slight currents are to be
on of the products liberated slowly and in minute
k into the solution. Currents produced in this
currents" and play an important rôle in the
robably also in conduction in solid electrolytes.
the less sharply marked is the decomposition
l salts the current-voltage curve is of the form
e difficult to say from this curve at what voltage

entally determined decomposition voltages of
s, bases and salts.

ON VOLTAGES OF NORMAL SOLUTIONS
Text-book of Electrochemistry, p. 289.)

oltage	Solution	Voltage
	Bases:	
1.62	Ammonium hydrate....	1.74
1.66	½ n. diethylamine.....	1.68
1.29	¼ n. methylamine.....	1.75
0.52	Potassium hydrate.....	1.67
0.94	Sodium hydrate.....	1.69
1.31	⅛ n. tetramethyl	
1.69	ammonium hydrate	1.74
1.72	Salts:	
1.69	$AgNO_3$.....	0.70
0.95	$CdCl_2$.....	1.88
1.65	$Cd(NO_3)_2$.....	1.98
1.70	$CdSO_4$.....	2.03
1.57	$CoCl_2$.....	1.78
1.67	$CoSO_4$.....	1.92
1.51	$NiCl_2$.....	1.85
	$NiSo_4$.....	2.09
	$Pb(NO_3)_2$.....	1.52
	$ZnBr_2$.....	1.80
	$ZnSO_4$.....	2.35

tion Voltage from Heat of Reaction. — If
rsible in the thermodynamic sense, then Gibbs-
e) is directly applicable. Since however the
naximum work (or free energy) is known in but

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a few instances, one usually employs Thomson's rule, which gives a fair mation in the case of most commercial processes, even though these are not strictly reversible. That is, calling H the heat of formatio compound which is decomposed from the substances which are liberate electrodes (i.e., H is the heat of the reverse reaction correspondi complete chemical actions which take place in the cell), the decon voltage is

$$E = \frac{H}{230.5\,n},$$

where n = the valency of the ion of highest valency involved in the r and H is expressed in large mean calories per gram-molecule.

Tables giving the voltages required to liberate a number of eleme radicals from various electrolytes computed by Thomson's rule fro of formation in dilute solutions are given by J. W. Richards in *Jour. lin Institute*, 1906.

Example. — In the formation of one mol of solid lead chlori metallic lead and chlorine gas 828 large mean calories are liberate valency of lead is 2; of chlorine, 1. As solid lead chloride does not electricity appreciably at ordinary temperatures, to decompose it ele cally, it must be either dissolved or fused. If a saturated solution co an excess of solid lead chloride be electrolyzed, metallic lead will be d at the cathode, chlorine gas liberated at the anode, and an equivalent of solid lead chloride will pass into solution, the net result then bei composition of solid lead chloride into its elements lead and chlorine. these conditions the decomposition voltage by Thomson's rule is

$$E = \frac{828}{230.5 \times 2} = 1.79 \text{ volts},$$

as against 1.612 volts by actual measurement.

It should be pointed out that Nernst has recently applied his new heat (*see above*) to the calculation of the e.m.f. of cells similar to the abo very satisfactory results. Thus the computed value of the e.m.f. in th case from thermal data by the formula developed by Nernst is $E = 1.59$ in excellent agreement with the observed value. See Nernst's *Th Chemistry*.

Calculation of Decomposition Voltage from Electrode Potent Le Blanc was the first to measure by means of a normal electrode th potential drop at the cathode when various salts were electrolyzed an that the cathodic drop in potential necessary to discharge a given c numerically equal to the electrode potential which would be establishe separated metal were substituted for the actual cathode. For exam deposit metallic zinc from a normal zinc-sulphate solution it is nece impress a potential from solution to electrode as measured against a hydrogen electrode of at least 0.76 volt, to overcome the natural rise of p from the zinc electrode to the solution (as measured by the normal h electrode) of this amount. See table page 460.

Before continuous electrolysis can begin, however, not only must the e.m.f. be sufficient to establish the necessary cathodic drop e_c, but in a it must also raise the anode potential to a value e_a, corresponding to t trode potential of the anion which is liberated. If, as is usually the case, different anions are present in the electrolyte that one will be liberat which can part with its negative charge with the least expenditure of i.e., at the lowest voltage. It frequently happens that e_c is establish

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here e_a is reached, in which case Le Blanc found that e_c remains constant ile the impressed voltage E (and hence e_a) is increased up to the decom-ition point. The minimum e.m.f. at which decomposition of a given trolyte begins may therefore be written $E = e_c + e_a$ where e_c and e_a the cathodic and anodic polarization values produced by that cation and ion respectively which gives up its charge most readily. In an electrolyte taining several different anions and cations all take part in the *conduction* a current through the solution, but only specific ions are effective in elec-lysis, i.e., in giving up their charges to the electrodes.

Overvoltage. — When a gas is evolved at either electrode the above ations are usually more complicated owing to the phenomenon known as over-tage. Thus in the electrolysis of an acid between polished platinum or er metal electrodes, hydrogen gas is evolved, to liberate which the cathode ential must be raised to a value in excess of that required to liberate drogen at a reversible (platinum black) electrode.

The excess of voltage which is necessary to liberate a gas at any electrode r that required to liberate the same gas against a *reversible* gas electrode is ed "overvoltage." Its value depends upon the character of the material the electrode against which the gas is set free and upon the nature of the gas. s particularly large in the case of hydrogen. In Table VI are given values the overvoltage for hydrogen as determined by Caspari when this gas is *visibly* free. The magnitude of the effect is closely related to the power of the al surface to occlude the gas in question. Thus, platinum and (to a less ent) iron absorb hydrogen readily and hence these metals exhibit slight rvoltage phenomena. Zinc and mercury, on the other hand, have little or tendency to absorb hydrogen and hence this gas is liberated with great diffi-ty against cathodes of these metals, with correspondingly high overvoltages. For discussion of overvoltage phenomenon, see Möller, *Ann. d. Physik*, 27, 566, 08; Crabtree, *Trans. Faraday Soc.*, Vol. 9, 125, 1913; Bennett and Thompson, c. *Am. Elec. Chem. Soc.*, 29, 269, 1916; MacInnes, *Am. Chem. J.* XLI, 194, 09.

TABLE VI. — OVERVOLTAGE OF HYDROGEN FOR VISIBLE ELECTROLYSIS.*

Electrode	Over-voltage in volts	Electrode	Over-voltage in volts
Pt, platinized	0.005	Cu.....	0.23
Au.....	0.02	Cd.....	0.48
Fe.....	0.08	Sn.....	0.53
Pt, polished.....	0.09	Pb.....	0.64
Ag.....	0.15	Zn.....	0.70
Ni.....	0.21	Hg.....	0.78

* *Zeit. für Phys. Chem.*, Vol. 30, p. 89, 1899.

Electrolytic Separation of Metals. — The reason that two or more tals can be electrolytically separated from each other by a regulation of oltage follows from the preceding discussion. Consider a solution con-ining two salts, say silver and copper nitrates, each of normal concentration. a gradually increasing e.m.f. be applied to inert electrodes dipping into this olution, electrolysis will begin when a voltage is reached sufficient to set free

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simultaneously any anions and cations present in the solution. Re
Table IV, it will be seen that copper stands 0.80 − 0.34 = 0.46 v
silver in the electrochemical series, and hence, the latter metal can be
from the solution with e.m.f. nearly half a volt less than copper. N
ions can separate until the applied e.m.f. has been increased 0.46 v
that necessary to first separate the silver. The decomposition e.m.f.
will, of course, depend on the nature and concentration of the anion
As electrolysis proceeds, the solution becomes weaker and weaker wit
to silver ions and the voltage necessary to separate them from the
increases. If the electrolysis is continued until the silver remaining i
has a concentration only 1/1,000,000 that at the start (the limit of
determinations), the change in voltage will be approximately 0.35
section above on Variation of Electrode Potentials with Concentration).
still insufficient to bring the applied e.m.f. up to a value sufficient
the copper to deposit, and hence, silver and copper may be complete
practical purposes, separated from each other.

It is to be noted that as the electrolysis proceeds and the silver is
from the solution a greater and greater percentage of the current is
by the copper. The solution in the neighborhood of the cathode
continually weaker with respect to silver ions. In a quiet electrolysis
ions at the cathode are replenished by diffusion from the interior of
trolyte. This process may be greatly accelerated by violently sti
solution, as, for example, by the use of a rapidly rotating electrode.
mits good deposits being obtained with higher current density an
reduces the time required for the separation.

Secondary Reactions. — In the preceding sections the principle
lying *primary* electrolysis have been explained. The ultimate produ
are produced at the anode and cathode are often quite different from t
ions or ionic complexes liberated by the action of the current. In ge
primary process of discharge of ions at cathode and anode is follo
secondary reaction of one of the following types:

1. The discharged ions form molecules, e.g.:

   At cathode $2\,H = H_2$ gas,
   At cathode $x\,Cu = Cu_x$ solid,
   At anode $2\,Cl = Cl_2$ gas.

   This may occur at both anode and cathode.

2. The discharged ions react with each other or break up, e.g :

   At anode $2\,OH = H_2O + \frac{1}{2}\,O_2$,
   At anode $\begin{matrix} COO \\ | \\ COO \end{matrix} = 2\,CO_2$,
   At anode $2\,CH_3COO = 2\,CO_2 + C_2H_6$.

   This is very characteristic at the anode, particularly of organic anic

3. The discharged ions react with the solvent, e.g.:

   At cathode $Na + H_2O = NaOH + \frac{1}{2}\,H_2$,
   At anode $SO_4 + H_2O = H_2SO_4 + \frac{1}{2}\,O_2$.

4. The discharged ions react with the solute, e.g.:

   At cathode $8\,H + 2\,H_2SO_4 = H_2S + 5\,H_2O$,
   At cathode $K + KAg(CN)_2 = Ag + 2\,KCN$.

5. Discharged ions react with the electrode, e.g.:

   At cathode $4\,H + PbO_2 = Pb + 2\,H_2O$,
   At anode $2\,Cl + Cu = CuCl_2$.

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Which of the above reactions is most likely to occur in any given case depends some extent upon, (a) current density; (b) temperature; (c) concentration the solution.

In general, it may be said that at the cathode a reduction takes place, while the anode oxidation (in its general sense) occurs. The intensity of these tions depends upon the electrode potential at which the reaction takes ce. This can be varied by the use of different electrode materials (thereby easing the overvoltage). The efficiency of certain secondary reactions has been found to depend upon the nature of the electrode (catalytic action). e efficacy of electrolytic reduction and oxidation in organic chemistry where e intensity of the reaction must be carefully regulated likewise rests on the ese factors.

Passivity. — A metal is said to assume the "passive" state when it comports lf towards acids like a noble metal, i.e., becomes insoluble. Iron affords a ry striking example of this phenomenon, although it is exhibited by other tals as well. Thus, if dipped in strong nitric acid, or if anodically polarized, becomes passive. Several explanations have been advanced to account for the nomenon, one being that it is due to an invisible film of oxide on the surface, d another that the surface assumes a condition in virtue of which the velocity f reaction between it and the surrounding solution is infinitely slow. For mmé of theories see *Trans. Am. Elec. Chem. Soc.*, *29*, 217, 1916.

Alternating-current Electrolysis. — The decomposition of an electrolyte, d the solution of metal electrodes by electrolysis, can be effected under certain nditions by an alternating current as well as by a direct current. The chief termining factors are the velocity with which the chemical reaction takes ce and the periodicity of the alternating current.

THEORY OF SOLUTIONS. — To understand the theory of the various nomena described above, a knowledge of the theory of solutions is necessary.

Osmotic Pressure. — The present theory is based upon Van't Hoff's thermodynamic and experimental investigations published in 1887. When a substance is brought into contact with a second substance in which it is more or less luble, it dissolves in virtue of a force (the nature of which is imperfectly derstood), which is called its "solution tension" or "solution pressure." If the solute is present in excess, the process of solution continues until the lution becomes saturated, i.e., until equilibrium is established between the lute and solution, such that the solution pressure of the former is just balanced by an opposing pressure created within the solution which tends to cause the dissolved substance to separate out. This pressure is called the osmotic pressure of the solution. Under these conditions there are just as many molecules of solute passing into solution as separate out of the solution during any interval of time. A clearer conception of the osmotic pressure of a solution, as above defined, may be obtained from the following considerations.

Semi-permeable Membranes. — If a solution be placed at the bottom of a cylinder and carefully covered with a layer of pure solvent, the process of diffusion will begin at once and continue until a homogeneous dilute solution is formed. If the experiment be repeated with the single modification, that the pure solvent is separated from the solution by a piston consisting of a semi-permeable diaphragm which will permit the solvent to pass freely through it in either direction, but which will not allow the solute to pass through, the process of diffusion will take place as before, provided the piston is movable. Thus the piston will be forced back by the osmotic pressure of the solution while the solvent passes freely through it thereby diluting the solution. Membranes possessing the property of semi-permeability are not only theoretically con-

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ceivable but may actually be prepared. Such a membrane is forme precipitate of copper ferrocyanide deposited within the walls of an porous cell when copper sulphate and potassium ferrocyanide solu allowed to diffuse into the cell from within and without respective membrane is permeable to water, but impermeable to sugar and ma organic and inorganic substances, such as the copper and potassium s which it is formed. Most membranes, in fact, possess the property permeability to a limited degree.

Measurement of Osmotic Pressure. — To prevent the pisto forced up by the diffusing solution, a downward pressure P must be a it equal to that exerted upon it from below by the solution. The m of P is, therefore, a measure of the osmotic pressure of the solution. experimental difficulties, it is impracticable to measure osmotic pre precisely the manner just described, but by slightly modifying the arra of the apparatus it may readily be done. Thus, if the solution is con a closed vessel, A, Fig. 3, the walls of which are made semi-permeabl positing a membrane of copper ferrocyanide within the pores of the cell, and this be immersed in the solvent B, the osmotic pressure will be exerted as before against the membrane from within. If the latter could stretch like a rubber balloon, it would do so as the solution became diluted; being, however, restrained by the material of the walls of the cell on and in which it is deposited from doing this, dilution of the solution can take place only by the solvent passing through the fixed membrane into the solution cell. This it will do unless the cell A is hermetically sealed. If an open manometer M of small bore be inserted in the top of A, the solvent as it passes into the cell will cause the solution to rise gradually in M until the hydrostatic pressure thus produced prevents further entrance of solvent. When equilibrium is established, the hydrostatic pressure gives a measure of the osmotic pressure of the solution then existing in the cell. As the entrance of an appreciable amount of solvent into the cell reduces the concentration of the solution, the pressure thus measured is less than that of the original solution; hence for quantitative work an open mano replaced by a closed mercury manometer.

Laws of Osmotic Pressure in Non-electrolytic Solutions. — By ratus similar in principle to that just described the following laws ha verified. They hold for dilute aqueous solutions of many organic sul such as sugar, and for many solutions in organic solvents, all of which po common property of being non-electrolytes.

1. The osmotic pressure of a solution is directly proportional to its tration (and therefore inversely proportional to the volume in which mass of the solute is dissolved).

2. It is directly proportional to the absolute temperature.

3. It is independent of the nature of the solute, being a function the number of mols of substance dissolved in unit volume of solution.

4. The numerical magnitude of the osmotic pressure p of one mo substance dissolved in a volume v of solution at the absolute temperat identical with the gaseous pressure exerted by one mol of a perfect ga temperature T and occupying the same volume v.

The gas laws are therefore not only directly applicable to solutions, numerical value of the gas constant R is the same for each. Thus the o laws of Boyle and Gay-Lussac for gases have the same form for solutions,

$$pv = RT,$$

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re p = the osmotic pressure, v = the volume of the solution containing one l of solute, and T = the absolute temperature.

The accompanying le gives the numeri- value of $\overline{R}$ when the ious quantities are ex- ssed in the units des- ated. In heat units

$$\overline{R} = 1.985 \frac{\text{calories}}{\text{deg. cent.}}.$$

Abs. pressure p	Volume v	Abs. temp. T	Gas constant $\overline{R}$
Atmospheres	Liters	Deg. cent.	0.0821
Grams per sq. cm.	Cu. cm.	Deg. cent.	84,800
Dynes per sq. cm.	Cu. cm.	Deg. cent.	0.83161×10^8

When applied to con- trated solutions of non-electrolytes the above laws suffer deviations analo- us to those which they exhibit when applied to highly compressed gases.

Osmotic Pressure in Electrolytic Solutions. — The first of the above laws r non-electrolytic solutions applies to electrolytic solutions only within nar- limits, while the third and fourth laws fail absolutely. The osmotic pres- e of this class of solutions is much greater than the equation $pv = \overline{R}T$ would ad one to expect. Thus, a 0.1 normal sodium chloride solution has an motic pressure 1.9 times as great as that which it should have on the basis of above formula. A potassium sulphate solution containing 0.1 gram-equiva- lent per liter has an osmotic pressure 2.3 times as great as that calculated. o bring these results within the scope of the gas-law formula, Van't Hoff mposed the empirical equation $pv = i\overline{R}T$, where i is a constant having the alue unity for non-electrolytes and a value greater than unity for electrolytes.

THE DISSOCIATION THEORY. — Arrhenius, in 1887, gave the first atisfactory explanation of the anomalous behavior of electrolytes, which show ot only abnormally high osmotic pressures, but also abnormally high boiling points and abnormally low vapor pressures and freezing points. On thermo- dynamic principles these phenomena can all be shown to be proportional to the total number of molecular complexes per unit volume and entirely independent of their chemical constitution. Abnormally high osmotic pressures may there- fore be explained on the assumption that each molecule, when dissolved, exists in a more or less dissociated condition, i.e., at any given instant there are in the solution more discrete particles or complexes than there would be if each mole- cule remained continuously intact. The ions are not supposed to be per- manently separated, but a continuous process of dissociation and combination is assumed to be going on all the time. If the further assumption be made that the dissolved substance is electrolytically active only during that fraction of time while it exists in a dissociated or ionized state, in other words, that dis- sociated molecules are alone capable of being acted upon by electric forces, the connection between electrolytes and solutions showing deviations from the gas laws is explained.

On the assumptions of this theory, sodium chloride, NaCl, in aqueous solution is partially dissociated or ionized according to the equation, $NaCl \rightleftarrows \overset{+}{Na} + \overset{-}{Cl}$, and therefore at any instant there are present in the solution not only sodium- chloride molecules, but also positively charged sodium ions and an equal number of negatively charged chlorine ions, the number of which at any instant depends upon the average fraction of a second during which the molecules are dis- sociated or "ionized." If the salt were "completely, i.e., 100 per cent ionized" there would be no molecules, as such, present in the solution, but instead twice the number of ions as there were molecules originally dissolved. Hence the osmotic pressure of such a solution would be twice as great as that calculated

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from the equation $pv = RT$; in equation $pv = iRT$, i would be equ
Again, if a given volume of solution contains one mol of potassium
K_2SO_4, which is 75 per cent ionized according to the equation
$K_2SO_4 \rightleftarrows 2K^+ + SO_4^=$, then at any instant there will be $1 - 0.75 = 0.25$ mol
molecules, 0.75 mol of $SO_4^=$ ions, and $2 \times 0.75 = 1.50$ mol of K^+ ions p
the solution, or $0.25 + 0.75 + 1.50 = 2.5$ molecular complexes for ever
sulphate dissolved; hence $i = 2.5$.

Although the nature of the ions resulting from the ionization of aci
and salts is now known to be more complicated in many cases than ass
such simple ionization reactions as the above, owing to their hydration
tion with molecules of the solvent, still the above hypothesis of Arrhe
proved the most fruitful conception which has been introduced into c
during the last thirty-five years and it remains to-day, modified in the
recent research, the best working hypothesis with which to interpret ele
phenomena in aqueous solutions. It is a natural sequel to the free io
of Clausius which in turn displaced the old chain theory of Grotthuss.

THEORY OF ELECTROLYTIC CONDUCTION. — The extern
of a current flowing through an electrolyte cannot be distinguished fr
produced by a current of the same strength conducted by a metal. T
magnetic effect of a current flowing through a helical glass tube fil
electrolyte is the same as that produced by the same current flowing
an equivalent circuit of an equal number of turns of copper wire. A
may be induced in a closed ring of electrolyte just as in a ring of metal.
Law and Joule's Law hold for conduction in electrolytes as well as in
The mechanism of the conduction in the two cases, however, is very d
as shown by the phenomena produced at the junction of two conductor
of which the conduction is metallic or "electronic" and in the other of
is electrolytic or "ionic."

Migration of Ions. — Electrical conduction, both metallic and elec
is believed to be a convection phenomenon. In the case of electroly
duction there is much evidence to indicate that the convection consist
transport of electrically charged ions through the electrolyte, both w
against the direction in which the current is assumed to flow. Simul
convection of anions and cations in opposite directions may not only
visible to the eye but their velocities may also be directly measured.
assumption that the ions are the carriers of charges, the motion of whi
stitutes the current, the "velocity of migration" can also be calculat
conductivity measurements and the experimentally determined "t
ratios" (*see below*).

Velocity of Migration. — In Table VII are given the results o
measurements of the migration velocity of various ions and also the ca
velocities, both expressed in centimeters per second and for a potential
of one volt per centimeter.

The velocities are directly proportional to the potential gradient. T
increase rapidly with the temperature. They vary but slightly with t
centration of the solution if the concentration is not too great, and fo
solutions may be regarded as practically constant.

From the table it is seen that hydrogen migrates with the maximum
Hydroxyl OH^- has the next greatest velocity. The high velocity of the h
ion explains the fact that aqueous solutions of the mineral acids are as
the best electrolytic conductors, and the high velocity of the hydro
accounts for the relatively good conductivity of the inorganic bases.

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an ion migrates under the action of a given force
hich it has to overcome in moving through the
hould be expected between it and the rate of dif-
of viscosity) of the solution. The viscosity of
uidity increases rapidly with an increase in tem-
cent per degree) and experiment shows that the
t approximately the same rate. The increased
ons with rising temperature is the cause of the
of electrolytes.

OCITIES OF MIGRATION OF IONS

Velocities in cm. per sec. per volt per cm.

ram-equivalent per liter, 18° C.		Infinite dilution, 18° C.
erved	Calculated	Calculated
026	0.0028	0.003263
....	.....	0.001802
....	.....	0.000677
....	.....	0.000669
....	.....	0.000663
....	.....	0.000639
....	.....	0.000570
....	.....	0.000562
0045	0.00049	.....
0047	0.00047	.....
0049	0.00046	.....
0039	0.00037	.....
0035	0.00029	.....

a solution is subjected to electrolysis a change in
place in the immediate vicinity of the anode and
hange takes place in the middle portion of the
mployed to prevent convection and diffusion from
the solution about the anode and cathode respect-
n current has passed for a known time.

n-equivalents of the *solute* which disappear from
ut the anode.
n-equivalents of the *solute* which disappear from
ut the cathode.
gram-equivalents of the solute which is decom-

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The ratio $n_a = c/(a+c)$ is called the transport ratio for the anion and $n_c = 1 - n_a = a/(a+c)$ is called the transport ratio for the cation. T are also frequently referred to as "Hittorf's transference numbers. given electrolyte n_a is proportional to the number of gram-equivale anions which migrate through the solution from the cathode towards and n_c to the number of gram-equivalents of the cations transporte anode towards the cathode.

On the assumption that the ions are the sole carriers of the charges t of which constitutes the electric current, the ratio of the current carr anions or cations to the total current is the same as the above tran for these ions, since the charge carried by one gram-equivalent of e constant = 96,540 coulombs.

TABLE VIII. — TRANSPORT RATIOS n_a OF ANIONS IN A SOLUTIONS AT ABOUT 18° C.

(Values in parenthesis are somewhat uncertain. From Le Blanc's *Electro*

Gram-equivalents per liter	0.01	0.05	0.2	1	2
Liters per gram-equivalent	100	20	5	1	0.5
$K\begin{Bmatrix}Cl\\Br\\I\end{Bmatrix}$, NH_4Cl	0.506	0.506	.....	.....	.....
NaBr, NaCl	0.604	0.604	.....	.....	.....
LiCl	0.670	0.680	0.697	.....	.....
KNO_3	.....	.....	0.496	0.487	0.479
$NaNO_3$	.....	.....	0.614	(0.611)	(0.608)
$AgNO_3$	0.528	0.528	0.527	0.501	0.476
$KC_2H_3O_2$	.....	.....	0.33	(0.331)	(0.332)
$NaC_2H_3O_2$	.....	.....	(0.43)	(0.425)	0.421
KOH	.....	.....	0.736	(0.740)	.....
NaOH	.....	(0.81)	(0.82)	0.825	.....
LiOH	.....	.....	0.85	(0.873)	.....
HCl	0.167	0.165	.....	.....	.....
HNO$_3$	0.170	0.170	0.170	.....	.....
½ $BaCl_2$	0.553	.....	.....	.....	.....
½ $CaCl_2$	(0.58)	(0.61)	(0.66)	0.686	(0.700)
½ $MgCl_2$	.....	(0.63)	0.68	0.709	(0.729)
½ $CdCl_2$	0.570	0.570	(0.65)	(0.72)	0.745
½ CdI_2	0.558	0.606	0.86	.....	.....
½ Ba $(NO_3)_2$ at 25°	.....	0.544	0.545	.....	.....
½ K_2CO_3	.....	(0.39)	(0.41)	0.434	0.413
½ Na_2CO_3	.....	(0.52)	(0.53)	0.548	(0.542)
½ K_2SO_4	0.505	0.512	.....	.....	.....
½ Na_2SO_4	0.610	0.624	.....	.....	.....
½ $CdSO_4$	0.616	0.635	0.672	0.746	.....
½ $MgSO_4$	0.620	0.633	(0.66)	0.74	(0.76)
½ $CuSO_4$	.....	0.625	0.657	.....	.....
½ H_2SO_4	0.176	0.175	....	.....	.....

Note. — The ½ before the various bivalent electrolytes indicates tha equivalent = ½ mol.

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able VIII contains the generally accepted values of the transport ratios for more common ions. These numbers vary but slightly with the temature. They tend to approach the value 0.5 with increasing temperature, as the temperature rises both ions of a given electrolyte tend to conduct al per cents of the current. With increasing dilution the transport ratios good electrolytes approach constant limiting values; these are practically ned in solutions whose concentration is 0.01 gram-equivalent per liter.

lation between Velocity of Migration and Transport Ratios. — On the mption that the ions are the carriers of the charges the motion of which stitutes the electric current, and on the further assumption that the moving s do not carry along with them different quantities of the solvent, the ratio the velocity u_a of the anions to the velocity u_c of the cations in any ition must be equal to the ratio of the transport ratios $n_a = c/(a+c)$ and $= a/(a+c)$ of the anions and cations respectively, i.e.,

$$\frac{u_a}{u_c} = \frac{n_a}{n_c} = \frac{c}{a}.$$

e transport ratios n_a and n_c may be determined experimentally as described ve and by the use of this relation the *relative* velocities of migration may compared with the ratio calculated from the direct determination of the ities u_a and u_c. See Washburn's *Principles of Physical Chemistry*.

Hydration or Solvation of Ions. — The above relation between the ities of migration and the transport ratios has been found to hold y approximately in a number of instances. The probable explanation this lack of agreement between theory and experiment is that the nges in concentration at the two electrodes are due not only to the migra- n velocities of the ions, but also to the fact that the ions carry along with ain molecules of the solvent, the amount of solvent carried by the anions d cations being different. This "hydration" or "solvation" of the ions has ently been proved by direct eriment (*Washburn, Zeit. für ys. Chem., Vol. 66, p. 513,*). by adding to the solution an ifferent substance upon which e electric current produces no igratory effect (e.g., sugar or ifinose). See also Lewis, J., *Am. em. Soc., Vol. 32, p. 862, 1910.*

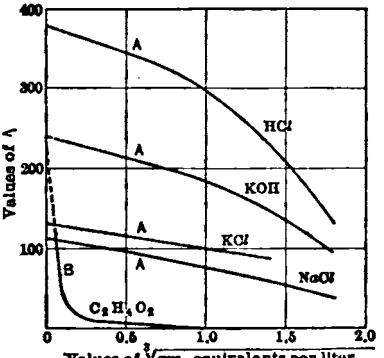


Fig. 4.

Conductance of Electrolytes. — (*See also article on Resistance and Conductance.*) While no simple relations have been found to hold between the *specific* conductances of different electrolytic solutions, very important results follow at once from a comparison of their *equivalent* conductances.

Table IX shows the relation between the equivalent conductance Λ and the concentration m in gram-equivalents per liter for some typical aqueous solutions. In Fig. 4 certain of these data are shown graphically. From a study of these results the following important conclusions may be drawn.

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TABLE IX. — EQUIVALENT CONDUCTANCE Λ OF TYPICAL TROLYTES DISSOLVED IN DIFFERENT QUANTITIES O WATER, AT 18° C.

Concentration in gm.-equivalents per liter = $m = 1000\gamma$	Dilution in liters per gm.-equivalent = $v = \phi/1000$	KCl	NaCl	KNO_3	$AgNO_3$	½ $CuSO_4$	½ H_2SO_4	HCl	CH_3COOH	KOH
0.0001	10,000	129.07	108.10	125.50	115.01	109.95	.....	(378)	107	....
0.0002	5,000	128.77	107.82	125.18	114.56	107.90	.....	(378)	80	....
0.0005	2,000	128.11	107.18	124.44	113.88	103.56	(368)	377	57	....
0.001	1,000	127.34	106.49	123.65	113.14	98.56	361	376	41	(234
0.002	500	126.31	105.55	122.60	112.07	91.94	351	375	30.2	(233
0.005	200	124.41	103.78	120.47	110.03	80.98	330	373	20.0	230
0.01	100	122.43	101.95	118.19	107.80	71.74	308	369	14.3	228
0.02	50	119.96	99.62	115.21	.....	62.40	286	366	10.4	225
0.05	20	115.75	95.71	109.86	99.50	51.16	253	358	6.48	219
0.1	10	112.03	92.02	104.79	94.33	43.85	225	351	4.60	213
0.2	5	107.96	87.73	98.74	.....	37.66	214	342	3.24	206
0.5	2	102.41	80.94	89.24	77.5	.....	205	327	2.01	197
1	1	98.27	74.35	80.46	67.6	25.77	198	301	1.32	184
2	0.5	92.6	64.8	69.4	.....	.....	183.0	254	0.80	160
3	0.33	88.3	56.5	(61.3)	.....	.....	166.8	215.0	0.54	140
5	0.2	.....	42.7	.....	.....	.....	135.0	152.2	0.285	105

Note. — The ½ before $CuSO_4$ and H_2SO_4 indicates 1 gram-equivalent = ½

For complete tables consult *Landolt and Börnstein, Kohlrausch and* and *Tables Annuelles Internationales de Constantes.*

1. The Equivalent Conductance of a Solution Increases Dilution of the Solution Increases and Approaches a Limiting M Value. — The maximum equivalent conductance, usually denoted by Λ is different for different solutions. It may be found graphically for g trolytes (giving curves of the form A, Fig. 4), by extrapolating the curv senting the observed data until it cuts the ordinate of zero concer This method fails however for weak electrolytes such as acetic acid, see C

2. Independent Migration of Ions. Ionic Mobilities. — Th uct of the equivalent conductance of any solution at infinite dilution the transport ratio of either of the ions forming the electrolyte is a for that ion and independent of the nature of the electrolyte. That is n_a and n_c the transport ratios of the anions and cations respectively, the $l_a = n_a\Lambda_\infty$ is a constant irrespective of the nature of the electrolyte this anion forms a part; similarly $l_c = n_c\Lambda_\infty$ is a constant for the cat spective of the nature of the electrolyte of which it forms a part. For e the product $n_c\Lambda_\infty$ for the potassium ion is a constant whether the sol one of potassium chloride, potassium bromide, potassium sulphate, etc. constants l_a and l_c are called the "mobilities" or "ionic conductivities ions. This relation was discovered by F. Kohlrausch in 1876 and state law of the independent migration of ions.

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r, it follows that

$\Lambda_\infty = l_a + l_c$.

nivalent conductivity of a solution (at infinite the mobilities of the anions and cations which bility of an ion depends solely upon the nature re of the substance of which it originally formed

y of any ion may be determined directly from the mobility of the ion with which it is asso-

the more common ions at 18° C. and at infinite From this table the equivalent conductance ite dilution may be readily calculated by the ilver nitrate, $AgNO_3$, at 18° C. $\Lambda_\infty = l_{Ag} + l_{NO_3}$

TYPICAL IONS AT INFINITE DILUTION AND 18° C.

the formula $l_t = l_{18}[1 + \alpha(t - 18) + \beta(t - 18)^2]$ (Kohlrausch)

β	Cations	l_{18}	α	β
.000094	Li	33.4	0.0261	0.000142
.000067	Na	43.5	0.0245	0.000116
.....	K	64.6	0.0220	0.000075
.000052	Rb	67.5	0.0217	0.000069
.....	Cs	68.0	.....	.....
.000054	NH_4	64.0	0.0223	0.000079
.....	Tl	66.0	.....	.....
.000096	Ag	54.3	0.0231	0.000093
.....	H	315.0	0.0154	−0.000033
.....	½ Ba	55.0	0.0239	0.000106
.000047	½ Sr	51.0	.....	.....
.....	½ Ca	51.0	.....	.....
.00008	½ Mg	45.0	0.0255	0.000132
.....	½ Zn	46.0	0.0256	0.000133
.000101	½ Cd	46.0	.....	.....
.000084	½ Cu	45.0	0.0240	0.000107
.....	½ Pb	61.0	0.0244	0.000114
.000155				
.....				

ution ϕ may also be determined in the same conductivity Λ_ϕ at this dilution and the cor- and n_c, but the product $n_a\Lambda_\phi$ or $n_c\Lambda_\phi$ for ions is not independent of the nature of the

ws of Electrolytic Conduction on the Dis-

retation of the above experimental facts in the

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light of the dissociation theory is simple. On this theory, the value o
determined by three factors, any one of which, if zero, will make $\Lambda_\phi = 0$.
are:

1. The fraction of the total number of molecules in one gram-equiv
the solute which are dissociated at any instant. This fraction, called t
gree of ionization" or "ionization coefficient," is usually denoted by
subscript ϕ indicating the dilution to which it refers.

2. The average velocities with which the ions migrate while free. Let
u_a be these velocities, in centimeters per second, for the cations and
respectively, for a potential gradient of one volt per centimeter.

3. The charge carried by the ions. This is fixed, since one equivalent
of every ion carries with it $F = 96{,}540$ coulombs.

If a volume ϕ of the solution containing one gram-equiv. of the so
imagined placed between two parallel plate electrodes 1 cm. apart,
e.m.f. of one volt be applied, the quantity of electricity conducted acr
electrolyte in one second, i.e., the current, will be equal to the equivale
ductance Λ_ϕ (definition of Λ_ϕ). The current is also equal to the total q
of electricity conducted by the cations plus that conducted by the anions

$$\Lambda_\phi = \gamma_\phi F u_a + \gamma_\phi F u_c = \gamma_\phi F (u_a + u_c).$$

The experimental fact that for many electrolytes at infinite dilution
equal to the sum of two constants l_a and l_c (the mobilities of the ions
depend only on the nature of the ions, indicates that the velocity of mi
u_a or u_c of any given ion depends only upon the nature of the ion a
upon the electrolyte of which it forms a part, and that the degree of ion
at infinite dilution is the same for all such solutions; there is much evid
indicate that this is practically 100 per cent (*see below*).

Degree of Ionization. — The fact that Λ_ϕ increases with the
may be due either to the velocities u_a and u_c or to γ_ϕ increasing w
dilution, or to both causes combined; F is a constant. In concentrate
tions both the velocities and the degree of ionization undoubtedly decr
the concentration increases. For dilute solutions, however, there is consi
evidence to show that the frictional resistance opposed to the motion of t
changes but slightly with increasing dilution, and hence the values of the
tion velocities in such solutions may be regarded as nearly constant.
be assumed, and also that the *nature* of the ions remains unchanged, i.
u_c and u_a at the dilution ϕ are practically the same as at infinite d
$\phi = \infty$, then the observed increase in Λ_ϕ with the dilution must be du
increase in γ_ϕ. On these assumptions, the solute becomes more and mo
ized as the dilution increases, and at infinitely great dilution all the mole
the solute are continuously dissociated or ionized, i.e., as ϕ approaches i
γ approaches unity.

Hence for $\phi = \infty$, $\Lambda_\infty = F (u_c + u_a)$, and therefore

$$\frac{\Lambda_\phi}{\Lambda_\infty} = \frac{\gamma_\phi F (u_c + u_a)}{F (u_c + u_a)} = \gamma_\phi.$$

This relation affords the simplest way of determining the coefficient of
tion γ_ϕ of an electrolyte, namely, finding the ratio of its equivalent co
ance at dilution ϕ to its maximum conductance at infinite dilution. T
assumptions mentioned above should not be lost sight of when applyi
formula. In general, the viscosity of the solution must be corrected for
at great dilutions. See Washburn and Clark, *Jour. Am. Chem. Soc.*, 38

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e above simple formula for a number of typical
I.

OEFFICIENTS OF TYPICAL ELECTRO-
IONS COMPUTED FROM RATIO $\frac{\Lambda_\phi}{\Lambda_\infty} = \gamma_\phi$
h and Holborn's data)

HCl	KOH	½CuSO$_4$	NH$_4$OH	C$_2$H$_4$O$_2$
0.784	0.770	0.217	0.0037	0.0036
0.914	0.891	0.379	0.0139	0.0131
0.964	0.954	0.608	0.0403	0.0406
0.982	0.979	0.856	0.118	0.117

dicates that 1 gram-equivalent of $H_2SO_4 = \frac{1}{2}$ mol.

f Migration of Ions. — From a knowledge of velocity of migration may be easily computed iation theory. Thus for aqueous solutions at onization may be assumed complete, $l_c = Fu_c$ $u_a = \frac{l_a}{F}$. From Table X we have for the chlorine ion $l_{Cl} = 65.5$; therefore the velocity per centimeter with which these ions migrate $\frac{\text{cm.}}{\text{sec.}}$ and $\frac{65.5}{96,540} = 0.000677 \frac{\text{cm.}}{\text{sec.}}$ respectively. ionization must be taken into account. The tained in this way. For the relation of veloc- henomena see Nernst's *Theoretical Chemistry*.

on Degree of Ionization. — It has been on of a solution has relatively little effect on migrate, except at high concentrations. Hence nt conductance with the dilution ϕ, see *Fig. 4*, change in the degree of ionization. It can be t the ionization coefficient γ of a binary elec- ution ϕ or concentration η according to the

$$= K \quad \text{or} \quad \frac{\eta\gamma^2}{1-\gamma} = K,$$

"the equilibrium constant of the ionization ture and pressure. This formula, known as exactly only for weak electrolytes, i.e., those organic acids, and which give rise to dilution or good electrolytes, giving curves of the type A wholly satisfactory explanation for this given. *(See discussion in address by James*

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Walker, British Association Meeting, 1911. Also G. N. Lewis, Zeit. f. Chem., 70, 216, 1910.) Instead of obeying the above law, curves of the satisfy an exponential equation of the form

$$\frac{(\eta\gamma)^n}{\eta(1-\gamma)} = \text{constant},$$

in which n is a constant depending upon the electrolyte and having between 1.40 and 1.56. Other "dilution laws" have also been prop Kohlrausch, Van't Hoff, Rudolphi, Kraus, Bray, and Bates.

Effect of Temperature on Ionization. — The per cent to whic stance is ionized in solution may increase or decrease with the temp The sign and magnitude of the effect depend upon whether the io reaction is accompanied by an absorption or evolution of heat. Sul which dissociate with evolution of heat become less ionized with in temperature; substances which dissociate with absorption of heat becor ionized with rising temperature. Highly dissociated substances like chloride, hydrochloric acid, etc., belong to the former class. Water very slightly ionized belongs to the latter class. In general a variation perature from 0° to 100° C. produces a change in ionization of only a cent. Recent investigations by Noyes carried out at temperatures up to have confirmed these predictions of theory. The effect of temperatu may be computed through its effect on K by means of Van't Hoff's dynamic relation

$$\frac{d \log K}{dt} = \frac{Q}{RT^2},$$

where K is the above equilibrium constant of the ionization reaction, Q t of the corresponding reaction, R the gas constant and T the absolute te ture to which the values of K and Q refer. For derivation of this equa Nernst's *Theoretical Chemistry*.

Negative Temperature Coefficients of Electrical Conductivity. fact that certain electrolytes, e.g., a phosphoric-acid solution, may negative temperature coefficient is readily explained in terms of the relations. If the increase in the velocity of migration of the ions wit temperature is more than offset by a diminution in the average number ions, resulting from a decrease in ionization, the conductivity of the solut diminish. By combining solutions having positive and negative temp coefficients in suitable proportions, electrolytes have been prepared whi nearly a zero temperature coefficient over quite a range of temperatur following mixture, proposed by Manganini, has this property: 121 gran nite, 41 grams boracic acid, 0.06 gram potassium chloride dissolved in s water to make one liter. Its specific conductance at 18° C. is $\kappa =$ Such a solution is well adapted for a liquid resistance just as manganine adapted for resistance coils.

Conductivity of Fused Electrolytes. — In Table XII are given the conductance (κ) and the equivalent conductance (Λ) of several typica salts at their respective melting points; also for comparison the equ conductance of these salts in infinitely dilute aqueous solutions at 18° will be seen that the values of the specific conductance (κ) of the salts respective melting points are much greater than the values of the conductance of the same salts in normal aqueous solutions. On th hand, if the volume ϕ occupied by one gram-equivalent of the salts fused state is determined by specific gravity measurements and the equ conductance Λ computed ($\Lambda = \phi\kappa$), it will be seen that these values

) the maximum equivalent conductance Λ_∞ of the same salt in aqueous tions. Thus the conducting power of one equivalent of fused sodium te at 305° C. is less than when the same weight of salt is dissolved in one ure liters of water.

LE XII. — SPECIFIC AND EQUIVALENT CONDUCTANCE OF TYPICAL FUSED SALTS AT THEIR MELTING POINTS

Salt	Temperature, melting point, °C.	Specific conductance, κ	Equivalent conductance, Λ	Λ_∞ at 18° C. in aqueous solution
KNO_3	305	0.9510	42.15	105.2
NO_3	334	0.6225	33.59	126.3
NO_3	250	0.7886	30.36	95.1
NO_3	218	0.6815	29.22	116.0
NO_3	215	0.3676	18.09	109.3

lectrical conduction in fusions is wholly electrolytic it is probable that it ermined by the same three factors which determine the conductance of tions, and that the equivalent conductance may be expressed by an equa- of the general form

$$\Lambda = \gamma F (u_c + u_a).$$

yet, however, all attempts to measure the velocity with which ions migrate used salts have led to no satisfactory or conclusive results. Hittorf's transnce ratios cannot be determined as in solutions, since in a pure fused salt ncentration differences do not occur at the electrodes. Only indirect estimates the value of γ have been possible. The evidence thus far obtained, however, nts to a high rather than to a low state of ionization in molten salts. For a mé of the present status of this question see Goodwin, *Trans. Am. Electroem. Soc., 1912.*

The equivalent conductance of fused salts increases in general from 1 to 1½ r cent per degree centigrade. As the increase has been found in a number of es to be almost identical with the increase in the fluidity of one equivalent ight of the fused mass, it is probable that the velocity of migration of the ions reases in this proportion. The ionization of fused salts is certainly not a ict of temperature, as in the case of gases; there is evidence, in fact, that ionization of some fused salts may decrease with increasing temperature as does in their aqueous solutions.

THEORY OF CONTACT POTENTIALS. — In the case of liquid-liquid actions and metal-liquid junctions a satisfactory theory, based on the dissociation theory and the theory of solutions, has been worked out.

Theory of Liquid-liquid Potentials. — Nernst (*Zeit. für Phys. Chem., 4, 129, 1889*) was the first to show that in the case of electrolytes a difference potential necessarily arises between two solutions in contact which gradually nishes, until the solutions are completely mixed. The general theory, rked out by Planck (*Ann. der Physik, Vol. 40, page 561, 1890*) is complicated. leads, however, to simple formulæ in the following special cases.

Case I. — The junction is between two dilute solutions of the *same solute at different concentrations* c_1 and c_2, both ions of the solute having the valency n:

for example, c_1-HCl — c_2-HCl or c_1-$ZnSO_4$ — c_2-$ZnSO_4$. The potential tween solutions 1 and 2 is given by the equation

$$e = \frac{RT}{nF}\frac{l_c - l_a}{l_c + l_a}\log_e \frac{c_1}{c_2}$$
$$= \frac{0.000198}{n} T \frac{l_c - l_a}{l_c + l_a} \log_{10} \frac{c_1}{c_2} \text{ volts},$$

where R = the gas constant; T = absolute temperature; F = the Far 96,540 coulombs; n = valence of ions; l_c and l_a the mobilities of the and anions, respectively; and c_1 and c_2 the concentrations (or, more the corresponding osmotic pressures) of the ions in the two solutions respe

It follows from this formula that the potential at a liquid junction app zero if the electrolyte is composed of two ions which migrate with near velocities, and increases as the difference in their velocities increases. K^+ and Cl^- ions have nearly identical mobilities, and hence between any lutions of potassium chloride there exists only a very small potential dif For a concentration ratio of 10 to 1 the potential difference at 18° C. 0.0004 volt. This theory also explains why liquid-liquid potentials ar est between acids or between alkali solutions, for hydrogen and hydro possess relatively great mobilities.

Case II. — The liquid junction is between solutions of two *different* each containing two ions of the same valence n and at the *same concer* Here again the process of diffusion gives rise to potential difference solution 1 and solution 2, the value of which may be computed by the

$$e = \frac{RT}{nF}\log_e \frac{l_{c_2} + l_{a_1}}{l_{c_1} + l_{a_2}}$$
$$= \frac{0.000198\ T}{n} \log_{10} \frac{l_{c_2} + l_{a_1}}{l_{c_1} + l_{a_2}} \text{ volts},$$

where l_{c_1}, l_{a_1} and l_{c_2}, l_{a_2} are the mobilities or migration velocities of the and anions in the two solutions respectively. The above formulæ as the general formula for mixed electrolytes have been satisfactorily veri experiment.

For most recent work see *Trans. Faraday Soc. Vol. 8, p. 86, 1912.*

Theory of Metal-liquid Potentials. — By extending the concep the process of solution of solids in liquids to the case of metals, which p solution only as positively charged ions, Nernst (*Zeit. f. Phys. Chem., 1889*) developed an osmotic theory of metal-liquid potentials. This to all kinds of electrodes which are reversible in the thermodynamic se which from an experimental standpoint are non-polarizable. For a reversible electrodes Nernst has shown that the potential from metal to may be expressed by the relation

$$e = \frac{RT}{nF}\log_e \frac{P_M}{p}$$
$$= \frac{0.000198}{n} T \log_{10} \frac{P_M}{p} \text{ volts},$$

where again R is the gas constant, T the absolute temperature, n the val the metal ions, F the Faraday, p the partial osmotic pressure of the met present in the solution and P_M an integration constant characteristic fo metal, which depends upon the temperature and solvent, but is independ the nature of the solute.

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Electrolytic Solution Pressure. — The constant P_M in the above for- la is called the "electrolytic solution pressure of the metal M." Since $e = 0$ n $P_M = p$, the electrolytic solution pressure P_M is sometimes regarded as al to the osmotic pressure of the metal ions which would be just sufficient to ent the metal electrode from dissolving or passing into the ionic form, in ch case there would be no development of a potential difference at the metal- id junction due to this cause. Hence the numerical value of P_M for a given al and solvent may be considered as a measure of the tendency for the metal ssolve in the solvent, i.e., to pass from the metallic to the ionic form. Thus alkali and alkali-earth metals, which pass readily into the form of ions, e a very high electrolytic solution pressure, while the noble metals like gold, er and platinum have a very low solution pressure. From this point of view electrolytic solution pressure of a metal may be taken as a measure of its ce in the electrochemical series. The only method thus far proposed for luating the value of P_M is by computation from Nernst's formula for electrode tentials given above. The value to be assigned to e depends upon the experi- ital determination of the "absolute" difference in potential (*see next para- aph*) between the electrode and the solution with which it is in contact. At sent there is some question as to whether the actual difference of potential ween the electrode and solution may not be partially due to the phenome- of selective absorption of the ions, which is not taken into account in the e formula. For this reason the values of P_M frequently computed from measured electrode potentials are open to question. See Le Blanc's *Lehrbuch Elektrochemie, pages 230–235;* Lehfeld, *Phil. Mag. 48, 430, 1899.*

Absolute Electrode Potentials. — On the assumption that the poten- difference between a metal and a solution is zero when the surface tension the metal is a maximum and that this condition is fulfilled in "dropping ctrodes," or may be obtained in a properly adjusted Lippmann capillary ctrometer, the absolute potential rise from the solution to the mercury in the rmal calomel electrode has been found to be $e = 0.5600 + 0.0006(t - 18°\ C.)$ lt. It is in terms of this value for the normal calomel electrode that "abso- e" electrode potentials have been expressed. On account of the uncertainty taching to the interpretation of this value it is better for the present to adopt arbitrary value zero as the potential drop at the calomel electrode.

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ELECTRODYNAMOMETERS. — (*See also Ammeters; Balan rent; Wattmeters.*) One of the most reliable and accurate laborator ments for current and power measurements, particularly a-c. measu is the electrodynamometer.

This instrument depends upon the action of one circuit carrying upon another carrying the same current (*see Electricity and Magnetis ciples of*). The working parts of the instrument consist of two coils, and the other movable.

SIEMENS ELECTRODYNAMOMETER. — The simplest form o dynamometer is that devised by Siemens, shown diagrammatically i The coils are arranged at right angles to one another as shown, the he representing the fixed coil and the light lines representing the movable coil. The force of attraction or repulsion is proportional to the current in the fixed coil times the current in the moving coil, and consequently if the same current flows in the two coils, the deflection is proportional to the *square* of the current. This force is balanced by the torsion of a spring. By turning the torsion head at the top of the instrument the coils are kept at right angles. The torsional force is proportional to the angle D through which the head is turned; hence the current is



Fig. 1. Dyna

$$I = K\sqrt{D},$$

where K is a constant which is obtained by sending a known current the instrument. When arranged with separate binding posts for the or fixed coil and for the potential or swinging coil, as shown in Fig. 2, th ment may be used as a wattmeter for either direct-current or alternating-current power measurements. The power in watts is then

$$P = K^2 R_1 D,$$

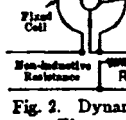


Fig. 2. Dynar Wattmet

where K has the same value as before, and R_1 is the total resistance of the potential circuit, including the coil and external resistance R. This power includes the loss in the potential circuit, which is V^2/R_1, where V is the impressed voltage; this correction is usually small.

Uses of Siemens Electrodynamometer. — The instrument may brated on direct current and may be used to measure either direct or alt current or power, since when properly designed its readings are inde of frequency and wave form. High-grade standard wattmeters suit the precise calibration of commercial indicating wattmeter or watt-hou on alternating current and non-unity power-factor circuits are made electrodynamometer principle (*see Wattmeters*).

Design of Siemens Electrodynamometer. — The movable coil is suspended by a silk thread. Attached to the coil, at the point of sus is a spiral spring, the other end of which is attached to a movabl This collar carries a pointer which moves over a scale and denotes the torsion of the spring. A second pointer is rigidly attached to the mova and registers with a fixed mark on the scale, when the fixed and mova are at right angles. The current is led in and out of the movable coil mercury cups.

Dynamometers and wattmeters for use with alternating current should little metal used in their construction as is practical, as eddy currents set up in the metal parts that will influence the coil system and change

nt of the instrument. The case and supporting frames should therefore be insulating material.

Range of Siemens Electrodynamometer. — Commercial instruments of h type for measuring currents are not suitable for measuring currents of less n 0.02 ampere. Precision wattmeters (q.v.) built on the same principle may sed to measure power of the order of 1,000,000 watts on unity power factor.

Sources of Error. — The interaction of the earth's magnetic field and the ent in the movable coil may be appreciable when the instrument is used r direct-current measurement unless the movable coil is perpendicular to the rth's field. This action may be detected by sending a direct current through e *movable coil only;* any deflection will be due to the earth's field.

When the instrument is used to measure alternating currents the earth's ld has no effect. However, eddy currents induced in the various parts of e windings or case, or in neighboring conductors, may produce a disturbing fluence. This may be tested by sending an alternating current through e *movable coil only*, the other coil being open; any deflection will be due to dy currents. The "zero" position of the pointer should also be such that ere is no mutual induction between the two coils when in the "zero" position. is can be tested by short-circuiting one coil and sending an alternating current ough the other; any deflection will be due to mutual induction.

The instrument can be used for measuring the power input to circuits of low wer factor only when the self induction of each coil and of the external so-lled "non-inductive" resistance (*see Fig. 2*) is negligible (*see Fleming, Hand-ok of the Electrical Laboratory and Testing Room*).

Degree of Precision. — When properly calibrated and properly used the adings of a good Siemens electrodynamometer may be relied upon as accurate within 1/10 per cent for a full-scale deflection. The smaller the deflection the ss the percentage accuracy.

Rowland Electrodynamometer. — This instrument is identical in principle th a Siemens electrodynamometer, except that instead of noting the angle hrough which a torsion head must be turned, the moving coil is allowed to flect and the deflection is noted by means of a telescope and scale. Its ief application is for measuring small alternating currents and small amounts f power in alternating-current circuits. It is seldom used except in special vestigations requiring a high degree of precision or for the measurement of lternating quantities of small magnitude; e.g., alternating currents of the der of 0.1 ampere or power of from 0.01 to 1 watt. Its uses are fully described Rowland's "Physical Papers," Johns Hopkins Press, Baltimore, 1902.

Irwin Astatic Electrodynamometer. — This instrument has two fixed cir-lar coaxial coils of the same diameter through which the current circulates in pposite directions, producing a field which is directed radially outward. The ovable element is suspended by a wire or silk fibre and consists of two semi-ircular coils mounted on a thin disc of mica, the current in each being in oppo-ite directions. Any effect which may be due to a non-uniform stray field is educed by the fact that the movable coils are close together.

COSTS (Pre-war prices). — A simple Siemens electrodynamometer suitable for measuring currents of from 0.025 to 5 amperes costs about $75. A Rowland electrodynamometer with shunt box costs about $450. An Irwin astatic gal-vanometer costs (in 1920) about $150.

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ELECTROLYSIS OF UNDERGROUND STRUCTURES.

also Electrochemical Processes, Industrial; Electrochemistry, Principles of

following discussion will be limited to the electrolysis of underground str
that is, to the corrosion of metal work in the earth, due to the action
currents from the grounded rails of electric railroads.

The track rails of electric railways practically always form part of the
circuit feeding the cars. As these rails are either laid in the ground or on
on the ground, and as the ground is a partial conductor, some of the cur
leave the rails and flow in the ground. If pipes, lead-sheathed cables
tural foundations happen to be in the ground near the railway, part of t
current from the rails will enter these underground structures and flo
them, leaving them at some other point to return to the station bus.
current is direct, the underground structure from which current leaves
the earth, becomes the anode of an electrolytic cell, the earth containing
trolyte. This anode corrodes, due to the liberation of acids from the sa
tained in the earth. Occasionally the cathode, or underground struct
which current enters from the earth, is liable to corrosion by secondary
In the case of railways using alternating current for distribution, t
currents are usually a large proportion of the total current, but t
trolytic effects are negligible. (See J. L. R. Hayden, *Trans. A.I.E.E.*,
p. 221.)

In the case of direct-current railways, it is therefore desirable to con
current to the track rails as far as practicable. This may be done b
taining the rail bonds in a high degree of efficiency and by keeping d
voltage drop in the rails by means of insulated negative feeders, as descr
G. I. Rhodes, *Trans. A.I.E.E., Vol. 26, p. 247, 1907.*

While such means will assist materially in mitigating electrolysis t
it is often necessary to take special steps to protect underground st
without relying upon the railway companies to confine their current
rails.

MINIMUM VOLTAGE TO PRODUCE ELECTROLYSIS. conduction of current through moist ground is almost entirely elect
ordinary conduction being almost negligible. Electrolytic corrosion
whenever current flows from metal into the ground, regardless of w
difference of potential may exist between different parts of the circuit.
that current may flow, however, it is in general necessary that the diffe
potential between anode and cathode exceeds the algebraic sum of the
of combination and separation of the compounds involved in the elec
process. An iron anode in a soil containing iron salts in solution will be a
when the e.m.f. is infinitesimal.

CORROSION EFFICIENCY AND PASSIVITY. — When an current is passed through an electrolyte, the mass of the anode dissolved
calculated theoretically by Faraday's law (see index). In practice this
may be exceeded, or the reverse. The term "coefficient of corrosi
"corrosion efficiency" is used to designate the ratio of the actual to th
retical mass of the anode dissolved. The corrosion efficiency is usually l
100 per cent owing to the occurrence of secondary reactions. Thus
rosion of iron, which primarily occurs by the formation of ferrous salts,
theoretically occur at the rate of 1.045 grams per ampere-hour, but in
the rate may be anywhere from zero to forty per cent more than the the
value. In the case of iron in soil, without protection, the corrosion effic
practically independent of the temperature over a range from 0° C. to
It is also independent of the kind of iron, whether wrought iron,

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machined cast iron. The efficiency is greater the lower the current density, varying from 20 to 140 per cent for a range of current densities between 5.0 and 365 milliamperes per square centimeter. It is greater with increasing moisture content up to saturation of the soil. Data on steel encased in concrete are given below, under "Protection of Steel by Concrete."

DISTRIBUTION OF EARTH CURRENTS. — The distribution of stray currents in the earth depends not only upon the resistance of the earth but also upon the resistance and distribution of the conducting structures in the earth.

Earth Resistance. — As the earth conducts electrolytically, its specific resistance can be calculated from the concentration of the salt solutions it contains. Such calculations are, however, generally useless, as, even with moderate specific conductance, the extent of the current path in the earth is so great that its resistance is very low, except near the electrodes. The effect of the electrodes is to concentrate the current streams into limited areas, thereby increasing the effective resistance of the earth. It is, therefore, obvious that the resistance of the earth depends more upon the electrode area than anything else.

The resistance of the earth is low when the electrodes consist of considerable lengths of track rails. This is particularly noticeable in the case of single phase lines, due to the skin effect and inductance of the rails. Thus J. Dalziel and J. Sayers (Inst. Civil Engineers, London, 1909) found that, on the Midland Railway, the current did not continue along the rails for any considerable length, but within a few hundred yards of the car sank gradually into the earth to re-enter the ballast at a very short distance from the power station. I. F. Parshall found that on a line eight miles long, the earth-return current was 60 per cent of the total. Probably the most exact data of this kind are those due to A. W. Copley (*Trans. A.I.E.E., Vol. 27, p. 1171, 1908*) who stated that on the New York, New Haven & Hartford Railroad, before the adoption of the three-wire system, the percentage of current in the earth was 25 per cent on the four-track sections and 60 per cent on the single-track sections.

Electrolytic Zone. — When a drop of potential occurs in a track rail, the current spreads out from it into the soil in much the same way that the leakage lines of magnetic force from a long electromagnet spread out into the air; that is, almost the entire leakage current is confined to a limited zone of the earth, the extent of this zone depending upon a complicated function of both the potential gradient and the total drop in the rails themselves. The stream lines of the current will tend to crowd into a pipe or cable sheath (on account of its low resistance) if such conductor is within this zone, but this tendency rapidly diminishes as the distance between the conductor and the rails increases. Compare with the tendency of an iron bar to become magnetized when placed in the leakage field of an electromagnet; the induced magnetization rapidly diminishes as the distance of the bar from the magnet is increased. Conductors at a comparatively short distance from the rails are, therefore, not liable to electrolysis unless the difference of potential between them and the rails is large or the leakage path of the current from the rails to the conductors is of low resistance. Thus in England, where the drop in the grounded return is limited to a total of seven volts, Messrs. Cunliffe found experimentally that the electrolytic zone is confined to within three feet of the track. The voltage drop under this rule is taken as the mean between the average and the momentary maximum values during a 15 to 30 minute period of a schedule run, at the time of maximum traffic, exclusive of exceptional occasions.

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STRUCTURES AFFECTED BY CORROSION. — Stray curr
set up corrosion of the rails, rail spikes, cross-bonds, steel columns, etc.,
which they escape into the earth, and they can set up corrosion of gas a
pipes, cable sheaths, building structures, etc., which they may enter a
in their course through the earth. The protection of the former class
ials is entirely the concern of the railroad company which originates t
currents; not so with the latter class, which is often of great concer
municipalities or public-service corporations which own them. Ele
surveys should, therefore, be made with a clear understanding of whic
property is under suspicion of danger. As a rule, electrolysis is most
tive to the grounded metal of the railroads; foreign pipes, cable shea
being affected in comparatively rare instances. Of all properties foreig
railroads, the thin sheaths of telephone cables are most susceptible to ele
corrosion.

Destruction of Concrete by Electrolysis.— Some experimenters ha
that where iron imbedded in concrete becomes an anode, not only is
corroded but the concrete also is cracked. This action is due to the
stress set up by the increase of volume which the iron suffers when it
to an oxide or salt. The current has no direct effect upon the concre
anode even when sufficiently strong to liberate chlorine from the brine
impregnate it. (C. E. Magnusson, *Trans. A.I.E.E., June, 1911.*)
cathode, however, the concrete becomes softened and loses its bond
electrode. See papers by E. B. Rosa, B. McCallum and A. S. Pete
Assn. of Cement Users, 1912, and abstracted in *Eng. News, Vol. 68, p. 11*
No action, however, occurs on concrete through which current flows, e
the electrodes.

ELECTROLYTIC SURVEYS. — An electrolytic survey is an in
tion made to determine the condition of grounded metallic structures
soil in which they are imbedded and of their electrical conditions with the view of ascertaining what conditions tending to produce damage, may exist.

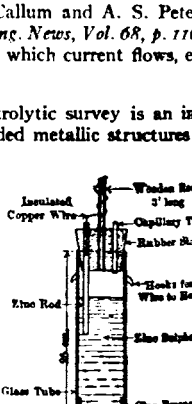


Fig. 1.

Potential Readings. — Random readings between rails and pipes give no quantitative information about electrolytic conditions. As a matter of fact, a difference of potential between a pipe and rail at any point is often greater the less the stray currents at that point. To illustrate this, we may assume a pipe to be outside the electrolytic zone and, therefore, safe from electrolytic corrosion. If, at any point, the rail is at the same potential as the pipe, the potential of the rail at every other point will differ from the pipe. Also, if the part of the rail which is at the potential of the pipe happens to be at some distance from the power
the pipe will be positive to the rail at all points between the earthe
and the power station. Hence the fact that the pipe is positive to
does not indicate that it is subject to electrolysis. A more importan
tration is the case of a pipe carrying little current itself but conne
some distant pipe which is carrying considerable current. In such a
pipe may be highly electropositive to the rails and yet be quite i
of electrolytic tendencies. These illustrations are merely specific cases

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general principle that potential readings are useless unless taken with reference to the resistance of the earth between rails and conductors, which in turn depends upon the direction and distribution of the current stream lines. The potential difference between the structure tested and earth affords more complete information than can be secured from any other practicable class of observations. For this purpose, it is necessary to use a non-polarizable electrode such as that shown in Fig. 1. The zinc sulphate paste shown therein is made by adding saturated zinc sulphate solution to the zinc sulphate crystals until the mixture has attained a semi-fluid condition. The Bureau of Standards is developing improved types of electrodes.

Measurement of Leakage Current in Grounded Return System. — The columns and foundations of elevated structures and subways, rail spikes, bare negative cables and bonds are the parts most likely to be attacked electrolytically.

In the case of the elevated railways of New York City, after about nine years' operation with the steel structure a part of the return system, it was found necessary to remove all metallic connections in the Borough of Manhattan between the track rails and structure and to install negative feeder cables to compensate for the conductivity thereby sacrificed.

The corrosion of rail spikes, while happily rare, is a matter of such grave concern to the railroads and public that it should be carefully watched for. It occurs when ties are old and water-logged or when improperly treated with preservative. Timber is ordinarily classed with the non-conductors, because, when dry and well-seasoned, it has a high dielectric strength and practically infinite resistance. When green or moist, however, it becomes an electric conductor of comparatively low resistance. The resistance along the grain is much less than across it, and porous woods, such as oak, are better conductors than the non-porous woods such as pine. The conductivity of wood is due primarily to the presence in its pores of electrolytes formed from the salts found in natural timber, from preservatives and from salts originating from coal fumes or ashes. The flow of current, from the rails and spikes into the ties, fills the pores of the wood with iron salts, which add to the electrolytic conductivity and permit the leakage of more current. The effect is, therefore, cumulative, the leakage current increasing until the pores of the wood are completely saturated with electrolyte. Cases have been known where spikes were rotted more than half way through and where the rail flanges were badly corroded. Ties creosoted by the hollow-cell process, which leaves the fibers empty, are particularly likely to acquire high electrolytic conductivity. Red oak treated with zinc chloride is also a bad tie from the electrolytic point of view.

Columns of elevated railroads, subways, passenger stations, etc., are best tested for electrolytic trouble by means of a sensitive galvanometer used in the following way. Iron clamps with pointed tips are fastened to the column at points four or five feet apart, care being taken that the points penetrate the paint and make metallic contact with the steel. Wires are run from these clamps to a galvanometer and the deflection noted. The galvanometer having been calibrated, this gives the drop of potential in the column. The cross-sectional area of the column being known, its resistance may be calculated from the known resistivity of steel (usually 11 times that of copper). The potential drop, divided by the resistance, gives the flow of current in the column. Knowing the direction of flow, its amount and the efficiency of corrosion, the actual damage being done by electrolysis may be calculated as a definite weight of metal per annum. This method is being pursued with great success on the Electric Zone of the New York Central Railroad, the galvanometer employed

being a Queen & Co.'s E-8010 with tube E-8011, a calibration resist a tripod. A deflection of one scale division is equivalent to about volt. Considering an average column with a resistance of 0.000,004 a 4-foot length, a deflection of one scale division corresponds to three-f an ampere. Where the columns are to be encased in concrete, permar ing terminals should be provided, preferably in the form of small i screwed into the steel and ending flush with the concrete.

Measurement of Leakage Current in Pipes, Cable Sheaths, etc not uncommon to find potential readings taken between different sy pipes, without regard to the location of the connections, the results being as differences of potential between those systems of pipes. The poter pipe system, however, may vary from point to point, and consequer readings have no significance unless the points between which the difference is measured are specified. The significance of potential between specific points is that they afford an indication of the potent ent normal to the tracks and thereby help to determine the electroly

Making use of all possible connections to the pipe, the potential d between these points and the anode end of the grounded system s determined as described below and the limits of the "electrolytic zone tained by noting where the potential gradient in the pipe becomes n For this purpose, water hydrants and water pipes constitute the best tion points.

Potential readings between points on the same pipe line or cable sh sometimes made the basis of potential curves showing the drop in the sheath. Such potential curves may be very significant when taken fr sheaths, but are of little use for pipes on account of the variable joint r of the latter. Thus in case of a cable sheath of uniform resistance a entire length tested, where the potential curve is flat, the sheath c current; when it is a straight sloping line, the sheath carries current giving current to or taking current from the earth; where it changes current is either entering or leaving the sheath.

Hering's Method. — The current in a pipe may also be mea the following method. (*C. Hering, Trans. A.I.E.E., June, 1912.*) damental principle is as follows. Let *P*, Fig. 2, be a part of an und pipe which has been uncovered and through which an unknown current *I* is flowing. Let *D* be a sensitive galvanometer, millivoltmeter or any other suitable form of detector; there should preferably be no variable resistance like an unbonded pipe joint between the two contact points. Let *A* be an ammeter, *B* a few battery cells and *R* an adjustable resistance; the shunt circuit containing them is c as shown, anywhere outside of the points of application of the voltage the farther away the better; they may even be on the other side of a

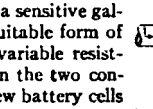


Fig. 2

To find the current flowing in the pipe adjust the resistance *R* until zero; then the current due to the battery *B* will be exactly equal and to the current in the pipe. Hence the reading of the ammeter *A* current in the pipe.

If *D* is a galvanometer with proportionate deflections, instead of a tector, then by taking a deflection immediately after the shunt circuit opened a reading proportionate to the drop of voltage for that curren obtained. The instrument *D* is thereby calibrated to read the pipe directly and can be used for this purpose thereafter; the test with th current is therefore merely of the nature of a preliminary calibration, be carried out only once for each station.

Instead of attempting to adjust the current in the shunt to bring th

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enient to use a regular measuring instrument ector, and to pass a definite current through the es, reading the two deflections of D when this this had best be repeated several times. The adings then corresponds to the current in the is that which will reduce the original deflection using the difference between a large and a small loose zero, which are so common with highly ced.

iating currents are given by Hering in the paper

oltmeter V at each of two neighboring stations, ve the pipe between them may be determined, by taking the readings of the two instruments sual or telephonic signals, preferably at times rily steady.

Leaving Pipe at Any Point. — The strength it is leaving the sheath may be determined by es the use of a temporary bond in the form of ly connected through an ammeter with both

the rails from *their* anodic center to the point ond is connected.

s" is meant the center of gravity of the leak-

tween the sheath and rail at the bonding point of the bond.

of a bond which carries I amperes. The current m the ammeter.

er the insertion of the bond will be

$$i = I \cdot \frac{k}{1-k},$$

$$k = \frac{v_1}{v} \cdot \frac{V-v}{V-v_1}.$$

ipe, without bonding, would be

$$\frac{V-v}{V-v_1}(I+i).$$

l drop in the rails to be 100 volts and the differ- ipe and the rails at the bonding point to be five d, and one volt after. Suppose the current in eres.

$$= 5. \qquad v_1 = 1. \qquad I = 50.$$

$$\frac{5}{1} = 0.19.$$

$$\frac{}{19} = 12 \text{ amperes, approximately.}$$

would be

$$12) = 50 \text{ amperes approximately.}$$

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The above formula is based upon the following assumptions:

(1) That the drop in the rails V is not affected by the insertion of t

(2) That the area over which the current from the pip or sheath e earth is short. For proof of formula, see *Elect. World, 1910, Vol. 35,*

MITIGATION OF ELECTROLYSIS.—Where stray currents are able, electrolysis may be mitigated by the use of drainage bonds, insul electric shielding.

Protection from Electrolysis by Drainage Bonds. — Bonds are useful for testing purposes; they may be applied permanently to re earth currents. There are certain effects, however, which may render inadvisable.

1. If one piping system is connected to the rails or bus, a difference of will be established between it and all other underground metallic struct it will, therefore, attract current from the latter and expose them to ele danger. A bonded piping system thus becomes a part of the trolle circuit and the owner may become a party to whatever damage may the other structures.

2. A considerable current in a gas pipe is a serious fire hazard and cable sheath is a menace to continuity of service.

3. Electrolysis is promoted at all imperfect joints and connections.

4. In the case of power cables, the sheath currents may be great enou unduly to the heating of the cables.

In spite of these objections bonds are very largely used to prote sheaths from corrosion. To be most effective, the sheath should be c to the negative bus by an insulated cable and the bus itself should be c to the track rails by insulated cables only.

Protection of Steel by Concrete. — The conductivity of concrete upon its porosity and wetness. Tests have shown that when wet the resistance may be as low as 20 or 30 ohms per yard cube and when dry, as 2000 ohms. When the potential gradient in the concrete around exceeds about 2 volts per centimeter, the temperature rises and the of iron is usually so rapid as to cause the concrete to crack open. At temperatures, the efficiency of corrosion of iron in concrete is low, b

Temperature, degrees, Centigrade	Corrosion efficiency, Per cent
10	2.0
20	2.5
30	3.0
40	3.5
50	5.0
60	11.5
70	22.5
80	37.5
90	44.5
100	47.0

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o the high current density or external causes, ecome quite high, as shown by the preceding *No. 18 of the Bureau of Standards*. For any corrosion for a given number of ampere-hours ength.

atures is due principally to the drying of the (*see Endosmose*) and to a less extent to the con- ear the cathode, where it becomes converted f the concrete. Both of these actions have the e from anode to cathode, but the effect of the ipal one while the current flows, does not last ent. (W. A. Del Mar and D. C. Woodbury, 6).

s good protection to steel work if the current essively heat the concrete.

concrete if there is the slightest probability of the addition of even a fraction of one per cent e the rate of corrosion a hundred fold.

at. — Experiments by M. Toch, C. E. Magnus- ave shown that unpainted steel imbedded in corroded at the anode, but that a good in- el prevents such corrosion. Acid-proof paints as are commonly used to protect steel im- ffective. A typical paint of this kind has the coal-tar paint, 4 parts Portland cement, 3 parts

hode and ground does not exceed 5 volts the so protected, is usually less than 1 per cent.

Tape or Braid. — H. W. Fisher found that covering the lead with a weatherproof tape or compound. With such coverings the elec- ntrated in spots and thus eat through the lead ason, lead-covered cables, laid in wooden boxes eriorate rapidly under electrolytic action.

St. Louis (*Elec. World, Vol. 57, p. 1103, 1911*) perience with tape protection. Their wrought- nch, was coated with a tar and pitch mixture, to flow easily, and onto this a 4-inch paper s edges overlapping. This paper covering was ped with paper, the process being repeated until ed. Pieces of pipe thus insulated were placed istinctive conditions of electrolysis, along with fter being taken up at the end of two years the tted and almost consumed, while the insulated as when laid. Although no test has yet been e to total disintegration, it is believed that pipe ast doubled, and if this is true an expenditure e cost of the bare pipe is justified. Only service t-iron mains being less subject to corrosion and s. The tar and paper coating is very hard when ed to be handled with no more care than bare

ints. — In a number of installations, flow of es has been prevented by the use of a sufficient

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number of insulating joints. It is found that where a pipe line is laid
joint insulated, the line has such a high electrical resistance that
able current flows, although considerable potential gradient may e
earth parallel to the pipe line. Insulating joints in cable sheath
found to afford an effective means of preventing electrolysis.

Protection by Shielding. — Underground structures have been
from electrolysis by connecting to the structure an auxiliary metallic
located so as to cause the current to flow to earth from the auxiliary
The shielding conductor must be so placed as to prevent the current fr
the structure to be protected, or at least, to cause its magnitude to
reduced.

Protection by Booster. — It is often proposed to render groun
work electronegative to the rail return by means of a booster, but such
are seldom carried into execution on account of the expense they inv

A scheme adopted with success at Karlsruhe, Germany, involves th
booster which does not have to carry the main current and which is
comparatively small. At places where there is danger for gas pipes
pipes, electrodes are placed in the earth in the neighborhood of the
these electrodes are connected to the positive pole of a low-voltage ge
storage battery, while the pipe to be protected is itself connected
negative pole. In this way electric current is forced to enter the pip
earth so that anodic destruction of the pipe is impossible. The power
tion is said to be insignificant. (Geppert & Liese, *Elek., Kraftb. Bahne*
1912.)

Boosters are used to prevent the pitting of condenser tubes, especi
salt water is used for cooling. An example of such an installation
Power Station of the Long Island Railroad on the East River, New Y

BIBLIOGRAPHY. — A very complete bibliography of the sub
1908 is given in a paper by W. H. Gee, *Electrolytic Corrosion*, Jour. Inst
1908, Vol. 41, p. 425. In addition to these references and those gi
text, the following more recent papers should be consulted:

Report of the American Committee on Electrolysis, 1921. (This conta
deal of valuable information on the subject, including a description of
practice and protective legislation. It also contains a bibliography
butions which are regarded by the Committee as having permanent

Bureau of Standards Technologic Papers, 15, 18, 25, 26, 27, 28, 32,
62, 63, 72, and 75. (These papers cover almost every phase of the su

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INDINGS. — (*See also Electricity and Magnets, Lifting and Plunger; Generators; Motors;*
inding carrying an electric current forms an elec-
nagnet is also generally used for such a coil, par-
tic core, whether it is actually carrying a current
t electromagnets is in the form of a cylindrical
uch a winding is called a solenoid. This winding
n, which may be fixed rigidly to a magnetic core,
be movable, in which case the electromagnet is
t. The electromagnet may also be built upon a
movable yoke or "armature" which is attracted
established in the winding. See *Electromagnets,*

TRUCTION OF WINDINGS — The problem
r a given voltage across its terminals, will produce
ns, and which will not overheat. Usually one or
coil are also fixed by the conditions under which
following factors must be taken into account in

esign of Bobbin. — When the core is fixed, two
anized fiber are forced on at either end of the core.
h a wrapping of paper, mica or oiled linen, and is
hen the core is movable, the two end washers are
ss tube or a tube made of the same material as the
be is used the washers are sometimes made of the
a quick-acting plunger magnet a metallic bobbin,
order to avoid eddy currents; this also applies to
nt electromagnets.

ulation Between Layers; Baking. — The wire
otton, silk or asbestos wind or by a coating of
lenoids the various layers of wire are insulated
ca or oiled linen wrappings, or the entire winding
ons separated by vertical washers of insulating
nay be further insulated by dipping it into an in-
or at atmospheric pressure, after which it is either

ons are used extensively by some manufacturers,
se the layer of oxide on the wire is the only insula-
uch as this insulation cannot be destroyed by heat,
higher temperatures, which is of special value for
devices. The oxide layer will stand a potential
article on *Use of Naked Aluminum Wire in Electro-*
Elec. Wld., 1912, Vol. 60, p. 400.

inding; Watts per Square Inch. — The rise of
will depend primarily upon the average rate at
ne electric current and the amount of exposed sur-
be radiated; the temperature rise will also depend
he circulation of the air, etc. The hottest spot in
ch a higher temperature than 105° C. When the
105° C. the temperature of the external surface, as
will usually be much less (15° C. less), as will also
sured by the change of resistance method.

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As a rough approximation a solenoid winding should be so designed t
average power developed will not exceed 0.5 watt per square inch of ra
surface for an open winding, and will not exceed 0.7 watt per square
radiating surface for an iron-clad solenoid. In figuring the radiating
of an open winding, the surface of the hole through the solenoid is not ir
and the end surfaces are included only when the solenoid is short. By t
ating surface in the case of an iron-clad solenoid is meant the surface
winding which is in contact with the iron. A radiation of 0.5 watt per
inch and 0.7 watt per square inch for an open and an iron-clad winding
tively corresponds roughly to an average temperature rise of approx
60° C.; for other rates of radiation the temperature rise will be approx
proportional to the watts per square inch radiated.

For short-time service, i.e., when the solenoid is energized only for sho
vals with long intervals between the applications of power, the thermal c
of the solenoid will permit of a greater dissipation of energy in the
without overheating it.

**Space Factors; Round Versus Square Wire; Layer Versus Hap
Windings.** — By the space factor of a winding is meant the ratio of th
occupied by the conductors to the total space occupied by the conduct
insulation on the conductors and the voids between conductors. Th
factor for strips and square wires is greater than for round wires, but s
square wires are not extensively used in small sizes because of the ir
amount of insulation required for a given section of conductor, and be
the tendency of such wires to twist in winding so that they lie upon their
instead of upon their faces. However, for conductors of larger secti
No. 10 B. & S. gauge, square wire is often used.

In winding wires larger than No. 18 B. & S. it always pays to wind the
fully in smooth layers ("layer" wound), but for smaller sizes used f
solenoids (as distinguished from iron-clad solenoids) the gain in spac
does not as a rule warrant this care and the wires are wound in a mor
haphazard fashion ("haphazard" wound). For iron-clad solenoids, h
a layer winding is always used, for economy of material requires that th
ing space be kept as small as possible. The dotted curves A and B i
for haphazard windings are taken from an article by F. A. Willard (*Ele
1906, Vol. 47, p. 823*).

Round wires are sometimes so wound that the wires of one layer li
hollows between the wires of the layer underneath; the wires in this
said to be embedded. Objections to this procedure, however, are th
layer must be started from the same end and the insulation on the wires
tightly compressed and therefore is less effective; in most instances t
labor and the diminution of insulating quality offset the small gain i
factor, which seldom exceeds 3 per cent.

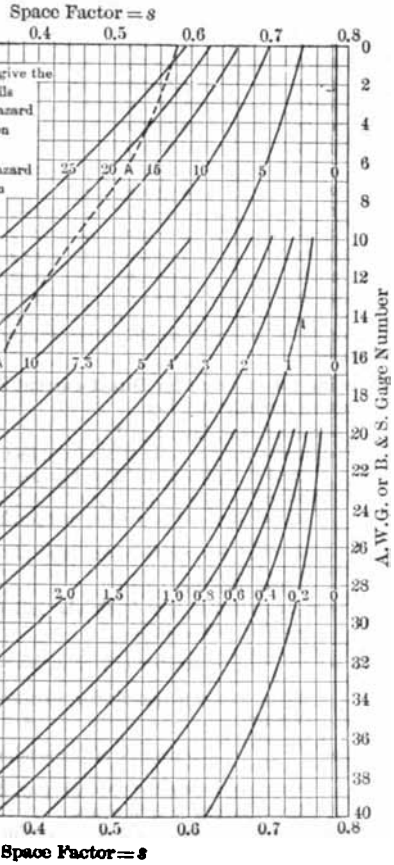
The space factor s for a layer winding of round wire without embedd
making no allowance for extra insulation between layers is

$$s = \frac{\pi}{4}\left(\frac{d}{d+2t}\right)^2,$$

where d is the diameter of the conductor and t the thickness of in
Values of s for various sizes of wire and various thickness of insulation a
by the curves in Fig. 1. The "over-all" space factor, including the al
for the space occupied by the extra insulation, if any, between layers, is
the value of s from these curves multiplied by $(1 - e)$, where e is the rat
space occupied by this extra insulation to the total winding space.

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– Magnet wire is usually referred to as "single
d "triple covered," depending upon the number
wrapped around it. Different manufacturers



Space Factor = s

. Space Factor Curves

ese layers, with the result that the thickness of
ton covered" wire of a given size or gauge num-
urer of the wire. In the following table is given
ess, taken from the catalogues of several large

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INSULATION THICKNESS IN MILS

Size of wire A.W.G. or B. & S.	Single* cotton covered	Single* silk covered	Asbestos covered (Deltabeston)	Ena cove
0000 - 00	4.5 - 7.5	.....	.....	.....
0 - 3	4.5 - 7.5	.....	18	.....
4 - 7	4.5 - 7.5	.....	16	.....
8 - 10	4.5 - 7.5	.....	14	.....
11 - 12	2.5 - 5.0	.....	12	.....
13 - 15	2.5 - 5.0	.....	10	1.5
16 - 19	2.5 - 5.0	1 - 2	10	1.1
20	2.0 - 4.0	1 - 2	10	1.1
21 - 23	2.0 - 4.0	1 - 2	.....	1.0 -
24 - 28	2.0 - 4.0	1 - 2	.....	0.8 -
29 - 33	2.0 - 4.0	1 - 2	.....	0.7 -
34 - 36	2.0 - 4.0	1 - 2	.....	0.4 -
37 - 40	2.0 - 4.0	1 - 2	.....	0.3 -

* "For double covered" multiply these thicknesses by 2, and for triple c multiply by 3.

Winding Calculations for Direct-current Solenoids. — Round solic are assumed throughout. Let

s = space factor, from Fig. 1.

k = ratio of specific resistance of conductor used to that of standa nealed copper at 20° C. For copper of 100 per cent conduc at 20° C., $k = 1$; for copper of any other per cent conductivit C per cent, at any other temperature, say t° C.,

$$k = \frac{100}{C} + 0.004\,(t - 20).$$ See also *Wires and Cables, Bar Wires, Resistor.*

A = cross section of wire in circular mils (= square of diameter in sandths of an inch).

$n = \frac{1{,}270{,}000\,s}{A}$ = number of conductors per square inch, the squar being taken perpendicular to the direction in which the w wound.

$\rho = \frac{1{,}100{,}000\,sk}{A^2}$ = resistance of the winding per cubic inch of the wi space, excluding the space, if any, occupied by extra insulatic tween layers; ρ is in ohms.

$w = 0.271\,s + 0.040$ = weight of the winding (copper and cotton insul per cubic inch of the winding space, exclusive of the space, i occupied by extra insulation between layers; w is in pounds.*

E = impressed volts.

(NI) = ampere-turns, where N is the total number of turns and I the cu in amperes.

* This formula also holds approximately for other kinds of insulation and for alloy resistance wires. Calling g_c the specific gravity of the conductor and specific gravity of the insulation, the exact formula is

$$w = 0.0362\,(g_c - g_i)\,s + 0.0284\,g_i.$$

Underhill gives g_i as 1.6 for asbestos, 1.4 for cotton, and 1.0 for silk.

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p = allowable watts per square inch of radiating surface (may be taken approximately as 0.5 for open and 0.7 for iron-clad solenoids, see above).

S = radiating surface, in square inches, calculated as described above under *Temperature Rise of Winding*.

l = mean length of turn in inches (see Fig. 2 for a simple solenoid).

T = depth of winding space in ipches (see Fig. 2), excluding the space occupied by the extra insulation, if any, between layers.

L = length of winding space in inches (see Fig. 2).

$V = LTl$ = volume of winding space in cubic inches, excluding space occupied by the extra insulation, if any, between layers.

The problem is usually to find the size of wire and necessary winding space for a coil which will give, without overheating, a required number of ampere-turns (NI) at a given impressed voltage E. The diameter of the core or spool is also usually known, or at least must not exceed certain fairly well-defined limits, depending upon the service for which it is to be used. The procedure is then to assume a reasonable value for the mean length of turn l. The size of wire is then immediately fixed by the relation

$$A = \frac{kl\,(NI)}{1.16\,E}. \tag{2}$$

From Fig. 1 the corresponding size of wire (A. W. G. or B. & S. gage) and the corresponding space factor s may then be found.

The volume V and radiating surface S of the coil must then satisfy the relation

$$\frac{LTS}{l} = \frac{k\,(NI)^2}{1{,}470{,}000\,ps}. \tag{3}$$

The length L and depth T of the winding space must be so chosen that this relation will be satisfied; as a rule this can be done only by cut and try. Note that changing the depth T of the winding space will also change the mean length of turn l, unless the diameter of the core or spool is so altered as to keep l constant. The cross section of the wire varies directly as l, as shown by equation (2), and therefore the value of the space factor s to be used in (3) will depend upon l, but only to a slight extent except in the case of very small wires.

Having determined the cross section of the wire (A), the mean length of turn l and the dimensions (L and T) of the winding space so that both (2) and (3) are satisfied, the total number of turns in the winding will be

$$N = nLT = \frac{1{,}270{,}000\,sLT}{A}, \tag{4}$$

and the current is then equal to the given number of ampere-turns divided by N and the total length of wire is equal to Nl.

The total resistance R and total weight W (including insulation) of the wire may then be found directly from a wire table, or may be calculated from the formulas

$$R = \rho V = \frac{klN}{1.16\,A} = \frac{1{,}100{,}000\,skLTl}{A^2}, \tag{5}$$

$$W = wV = (0.271\,s + 0.040)\,LTl. \tag{6}$$

See note at bottom of preceding page regarding w.

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Calculation of Open Solenoid of Circular Cross Section. — case of a coil wound on a spool of diameter D, see Fig. 2, the mean le turn is $l = \pi (D + T)$. Assuming that the outside cylindrical surface of the winding is the only radiating surface, which is only approximately true, as pointed out above, $S = \pi (D + 2T)L$. Whence, putting

$$Q = \frac{k(NI)^2}{1{,}470{,}000\ ps}, \qquad (7)$$

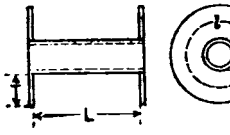


Fig. 2.

the required length of coil for a given diameter of core D and depth of w T is

$$L = \sqrt{\frac{(D+T)Q}{(D+2T)T}}.$$

When L is given instead of T, then the required depth of winding is

$$T = \frac{1}{4}\left[\left(\frac{Q}{L^2} - D\right) + \sqrt{\left(\frac{Q}{L^2} - D\right)^2 + \frac{8QD}{L^2}}\right].$$

In either case, the number of turns, total resistance, weight, etc, are fo described above for the general case.

Example. — Required to design an open solenoid 10 inches lo having an internal diameter of 1.5 inches, to give 12,000 ampere-turns volts, the heat developed not to exceed 0.5 watt per square inch of ra surface (taken as the outside cylindrical surface of the coil). Assume length of turn equal to 10 inches, then from (2) the required cross sectio wire, assuming copper at 70° C., is $A = 1130$ cir. mils. From Fig. 1 th factor is then $s = 0.62$, assuming single cotton-covered wire with 2-mil tion wound in layers. From (7) the value of Q is then $Q = 380$, when (9) the required depth of winding is $T = 2.36$ inches. The actual mean of turn is then $l = 12.1$ inches which substituted in (2) gives for the cr tion of the wire required, $A = 1368$. This wire section gives a space fac Fig. 1, of $s = 0.63$, which agrees practically with the value $s = 0.62$ used The nearest commercial size of wire is No. 19 B. & S., having a cross se 1288 cir. mils. If this size of wire is used the actual ampere-turns will b 11,300. From (4) the total number of turns will then be $N = 14{,}700$, a (5) the total resistance will be $R = 143$ ohms. The current is then amperes. The total weight of the winding is then from (6),

$$W = 60 \text{ pounds.}$$

BIBLIOGRAPHY. — Hedges, G. L., *Solenoid and Electromagnet W* A.I.E.E., Proc. 34, Nov., 1915; George and Pender, *Calculation of Electr Windings*, El. World, 65, p. 529, Feb. 27, 1915; see also *Bibliography* in on *Electromagnets, Lifting and Plunger*.

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IFTING AND PLUNGER. — (*See also ciples of; Electromagnet Windings.*) A solenoid tic core, or with a fixed core and movable "armaent means of causing an electric current to pro- This principle is utilized in various forms), contactors (*see Switches*), electric brakes, ns following are given the formulas required in inds of electromagnets in terms of their dimenso a brief statement of the applications of the

; **Leakage Factor.** — In applying the formulas that in general the effect of magnetic leakage or varies so greatly with the different forms of ble to go into this matter in detail in the limited The designer, in making an allowance for leak- previous experience with other magnets of the ons. Merely as a rough guide to the designer it may be stated that for magnets of reasonable ulas for pull given below may be relied upon to of less than ± 10 per cent, the actual pull usually pull. Under certain conditions the agreement ulated pull may be much closer than the differ-

PLUNGER. — The simplest type of electrohown in Fig. 1, consisting of a cylindrical coil of nd an iron plunger which fits into the inside of through the coil the plunger is attracted.

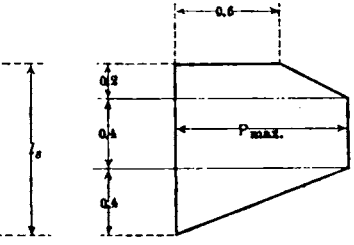


Fig. 2.

Solenoid During the Stroke. — The pull of een approximately zero when the plunger is at a maximum which is nearly constant over aplength of the coil. The maximum is reached he coil a distance of approximately 40 per cent. the coil 80 per cent of its length, the pull de-

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creases again, reaching a value of about 0.6 of the maximum pull w plunger is even with the top of the coil. The approximate pull var shown in the diagram, Fig. 2; of course the actual variation is a smoot such as shown by curve *A* in Fig. 6.

Calculation of Pull of Simple Solenoid. — The calculation of the ex of such a magnet is very complicated, being dependent not only upon the turns, but also upon the shape of the coil, the size and length of the plu the induction in same. For practical purposes the maximum pull, w plunger is at least as long as the coil, can be represented by the formul

$$P_1 = \frac{cANI}{l_0} \qquad \text{pounds,}$$

where c = the pull in pounds per square inch per ampere-turn per coil length,
A = the area of the cross-section of plunger, in square inches,
I = the current in the coil, in amperes,
N = the number of turns in the coil,
l_0 = the length of the coil, in inches.

It has been found by the author that c varies between 9×10^{-6} and 10.5 when the plunger is *magnetically saturated*. For practical purposes suf close results for a *saturated* plunger are obtained if c is taken equal t The formula shows that the maximum pull for a *saturated* plunger is proportional to the current, which makes this type of magnet especially for relays and instruments which should be very sensitive. When density in the plunger is well below the knee of the *B–H* curve, the varies almost directly as the ampere-turns, and the maximum pull, th varies approximately as the square of the ampere-turns.

The pull at any point in the stroke for a *saturated* plunger may expressed by the formula

$$P_1 = \frac{10^{-6} ANI}{l_0} \cdot k \qquad \text{pounds,}$$

where k is a factor which gives the ratio of the pull at any point of the s the maximum pull; Fig. 2 gives the approximate value of k at variou of the stroke.

IRON-CLAD ELECTROMAGNET WITH FLAT-END PLUNG

The simple solenoid is a very inefficient type of magnet, because a la centage of the reluctance of the magnetic path is found in the long air path outside the coil. Therefore, the plunger magnet is modified by putting an iron return circuit around the outside of the coil, thus reducing considerably the reluctance of the path and increasing the work which can be obtained with a certain amount of power, and with a certain expenditure of energy in the coil. Fig. 3 shows this type of "iron-clad" magnet. In its highest position the plunger strikes against the frame, so that in reality the magnet represented is a special form of magnet with stop, which is described below. If it is desired to have the pull decrease towards the end of the stroke, a hole similar to the one on the lower end is drilled in the upper end of the frame, and the permitted to protrude through it.

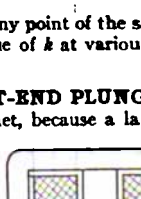


Fig. 3.

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Use of Stop to Increase Pull. — The total pull on a plunger depends on the total number of flux lines which pass through it. For a given number of ampere-turns the total number of flux lines may be increased by decreasing the reluctance of the magnetic circuit. This reluctance may be still further reduced by using a ring or stop in the upper part of the solenoid of such a length that the air-gap is central to the coil for the maximum travel which is required. This form is shown in Fig. 4.

Pull of Stop on Plunger; "Air-gap Pull." — The pull P_2 between the stop and plunger may be expressed by the formula

$$P_2 = \frac{B^2 A}{72 \times 10^6} \quad \text{pounds,} \qquad (3)$$

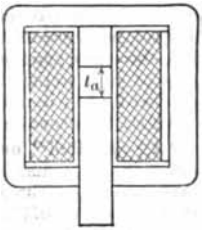


Fig. 4.

where B is the flux density in the air-gap * perpendicular to the end surface of the plunger, in lines (maxwells) per square inch, and A the area of the end of the plunger, in square inches (*see Electricity and Magnetism, Principles of*). The value of B may be calculated from the ampere-turns of the coil and the dimensions of the magnetic circuit in the same manner as the flux due to the field coils of a generator is calculated; see *Generators, Direct-current*. Or, neglecting leakage and the reluctance of the iron part of the path, B may be calculated approximately from the formula

$$B = \frac{3.19\,NI}{l_a} \quad \text{lines per sq. in.,} \qquad (4)$$

where NI is the total ampere-turns of the coil and l_a is the length of the air-gap in inches. Combining (3) and (4) gives

$$P_2 = 1.4 \times 10^{-7} A \left(\frac{NI}{l_a}\right)^2 \quad \text{pounds.} \qquad (5)$$

This pull of the stop on the plunger is usually referred to as the "air-gap pull." The actual variation of this air-gap pull with the length of the air-gap, for a particular magnet, is shown in curve *B*, Fig. 6.

Total Pull of Iron-clad Solenoid with Stop. — The total pull of the iron-clad solenoid with stop may be looked upon as due to two components, the solenoid effect P_1 given by equation (2) and the pull P_2 between stop and plunger given by equation (5); hence the total pull is

$$P = 10^{-7} ANI \left(\frac{k}{l_a} + \frac{1.4 \times 10^{-6} NI}{l_a^2}\right) \quad \text{pounds.} \qquad (6)$$

When the air-gap is short and at the center of the solenoid $k = 1$. The variation of this total pull with length of air-gap for a particular electromagnet is shown in curve *C*, Fig. 6.

IRON-CLAD SOLENOID WITH CONED PLUNGER. — It will be noted that for a given air-gap pull P_2, the ampere-turns required are directly

* Strictly, B in this formula is the actual air-gap flux density less the flux density which would be produced by the solenoid were there no iron whatever in its magnetic circuit. This correction, however, is smaller than the probable error in calculating B and may therefore be neglected.

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proportional to the length of the air-gap. If, therefore, for the same length of the path for the magnetic lines through the air-gap can be the pull for the same ampere-turns will be increased, or if the pull res stant the ampere-turns to obtain it can be decreased. This is accom coning the end of the plunger, as shown in Fig. 5. For such a magnet should not be much in excess of the plunger diameter, as the leakage considerably with longer strokes, and this defeats the object of the coning. As the induction in the iron plunger is greater than the induction in the air-gap, there is a limit to the practicable value which may be given to the cone angle; this limit is about reached for cast iron for a cone angle of 28° and for cast steel for a cone angle of 19 degrees.

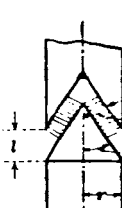


Fig. 5.

"Air-gap Pull" on Coned Plunger. — In the following it is assumed for simplicity's sake that a uniform flux at right angle to and distributed over the entire surface of the cones passes between plunger and plug. This is not strictly correct, especially for long strokes and the pull calculation is therefore only approximately correct.

Let

l = length of stroke, in inches,

A = total cross-section of plunger, in square inches, = πr^2 whe radius of the plunger, see Fig. 5,

α = angle of the cone, in degrees, see Fig. 5,

NI = total ampere-turns of coil.

Then the flux density in the plunger is

$$B_i = \frac{3.19\,NI}{l \sin^2 \alpha} \qquad \text{lines per sq. in.}$$

and the air-gap pull in the direction of the stroke is

$$P_2 = 1.4 \times 10^{-7} A \left(\frac{NI}{l \sin \alpha}\right)^2 \qquad \text{pounds.}$$

The solenoid pull, as found by experiment, is practically the same as end plunger, equation (1). Whence the total pull on the coned plunge

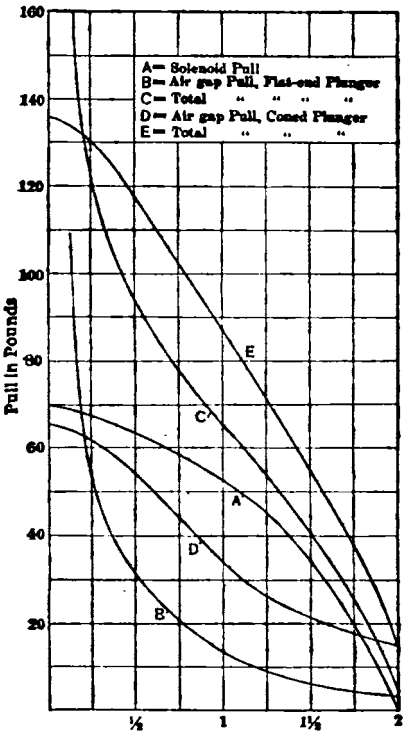
$$P = 10^{-8} ANI \left(\frac{1}{l_s} + \frac{1.4 \times 10^{-8} NI}{l^2 \sin^2 \alpha}\right) \qquad \text{pounds,}$$

where l_s is the length of the solenoid winding assuming the gap at the the solenoid ($k = 1$).

Note that $l \sin \alpha = l_a$ is the "effective" length of the air-gap, i.e., th perpendicular to the surface of the cone. Hence, comparing with equa it is seen that the pull on a coned plunger for the same effective air-g same as on a flat-end plunger, but the length of the stroke is increase ratio of $\frac{1}{\sin \alpha}$. Comparing equation (7) with equation (4), it is seen advantage is gained by increasing the flux density in the plunger square of $\frac{1}{\sin \alpha}$. For small air-gaps, therefore, the coned plunger becon rated much more quickly for the same current than does the flat-end

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the leakage and the reluctance of the iron part of the path produces an iable effect, causing the pull to become almost constant for small air- instead of increasing as shown by the approximate equation (9). This is clearly shown by the curves *D* and *E* in Fig. 6.



Pull Curves of D-C. Magnet. — Length of solenoid 3 inches; internal diameter of solenoid 1¾ inches; external diameter 2¾ inches; diameter of plunger 1¼ inches; angle of cone 20°; stop projects 1 inch inside coil; number of turns 300; current 57 amperes.

HORSESHOE-TYPE ELECTROMAGNETS. — Another type of electromagnet which is used quite extensively is the horseshoe-type electromagnet, shown in its simplest form in Fig. 7. This magnet is not suitable for very long strokes, because the leakage increases very rapidly with increasing distance between armature and poles. The total pull on the "armature" *K* of such a magnet, neglecting the leakage, may be expressed approximately by the relation

$$P = 2.8 \times 10^{-7} A \left(\frac{NI}{2 l_a + l'} \right)^2 \quad \text{pounds,} \qquad (10)$$

where A = cross-section of each pole, in square inches, NI = total ampere-turns, l_a = length of each air-gap in inches, and l' = length of air-gap equivalent to the

reluctance of the iron. This last depends on the permeability and di of the iron part of the circuit; calling l_1 the mean length of this iron ci μ its permeability, and assuming the mean cross-section of this path to be the same as the cross-section A of each pole, then $l' = l_1/\mu$. A more exact calculation of the pull may be made by calculating, as for a generator field (*see Generators, Direct-current*), the ampere-turns required to establish a given flux density of B lines per square inch in the gap, and then applying equation (3) to determine the pull.

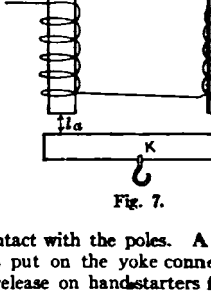


Fig. 7.

Applications of Horseshoe Type. — This type of electromagnet is frequently used where it is only desired to hold a weight after the armature has come into contact with the poles. A form of this magnet whereby the winding is put on the yoke conne two poles is used extensively as a no-voltage release on handstarters f current motors (*see Starters, Motors*).

Lifting Magnets for Handling Magnetic Materials. — Various horseshoe electromagnets are used for lifting magnetic material. F long pieces, such as pipes and rails, the magnet may be designed with a large distance between the poles, with the winding on the yoke; th usually referred to as the "bi-polar" type. For lifting shorter piece plates, slabs, billets, etc., a magnet with a relatively short distance b.e poles is better. This is readily secured by making the magnet with pole carrying the winding, with the second pole surrounding the wi central pole. Accordingly as the magnet has a rectangular or circu section it is called a "rectangular" or "concentric" magnet.

The concentric magnet is used for the greatest variety of purpos frequently referred to as a "general duty magnet." This type of especially suited for lifting pig iron, billets, skull-crackers, scrap, magnetic material of high reluctance.

In all types of lifting magnets the voids inside the coil winding a filled with impregnating material which also serves to make the magn proof.

Magnetic Disc Brakes. — A similar magnet is used for mag brakes. The magnet is usually mounted on the end plate of the moto tracts a disc-shaped armature which operates against a spring. Whe is under the influence of the spring pressure and the magnet deene presses against a series of stationary and movable discs, the latter b nected with the motor shaft, and causes friction between these par tends to retard and stop the motor. The movement of the armature disc brakes is very small, being of the order of ¼ inch.

Magnetic Clutches. — Of similar construction are magnetic In this case the magnet is mounted on the end of the shaft of the driving whereas the armature, which consists of a circular ring, mounted to means of a somewhat flexible connection, is connected with the driven When the magnet is energized the disc is attracted and takes part in tion, thereby driving the second shaft. A pair of collector rings are to convey the current from the stationary wires to the rotating magnet. case also the movement of the armature is very slight. In order to brake release quickly a non-magnetic material is often provided bet magnet and the armature which prevents sticking, due to residual mag

OF PLUNGER. — In order to obtain quick circuit, should reach its full value in as short a function of the current, the speed depends e current reaches its full value. The time s full value depends upon the quotient of the tive" resistance R of the circuit. The larger

"time constant" of the circuit (*see Transient*

he time required for the current to reach its proportional to the square of the number of inversely proportional to the total reluctance stance R depends not only upon the d-c. or it also upon the eddy currents and hysteresis nging.

urve showing the change of the current during -current magnet. It will be seen that, after ent first rises to a certain value which corre- ause a movement of the armature and lift the

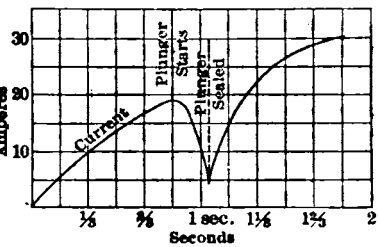


Fig. 8. Current-time Characteristics of D-C. Electromagnet

e value which is dependent upon the terminal coil.

Action. — To reduce the eddy-current effect, rame should be as small as consistent with y quick action is required it is sometimes it angles to the direction of the eddy currents mers. In such cases it is also advisable to the coil is very frequently wound and which to slot this brass tube parallel to its axis. It e the plunger.

uick action is to impress at the start a high tance into the circuit of the coil as the plunger t from overheating. This reduces the ampere- ch is permissible in most cases, because usually ery rapidly toward the end of the stroke, as is bove.

ELECTROMAGNETS. — Electromagnets may also be designed to operate on alternat- ternating-current magnet passes through zero varies with the square of the current, there- ycle, and it can be shown that it also varies

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according to a sine curve when the current is sinusoidal. The avera
ive pull is one-half of the maximum pull. Whenever the pull is
the load, there is a tendency for the plunger to move away from the
this causes rattling or humming of the magnet. This humming may
come in different ways, one method being to use a "shading coil,"
below.

Polyphase Electromagnets. — It can be shown that if three ma
used and each is supplied with current from one phase of a three-phas
or if two magnets are used and each is supplied with current from one p
two-phase source, then the resultant pull will be constant at any mom
if the plungers are rigidly connected there will then be no chatteri
most common form of three-phase magnet is shown in Fig. 9. This
of a core having three poles and a plunger of similar construction. C
pole there is wound a coil which is supplied from one of the three
the circuit. There are various modifications of the polyphase mag
their general principle is the same. In calculating the total pull, th
each pole is figured separately and the several pulls, which are equa
another, are combined vectorially, since they differ in time phase (
nating Currents).

**Calculation of Pull of Single-phase Electromagnets, or of On
of Polyphase Electromagnets.** — The formulas for pull given above f
current electromagnets also hold for alternating-current magnets, provided I is taken as the effective value of the current, B as the effective value of the flux density and P as the average or effective value of the pull.

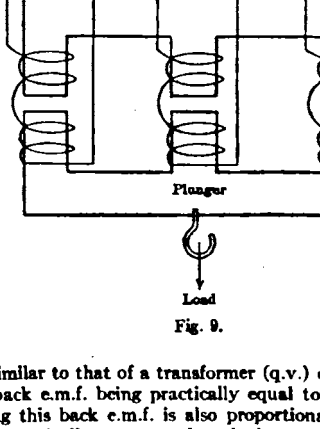


Fig. 9.

In contrast to the d-c. electromagnet, the flux in an a-c. electromagnet for a given impressed e.m.f. is approximately constant irrespective of the length of the air-gap. This is due to the fact that the opposition to the flow of current through the winding is due almost entirely to the back e.m.f., due to the alternation of the flux, and only to a very small extent to the resistance of the winding, the action in this respect being similar to that of a transformer (q.v.) tion motor (*see Motors*). The back e.m.f. being practically equal to pressed e.m.f., the flux producing this back e.m.f. is also proportion impressed e.m.f., and is therefore practically constant when the impress is constant.

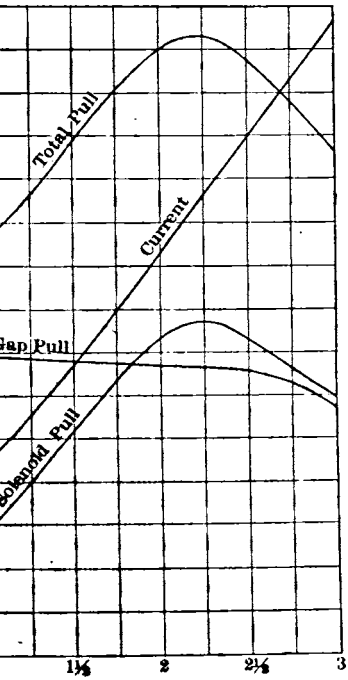
Since the flux remains practically constant, the current I, as may from equation (4), must vary approximately proportionally to the leng air-gap l_a; this proportionality holds only approximately, since equa neglects the magnetic leakage and the reluctance of the iron part of the circuit. The actual variation of the current with the length of the air-g particular a-c. electromagnet is shown in Fig. 10.

Using the same notation as used above for d-c. electromagnets and in putting E = effective value of impressed voltage per phase, and f = fr of impressed voltage in cycles per second, the current taken by each

osses, leakage and reluctance of the iron part

$$\frac{10^7 El_a}{fNA^2} \quad \text{amperes.} \qquad (11)$$

he current, taking into account the losses and ected by the method used for calculating the *nsformers*).



d Parallel to Axis of Coil, in Inches

of A-C. Magnet.—Length of solenoid 5 inches; inches; external diameter 4½ inches; diameter of s 1½ inches inside of coil; turns 144; voltage 220;

e current given by (11) in equation (6) for the t end gives the approximate formula

$$\left(\frac{kl_a}{l_e} + \frac{72E}{fNA}\right) \quad \text{pounds.} \qquad (12)$$

ned plunger, when l_a is taken equal to the length he face of the cone.

of an alternating-current magnet with flat-end

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stop and plunger. It will be noted that the current is roughly proport the air-gap. The solenoid pull reaches a maximum at an air-gap of ab inches and then falls again approximately proportional to the air-gap; gap pull is constant over a wide range of the travel. The result is a t curve which has a maximum at approximately 2¼ inches and which dro an air-gap of approximately ¾ inch is reached, and from there on it i again, due to the increase of the air-gap pull, the latter being caused diminution of the leakage flux as the air-gap decreases.

Limiting Flux Density and Losses in A-C. Electromagnets. — A must be paid to the fact that the iron losses, similar to those of the tran increase with the flux density and therefore the design must be such t flux density is not too high. The flux density in the iron in the case o end plunger, from equation (4), which neglects the magnetic leaka reluctance of the iron part of the magnetic path, is

$$B = \frac{1.6 \times 10^7 E}{fNA} \quad \text{maxwells per sq. in.}$$

and in the case of a coned plunger, under the same assumptions, from e (7), is

$$B = \frac{1.6 \times 10^7 E}{fNA \sin \alpha} \quad \text{maxwells per sq. in.}$$

where α is the cone angle, see Fig. 5.

These relations are approximate only. The magnetizing componen exciting current, and from it the flux density can be more accurately ca by the methods employed in the design of transformers or induction See *Transformers* and *Motors, Polyphase Induction*.

The iron and copper losses can also be calculated by similar methods, a these losses the energy component of the exciting current can be dete The total current and power factor of the electromagnet can then be d

Shading Coil for Single-phase Electromagnets. — The humming o phase magnets may be greatly reduced by introducing a so-called " coil" in the pole face. This shading coil is nothing more than a short-c secondary winding, consisting of one or more turns, which encloses only the total flux passing through the plunger. Due to the leakage reactance of this turn, the current induced in it is out of phase with the inducing flux, so that at the moment when the inducing flux, due to the main winding, is zero, there still remains a flux due to the current in the shading coil, which flux produces a pull. The result is that the combined pull from the main flux and the shading coil flux never becomes zero. Fig. 11 shows the arrangement of the shading coil. This coil is mounted in the plunger or in the plug close to the pole face, in order to reduce the length of the path for the magnetic lines which are interlinked with the shading coil. Naturally the shading coil has no effect with long air-gaps, and it is therefore imperative that a good magnetic contact be obtained when the plunger is in the sealed position to get the greatest possible effect of the shading coil.

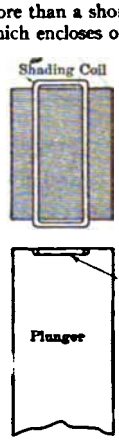


Fig. 11. Shading

Incidentally the shading coil also increases considerably the maximum pull for a given impressed e.m.f., as the maximum pull is also due to the com-

an example, a plunger magnet without shading pull of zero and a maximum pull of 28 pounds, he shading coil, a minimum pull of 18 pounds unds.

DIMENSIONS OF ELECTROMAGNETS.

the designs, it is not possible to give unit costs t of the most economical magnet design has been *A.I.E.E., 1911, Vol. 30, p. 2019*), but unfortu- ign will usually be found not to be suitable for sults in a magnet which is too long compared to y cannot be incorporated in the machine with re, magnets as they are found in practical appli- e most economical design. Also for the same sed as inch-pounds or foot-pounds) there is as pending upon the service conditions as to speed ch they have to meet. The following table of s and dimensions of some typical electro magnets e.

Total weight of active iron and copper, pounds	Length of stroke, inches	Pull at beginning of stroke, pounds	Voltage	Watts input at end of stroke	Power factor at end of stroke	Factory cost, 1914
2.9	1/8	0.15	110–500	9	....	$5.10
2.9	1/8	0.10	110–550	15	0.39	6.95
8	1	8	110–550	50	....	6 40
80	3	20	110–500	210	....	33.00
10	7/8	7	110–550	30	0.30	8.15
90	2 1/2	50	110–550	400	0.31	32 00
72	1/8	150	110–220	50	....	21.00
320	5/32	1260	110–220	210	....	39.00
82	1/8	60	110–220	52	....	19 00
210	1/4	400	110–220	115	....	35 00

erhill, C. R., *Solenoids, Electromagnets and Electro-*, Proc. A.I.E.E., April, 1914; Wikander, R., *ets*, Trans. A.I.E.E., Vol. 30, p. 2019; Thomälen, *agnet*, Electrician (London), 1918, p. 257; Schurig, *D-C Solenoids*, G. E. Rev., 1918, p. 560.

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ELECTROMETERS. — (*See also Electrodynamometers; Voltmeters.*) An electrometer is primarily an instrument for measuring differences, but under certain conditions may also be used as a watt the latter case it is usually called an electrostatic wattmeter. The of the instrument is due to the attraction or repulsion of electrostati It may be used for either direct- or alternating-current measurements

There are a great variety of forms of electrometers. On account o required in its use, the ordinary quadrant electrometer is seldom except for laboratory purposes, but various modifications of the ele provided with pointer and scale so as to be direct reading are used cially for high voltage measurements. Such instruments are known static voltmeters; for description see article on *Voltmeters*.

Electrometer versus Galvanometer or Electrodynamomete advantage of the electrometer over the galvanometer or electrodynam that it takes no current when used for constant (d-c.) voltage meas Due to its electrostatic capacity, however, it does take a certain a charge which should always be allowed for if the capacity of the ele is appreciable compared with any other capacity which affects its Also, when used for a-c. measurements, the charging current take electrometer should be allowed for, if this charging current is ap This charging current is usually considerably less than would be tak electrodynamometer of the same degree of sensitiveness.

KELVIN QUADRANT ELECTROMETER (Fig. 1). — Two br rants a and a' are connected together and two quadrants b and b nected together and these respective pairs are well insulated from one another. The "needle" n (a light aluminum vane) is suspended by a silk, silvered quartz or other fiber and insulated from the quadrants.



Fig. 1. Electro

A light aluminum vane v is suspended from the needle by a fine conducting wire and dips into a conducting solution, usually 60 per cent sulphuric acid, which serves as a means of connecting the needle to any external source of p.d. or to the ground. If a conducting suspension is used this may be employed to connect the needle to the external source of potential. The sulphuric acid also keeps the air dry in the case containing the quadrants, and the motion of the vane in the acid damps the vibrations of the needle. The suspension carries a mirror m by means of which the deflectio needle may be read.

Formulas for Quadrant Electrometer. — In order to obtain a line calibration curve the needle must be properly shaped and must pended midway (vertically) between the two quadrants and must hav metrical zero position with respect to the two quadrants. Under these c when the two pairs of quadrants are charged to potentials V_a and V_b needle to the potential V_n above any fixed potential, say that of the the angular deflection is

$$D = \frac{1}{K}(V_a - V_b)\left(V_n - \frac{V_a + V_b}{2}\right),$$

where K is a factor, which is practically a constant. The value and c of the factor K should be determined by calibration.

There are three ways of using the instrument, as indicated in the

, V the p.d. to be measured, a and b the two pairs

$$V = E \pm \sqrt{E^2 - 2KD}. \quad (\textit{See footnote.})$$

$$V = \frac{KD}{E}$$

$$V = \sqrt{2KD}.$$

ble to measurements of constant (d-c.) potentials for er- In als

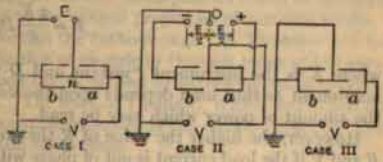


Fig. 2.

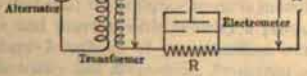
c- a en ds E en

d between the quadrants and the needle, and also l of the suspension fiber. Case III is not ap- of very low voltages. Electrometers can be pur- direct voltages as low as about 2 volts, and as lternating voltages as low as about 2 volts and as

by Use of Auxiliary Condensers (Fig. 3). — By sured across two condensers in series and measur- ne of them, the instrument may be used for the of practically any magnitude. The connections e condensers have no leakage, then

$$V = V_1 \frac{C_1 + C_2 + c}{C_2},$$

by the electrometer, C_1 and C_2 the capacities of apacity of the condenser formed by the electrom-



x- Fig. 4. Electrostatic Wattmeter

If C_1 and C_2 are large compared with c, then c ger C_1 and C_2 the greater will be the charge (and , in case of an a-c. measurement) taken by the

as Electrostatic Wattmeter (Fig. 4). — The used to measure with a fair degree of precision n E, the + sign if V is greater than E, and call the de-

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very small amounts of power, of the order of 1 watt, when the volt
this power is 5000 volts or more. It therefore serves as a very conveni
of measuring the power loss in small samples of insulating materia
voltages. See paper by E. H. Rayner, *Jour. Inst. Elec. Eng.*, 1912, V

The connections used by Rayner are shown in Fig. 4. R is a non
resistance. The needle of the electrometer is connected to the middl
the high-tension winding of the transformer. *On the assumption that*
ing current of the electrometer and the difference in phase between V and
neglected, the power supplied to the load is

$$P = \frac{2K}{R} D,$$

where K is the instrument constant and D the deflection. The ran
instrument as thus used depends upon the value of R, the higher R t
the amount of power which may be read.

However, the higher the value of R the greater the phase differenc
E and V if the load current is out of phase with V, and therefore for sm
measurements when the load has a low power factor *e.g.*, when it is a
an allowance must be made for this difference in phase angle. Also,
charging current of the electrometer is comparable in magnitude wit
current a correction must also be applied on this account. These c
are discussed in detail in Rayner's paper.

COST (Pre-war prices).—An ordinary Kelvin quadrant electromet
for measuring potentials of from 400 to 1300 volts costs approximatel

BIBLIOGRAPHY. — Laws, F. A., *Electrical Measurements;* Eric
Mesures Electrique; G. D. Aspinall Parr, *Electrical Engineering*
Instruments.

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I. — (*See also Electricity and Magnetism, Principles les of.*) The electron is the smallest known separate y. The basic assumption of the electron theory is ances contain one or more electrons. The atoms, cal condition, become positively charged by the loss *his assumption that in every body, whether charged or city of both signs distributed not continuously but as* troduced,* long before the discovery of the separate account for certain discrepancies found in applying f light to the optical properties of material media. Crookes on the cathode rays J. J. Thomson was led conduction of electricity through gases at low pres- cathode ray, is carried by extremely small particles trons. The work of Thomson, Wilson and others led the separate existence of the electron together with arge and of its mass.

tive Electron. — The results of numerous experi- assumptions regarding the electron.

a single electron is the smallest possible charge d no charge of electricity can be produced which is this charge. The value of the charge carried by a ely

$$\text{to}^{-10} \qquad \text{c.g.s electrostatic units}$$

omagnetic units). This charge is also equal to that tom in electrolysis. (There is also considerable electron *is* electricity pure and simple, having no *see below.*) .

of an electron may be defined as the force required All experiments indicate that the "effective" mass d, is approximately

$$= 8.9 \times 10^{-28} \qquad \text{grams,}$$

moving with a velocity greater than one-tenth the ies greater than one-tenth that of light the "effect- creases with increase in velocity (*see below*). The one-seventeen hundredth ($\frac{1}{1700}$) that of a hydrogen

wherever the expression "mass of an electron" is e understod that this *effective* mass is meant.

charge e and moving with velocity v produces the elementary length ds of a conduction current of (*See Electricity and Magnetism, Principles of.*)

matter contains at least one electron which is held us to elastic forces, that is, an electron may oscillate displaced by an impressed electrostatic field. The same nature irrespective of the substance in which

rced from the atom by the influence (mutual repul- noving at a high velocity in its immediate vicinity.

s of the Amsterdam Academy, 1878.

he force, a the acceleration, and $m = \frac{f}{a}$ is the "effective"

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This action is usually spoken of as a bombardment, or collision, althou not necessary to assume that the free electron actually hits the atom.

6. When an electron is expelled from an atom the atom manifests th erties of a positively charged body.

7. In every substance there exists in addition to the electrons wi atoms a certain number of "free" electrons, i.e., electrons which can mo in the inter-atomic spaces; these free electrons may also pass from stance to another. Under certain conditions, e.g., in a gas at ordina sures, a free electron may attach to itself one or more atoms or molecul

Properties of the Positive Particle. — Experiment also justifies the ing assumptions regarding the positively charged particles:

1. The smallest positive charge that it has been found possible to pr numerically equal to that of an electron, viz., 4.9×10^{-10} c.g.s. elec units.

2. The smallest possible positive charge is always associated with a having a mass of the same order of magnitude as that of an atom, th being never less than that of a hydrogen atom.

3. The positively charged particle may be looked upon as an atom fro one or more electrons have been expelled; its mass therefore depends u nature of the atom. A "free" positively charged particle may also a itself one or more neutral atoms or molecules.

Relation between Electrons and Ions. — The term "ion" is reserved to designate any charged body having a mass of the order of ma of that of a molecule or atom. In this sense an electron is not an ion, positively charged particle is an ion. If, however, the electron becomes a to an atom or molecule, then this combination forms an ion. In the cas discharge of electricity through gases at low pressure, the electron, alth is not attached to an atom or molecule, is sometimes called an ion. *Electrochemistry, Principles of.*

APPLICATIONS OF THE ELECTRON THEORY. — All of t going conclusions have received ample experimental verification. The phe which have presented the most important evidence are the cathode ra condensation of water drops on free electrons, the emission of electro metals at high temperatures, and from certain metals under the influ ultra violet light, and the properties of radio-active substances. Fr mass of evidence it is now certain that the atoms of all substances con or more electrons; that many of the common properties of matter are with the numbers and arrangements of the electrons in the atoms; t neutral atoms may lose or gain electrons and so become charged ions; t electron may be separated from an atom and its independent existence s and that in all substances there are always present a certain number of fr trons in motion among the molecules and atoms due to their mutual c in accordance with the kinetic theory of matter; it appears probable t theory governs also the motion of the free electron.

The electron theory has led to simple explanations of many of the el and optical properties of matter, and the study of the properties of elect a number of useful applications in the field of electrical engineering. S the more striking results in both fields are briefly described in the fo paragraphs.

Electron Emission from Hot Bodies (Thermionic Discharge.) *also Radio Communication.*) When a metal is heated to a high tempera a high vacuum it gives off electrons freely. This fact was first stu Richardson. Langmuir by improvements in methods of obtaining hig

uch further, clearing up many disputed questions
ctical applications of far-reaching value. The
n is subject to the temperature of the metal or
eld at its surface, as due for example to a neigh-

ccordance with the kinetic theory of matter the
in a constant state of motion, and that of those
portion escape, a few at high, the greater number
ce with Maxwell's Distribution Law. When an
metal becomes positively charged, thus putting a
and tending to make it return The distance
eater the greater its initial velocity, and in the
al or positively charged surface it may not return
he temperature of the heated metal or cathode
electrons leaving it, and the greater the volume
llowing law due to Richardson has been cor-
ners

$$i = a\sqrt{T}\epsilon^{-\frac{b}{T}},$$

ed per unit area from the cathode, T its absolute
natural system of logarithms, and a and b are
.0042 ampere at 2000° C. and 31.7 amperes at
ir. The value of the current given by the fore-
e "saturation current," and it is independent of

nperature of the cathode and the voltage of the
se the current passing, a condition is reached in
ent of the temperature and increases with the
age. The value of the current for a cylindrical
l cylinder is:

$$i = \frac{2\sqrt{2}}{9}\sqrt{\frac{e}{m}}\frac{V^{3/2}}{r},$$

ential and $\frac{e}{m}$ is the ratio of the charge to the mass

the negative field at the surface of the cathode
ive charge existing in the stream of electrons in
cathode; this is known as the "space-charge
ves back into the cathode all electrons leaving it
alance the field of the positive electrode. Thus
e potential of the anode and independent of the

tic of the thermionic tube is thus regulated by
tube. In the first region, best observed at low-
rent is low, the space-charge effect is absent, and
e initial velocities of the electrons emitted by the
ely obscured for the hotter cathodes commonly
-ampere characteristic is determined at the lower
effect. At higher voltages the third region is
n current is reached, dependent on the tempera-
oltage.
ducts in only one direction and is an excellent
ternating currents. This is the principle of the

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Fleming valve and kenotron. If a third electrode, in mesh or grid placed between the cathode and anode, very small potentials on the cause wide variations in the potential gradient at the surface of the and so cause wide changes in the value of the electron discharge. Th has proved of immense value as a relay for magnifying radio signals phonic speech, as exemplified in the audion and thermionic amplifi same principle is used in larger tubes for generating sustained oscilla rents for radio transmission, as exemplified in the pliotron. At pres rectifying and generating tubes are limited to small current capac *Radio Communication*) owing to difficulties of tube construction.

Cathode Rays. — When an electric discharge is passing in a vacu at a certain value of the pressure of the gas contained in the tube it i that a greenish phosphorescence occurs on the walls of the tube. B solid bodies in the tube it is found that the phosphorescence is due to s proceeding in straight lines perpendicularly from the surface of the catho name "cathode rays" has been given to this agent which produces t phorescence. These rays are deflected by both electric and magnetic f communicate a negative electric charge to an insulated conductor "rays" consist of a rapidly moving stream of electrons. The amou deflection of the rays, under the action of magnetic and electrostatic fi be calculated on the assumptions of the electron theory, and a comp the calculated with the observed deflections shows the two to be in clo ment.

The cathode rays give rise to X-rays when they strike a target obstacle. The use of a hot cathode with a focusing negative shield for r the velocities of emission has led to great improvements in X-ray tubes to further knowledge of the X-rays (see *X-rays*). In this way it is po obtain X-rays of single values of frequency and these by interference have led to important evidence as to the molecular structure of matter

Kanalstrahlen. — If the cathode of a tube producing cathode ray forated, faint luminous streaks are seen to proceed through these perfor a direction opposite to that of the cathode rays. The name "kanals has been given to this phenomenon (the German name is very generally in English). These rays are also deflected by both electric and magne but to a lesser extent and in relatively the opposite direction from the c of cathode rays, and communicate a *positive* charge to an insulated co

In terms of the electron theory these rays are positively charged *ion* culations from actual measurements, making this assumption, show charge carried by each of these ions is numerically equal to that of an and that the mass of each ion is never less than the mass of a hydrog but may be greater, depending upon the nature of the gas and the pr the tube. That is, the cathode particle is an electron traveling in one and the kanalstrahlen particle is what is left of the atom which has electron, traveling in the opposite direction.

Electrical and Thermal Conductivity. — One of the fundamental tions of the electron theory is that in conductors there are many electro are free to move about among the molecules besides those electron fixed positions of equilibrium. It is likely that these electrons are no the same ones; the molecules are probably continually gaining an electrons. It is reasonable to assume that the more free electrons (on age) in a body the better electrical conductor it is. According to th theory of matter, the molecules of all substances not at the absolut temperature are in a state of ceaseless agitation; if the assumption that the *free* electrons share in the motion of the molecules, then the n

al the more rapidly will kinetic energy be communi-
o neighboring ones, that is, the better conductor of

tively with the matter some assumption as to numer-
the one that has been made is that the mean kinetic
equal to the mean kinetic energy of the molecules.
on and also making one as to the relation between
er unit volume and the temperature, it has been
1. Joule's law for the production of heat in a con-
current; 2. the Wiedemann–Franz law ,which states
atio of the thermal to the electrical conductivity is
f the metal and is proportional to the absolute tem-
d Thomson effects. The theory also throws much
Hall effect.

's laws of electrolysis (*see Electrochemistry, Principles*
terms of the electron theory. It is only necessary
univalent ion in the solution is an atom from which
ed, each positive bivalent ion is an atom from which
pelled, etc., and that each negative univalent ion is
electron has attached itself, each negative bivalent
ich two electrons have attached themselves, etc.

The magnetic properties of bodies may be explained
ory by assuming that the electrons in the molecules
olve in orbits within the molecule, thus making each
ic field similar to that produced by a single turn of
rent.

Gases at or near atmospheric pressure are normally
ave an extremely high insulation resistance. How-
a fairly good conductor in a number of ways, viz.,
it, letting ultra-violet light fall upon a metal plate
t to the influence of the rays given off by radium,
a hot piece of metal or by establishing in it a brush
A gas rendered conducting in any of these ways is

eory the conductivity thus given to a gas is attributed
f the molecules of the gas into positive and negative
observed facts it is necessary to assume that, at
by barometer, the electrons and positive ions thus
molecules to themselves just as an electrified rod
ce the force of attraction is independent of the sign
vely and negatively charged particles thus produced
same manner. In gases at low pressures, however,
ion, would rarely come within attracting distance of
id collect molecules about itself a *collision* with a
duce it to its simplest form at once. A collision in
ply has the same effect but the ion very soon reforms
r of molecules in its vicinity.

ion. — The electron theory assumes that at least
charged particles or electrons with one or more
every substance. The fewer these free ions, the
rties of the substance. Under the action of an
given a velocity which depends upon their mass and
ey can travel before colliding with other molecules

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or ions. In the case of a gas the "mean free path" is relatively lar greater the less the density.

The ions present in a gas may therefore acquire, under the action of a field, a very considerable velocity. When one of these rapidly mo comes very close to a molecule of the gas it exercises a large force of on the electrons in the molecule and may thereby expel one or more from the atom. The electric field therefore causes a large increase in ber of ions present in the gas and consequently the conductivity of largely increased.

Townsend has explained spark-over in terms of this theory. So lo current is due only to the free electrons originally present and those c collision the current for a given voltage cannot continue indefinitely. the voltage is high enough to give ionizing velocities to the positive io cumulative generation of both positive ions and negative electron giving an indefinite increase of current, i.e., a spark-over.

Efforts have also been made to explain the arc, but these are not co satisfying. The hot cathode is essential for the arc, and its tempe probably due to the bombardment of the positive ions.

Theory of the Corona. — (*See also article on Corona.*) The electr strongest at the surface of a transmission wire, and stronger the sm radius. Thus with increasing voltage, ionization sets in first at the This results in conductivity of the surrounding air or gas, causing an in the effective diameter of the wire to a point where the decreasing field is just balanced by the electric strength of the air. The law o formation on a clean round wire in air is, very closely:

$$E = 33\,\delta\left(1 + \frac{0.26}{\sqrt{\delta r}}\right),$$

where E is the surface electric intensity in kilovolts per cm., δ the relativ of the air, and r the radius of the wire in cm.

Townsend has given an explanation of the above law in terms of th of ionization by collision. Corona is a spark phenomenon. The infl the radius of the conductor is satisfactorily shown, but the explanatio influence of the density of the air depends on experiments made at very pressures and is not so clear. The law of the power loss between tran lines, due to corona, has not been explained.

The above law of corona formation is obeyed with great consta accuracy when clean round wires are used. This fact, together with th form of the law has led to the suggestion of the use of corona as a s and a means of measurement of high voltage (*Whitehead*).

Optical Phenomena. — A number of otherwise obscure optical phe are satisfactorily explained in terms of the ionization theory, on the ass that in general there exist in a given molecule one or more electrical sy electrons capable of vibrating at different frequencies. In this way it is to explain the change of refractive index with the wave length, selective tion, emission and reflection, the Zeeman effect, the Faraday effect, a optical phenomena.

MASS OF THE ELECTRON. — Since to account for the various c facts noted above it is necessary to assume that a moving electron pro magnetic field (which assumption is in accord with the experimental f a moving charged body of finite dimensions produces a magnetic field), it that the total energy of motion of an electron is

$$W = \tfrac{1}{2} m_0 v^2 + W_e.$$

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presents the energy which would be required to give
it had no electric charge whatever, and W_e is the energy
d established by the motion of the charge carried by
sion may also be written

$$\tfrac{1}{2}(m_0 + m_e)v^2,$$

quantity m_0 is the ordinary or mechanical mass of
y m_e is called the "electromagnetic mass" of the
rever, is more analogous to the coefficient of self-
hanical mass, since it is part of the expression for the
l established by the moving electron.
ss of the electron is then

$$m = m_0 + m_e.$$

ive" mass that enters into all calculations of $\frac{e}{m}$ from
npossible by direct experiment to determine m_0 and
m_e can be calculated in terms of the charge e and the
assumptions are made regarding the distribution of
several different formulas have been proposed, based
regarding the distribution of the charge. All these
ndependent of the velocity, and *this constant term,*
mental error, is found to be equal to the total mass m
l determinations of the ratio $\frac{e}{m}$ *and the charge e,* pro-
lectron is less than one-tenth that of light (see next
echanical mass m_0 of the electron is negligible, within
error, compared with the electromagnetic mass m_e.
ns are the basis of the assumption, now generally
the mass of the electron is *entirely* electromagnetic
ectricity pure and simple. In fact, some physicists
lain all mass in terms of electricity. A satisfactory
ver, cannot be developed until the properties of the
e are better understood. See J. J. Thomson, *The*
ter.

ss of the Electron with Velocity. — When the
pproaches that of light both theory and experiment
nagnetic mass increases. The formula which best
acts is that deduced by Lorentz, viz.,

$$m_e = \frac{8.9 \times 10^{-28}}{\sqrt{1 - \left(\frac{v}{V}\right)^2}}$$

the electron and V the velocity of light. For $\frac{v}{V}$ less
s a value for m_e constant to within an error of 1 per
al mass of the electron (if there is such) is negligible
bove formula also represents, within the limits of
riation of the total effective mass with velocity.

Campbell, N. R., *Modern Electrical Theory*; written
ctron theory and sets forth at considerable length all
ne case. Thomson, J. J., *Conduction of Electricity*
s a mine of information on everything pertaining to
y through gases. Thomson, J. J., *Corpuscular Theory*

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of Matter; gives an account of the structure of the atom and other mat
similar nature. Rutherford, E., *Radioactivity;* detailed information o
active processes; J. T. Townsend, *Ionization of Gases by Collision;* the
statement of the theory of ionization by collision; later papers on this
by the same author; recent work in this field by Paul D. Foote and c
the publications of the National Bureau of Standards. An excellent r
the earlier work on hot cathode tubes is found in Thomson's *Conduction
tricity through Gases*. The recent work by Langmuir and associates
lished in the Physical Review, (Vol. 2, p. 450, 1913, and later numbers)
eral other prominent scientific journals. The most recent work (192c
structure of the atom and kindred topics in the electron theory is A. S
field's *Structure of the Atom*.

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RECIPITATION OF SUSPENDED PAR-

ctricity and Magnetism, Principles of.) The removal ided solid or liquid particles carried in suspension in accomplished by the application of a high potential rrent to such gases.

ion Processes embodying this principle have been ilts in a large number of installations by the Research City and by the Western Precipitation Company of

tial elements of an electrical precipitator are two sets wn as the discharge electrodes, are of such form as to rge from their surface, as for instance a wire or a light having relatively sharp edges, while the other set, des, are of such shape as to prevent as far as possible surface, as for instance, a flat plate or a pipe with a These electrodes are so arranged in the precipitator pose each other and between them a silent or glow supplying to the discharge electrode electrical energy er and at a relatively high voltage.

g electrodes are grounded for reasons of convenience m of precipitator, for example, consists of a grounded s of which is placed a wire connected to a source of direct power.

rying the suspended liquid or solid particles which are ween the discharge and collecting electrodes. During spended matter are charged and are driven away from nd over to the collecting electrodes upon which they other gases are unaffected and pass on out of the pre-

ne most effective precipitating action is obtained when etween the electrodes is sufficient to produce a glow the discharge electrodes (*see Corona*), and when the harged negatively rather than positively.

in a precipitator depends upon the size and type of he gap distance between the discharge and collecting ature and other characteristics of the gas being treated. n between the velocity of the gases through the pre- f the path between the electrodes. In other words, the e influence of the electric field for a suitable period of tisfactory removal of these particles from the gases. depends to a considerable extent upon the character pitated. If the particles are fluffy in character, light, d, a longer time will be required than if they are rela- of a liquid or sticky nature.

on to use for collecting electrodes pipes ranging from and from 6 to 15 feet in length, and gas velocities from If the collected material is liquid in nature it will f the collecting electrodes and will drop into a suitable e purpose beneath the precipitator. In such cases the ng. If the collected material is dry or at all sticky in ary to dislodge it from the collecting electrodes by lly the cleaning is accomplished by striking or rapping ates, whereupon the material falls into hoppers placed In some cases it is also necessary to clean the dis-

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charge electrodes occasionally, and when such a condition is anticipate sion is also made for rapping the framework which supports the high te discharge electrodes.

The power consumption of an electrical precipitator is governed by the of electrodes and their length, type and size, as well as by the characte the gas to be cleaned, as regards temperature, conductivity, etc. Th consumption is in no cases excessive and is usually quite small. Th consumption of energy is from 1 to 2 kilowatt-hours per 100,000 cu of gas.

Typical Installations. — The Cottrell Processes are in use for the of suspended particles from the gases given off by sintering machines, re tory furnaces, lead and copper converters and blast furnaces, drying, and calcining kilns, electric furnaces, and gas producers. They are al for cleaning the hot gases from furnaces burning pyrites or other sulphur materials in sulphuric acid manufacturing plants, and for the remova mist from the gases given off by sulphuric acid concentrators, nitratin pickling vats, etc. They have been applied also for cleaning gases f blast furnaces and the recovery from such gases of potash, manganese a valuable materials.

At Garfield, Utah, 200,000 cubic feet of gas per minute coming from converters are treated for the recovery of material containing lead bismuth, etc.

At Duluth, Minnesota, 5000 cubic feet per minute of producer gas is in a Cottrell precipitator having twenty-five collecting electrode tu 10 inches in diameter and 12 feet in length, the suspended particles of t gases being completely removed so that the gas is readily available engine use.

At the plant of the Davison Chemical Company at Baltimore, M 30,000 cubic feet of gas per minute coming from sulphuric acid concentra treated by the Cottrell processes, with the recovery of over 20 tons pe 40° Bé. sulphuric acid.

At the Washoe smelter of the Anaconda Copper Company, at An Montana, Cottrell precipitators are being installed to handle all of t going to the main smelter stack, amounting to some 3,000,000 cubic minute. The Cottrell Processes will also be used at this plant for the tion and recovery of arsenic from the flue dust recovered in the main p tion installation.

At the plant of the Security Cement and Lime Company at Hag Maryland, the gases from four cement kilns are treated, recovering mately 20 tons per day of dust containing from 8 to 10 per cent water K_2O.

At the plant of the International Smelting Company at Miami, Arizo Cottrell installations are in service collecting and recovering suspended from the gases from four Wedge roasters used as driers and from three converters.

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ICAL. — (*See also Electrochemistry, Principles of; and Heat Effects.*) An element is a substance which osed into simpler substances by any known means of ne present time about 100 elements (including the e been discovered. Recent investigations in radio- substances now regarded as stable elements may be ansformation, the rate of which is, however, too slow own means. In the case of other highly radioactive aneous transformation is relatively great; thus it has is an element resulting from the disintegration of elements formed in the process of its breaking up. able elements varies from a few minutes to many

ements always combine in definite proportions (or proportions). It is possible to assign to each element elative proportions (by mass) in which two or more ple multiples of these numbers. The minimum com- oxygen has been chosen as 16, for certain practical this standard the smallest combining weights of the ined by experiment. The numbers thus obtained are or more commonly "atomic weights." Formerly rogen was taken as unity, in which case the atomic l 15.98. On the atomic theory the atomic weight s of the atom. The values of the atomic weights of o 1921 by the International Committee on Atomic following table.

The most important relation between the atomic Mendelejeff and Lothar Meyer and is known as the es that "*the properties of the chemical elements are tomic weights.*" Thus the elements may be arranged lues of their atomic weights in groups or families in l and physical properties of the elements are related. ties of several elements have been predicted by the r discovery.

Investigations on the X-ray spectra of the elements *umbers* may be assigned to them which are of more han their atomic weights. These numbers are deter- electrons in the atom; the frequency of the lines ectrum of an element is determined by them. See , Rutherford and Harkins.

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Element	Symbol	Atomic weight	Element	Symbol	A
Aluminium	Al	27.1	Molybdenum	Mo	
Antimony	Sb	120.2	Neodymium	Nd	1
Argon	A	39.9	Neon	Ne	
Arsenic	As	74.96	Nickel	Ni	
Barium	Ba	137.37	Nitron (radium emanation)	Nt	2
Bismuth	Bi	208.0	Nitrogen	N	
Boron	B	10.9	Osmium	Os	1
Bromine	Br	79.92	Oxygen	O	
Cadmium	Cd	112.40	Palladium	Pd	1
Caesium	Cs	132.81	Phosphorus	P	
Calcium	Ca	40.07	Platinum	Pt	1
Carbon	C	12.005	Potassium	K	
Cerium	Ce	140.25	Praseodymium	Pr	1
Chlorine	Cl	35.46	Radium	Ra	2
Chromium	Cr	52.0	Rhodium	Rh	1
Cobalt	Co	58.97	Rubidium	Rb	
Columbium	Cb	93.1	Ruthenium	Ru	1
Copper	Cu	63.57	Samarium	Sa	1
Dysprosium	Dy	162.5	Scandium	Sc	
Erbium	Er	167.7	Selenium	Se	
Europium	Eu	152.0	Silicon	Si	
Fluorine	F	19.0	Silver	Ag	1
Gadolinium	Gd	157.3	Sodium	Na	
Gallium	Ga	70.1	Strontium	Sr	
Germanium	Ge	72.5	Sulphur	S	
Glucinum	Gl	9.1	Tantalum	Ta	1
Gold	Au	197.2	Tellurium	Te	1
Helium	He	4.00	Terbium	Tb	1
Holmium	Ho	163.5	Thallium	Tl	2
Hydrogen	H	1.008	Thorium	Th	2
Indium	In	114.8	Thulium	Tm	1
Iodine	I	126.92	Tin	Sn	1
Iridium	Ir	193.1	Titanium	Ti	
Iron	Fe	55.84	Tungsten	W	1
Krypton	Kr	82.92	Uranium	U	2
Lanthanum	La	139.0	Vanadium	V	
Lead	Pb	207.20	Xenon	Xe	1
Lithium	Li	6.94	Ytterbium (Neoytterbium)	Yb	1
Lutecium	Lu	175.0	Yttrium	Yt	
Magnesium	Mg	24.32	Zinc	Zn	
Manganese	Mn	54.93	Zirconium	Zr	
Mercury	Hg	200.6			

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TRIC. — (*See also Hoists; Motors, Industrial Appli-*
be divided in two general classes, freight and passen-
divided into (1) slow-speed elevators (75 feet per
uent duty elevators and (3) high-speed (250 feet per
andling elevators provided with accurate means for
date wheeled vehicles. The latter may be divided
per minute and less), which requires rapid rates of
anding; and high-speed express (600 feet per minute
smooth acceleration and efficient landing. These
s must be operated as local elevators for a few floors
nd are often of the two-speed type.

he horse-power of an elevator motor depends on the
of travel and the elevator efficiency, that is, the com-
r, the gear and the drive. It is customary to counter-
cage, and if it is under or overbalanced this amount
d from the live load to get the actual load.

$$\frac{\text{(Live load in lb.)} \times \text{(Speed of elevator in ft. per min.)}}{33{,}000 \times \text{(Efficiency)}}$$

enerally used in problems of this kind.

ttent the motors are generally rated on the basis of
r one-half hour. The starting torque should be from
rque.

ternating-current Systems are both in general use
-c. systems the induction motor, either of the squirrel-
is used. These motors may be either single-speed,
upon the kind of service.

Freight Elevators, single-speed motors of either
compound wound direct-current motor whose series
fully up to speed, or the single-speed squirrel-cage
ngle-speed slip-ring induction motor. Squirrel-cage
etimes not permitted on power systems, which lack
ally permitted up to 25 h.p.

Material-handling Elevators, which are intended
it is necessary to provide an extremely positive and
ding, and for this purpose the adjustable-speed direct-
th dynamic braking control is suited.

ssenger Elevators for 450 feet per minute and less
of about 150 feet per minute and require extremely
celeration. For this purpose the single speed, a-c. or
to about 150 feet per minute. Between 150 and 450
stable speed motor in either a-c. or d-c. is necessary.
ith direct current, the direct-coupled motor is some-
ing current the geared motor is necessary in all speeds.

Express Passenger Elevators, the direct-coupled,
d exclusively at present. This motor is direct-coupled
ns at 60 revolutions per minute. Its speed is con-
n to 45 revolutions per minute and below this by
about 15 revolutions per minute. Sometimes this
necting its armature to a multi-voltage supply system
lts.

must fulfill the most exacting service requirements

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They must insure a smooth acceleration, afford positive speed contr widely varying loads, bring the elevator quickly, but smoothly, to a from high to low speeds, regardless of load. Accurate stops at the must be made and devices should be provided to protect against sla overtravel, overloads, failure of voltage, etc. Controllers may be of magnet type, the semi-magnet type or the mechanically operated type speed passenger elevators running from about 100 to 600 feet per mi practically always installed with full-magnet controllers.

Direct-current Control Equipment. — With a direct-curren ment the car is started by moving the car switch or car-controller handl to the full on position. This releases the solenoid brake, after which t starts with full field strength and with resistance in the armature circui the motor has started, the contactors on the contactor panel automati out the dynamic brake resistance, the armature resistance and the se (if used), when the motor reaches its normal speed. Current relays current taken during the acceleration to a predetermined value. An circuit breaker is provided which opens the circuit, while running, in abnormal current would tend to flow. This overload circuit breaker is interlocked with the car switch in such a way that should the motor be by the action of the circuit breaker relay, this can be reset from the car b moving the control lever to the off position. The control equipment is arranged to give two speeds — one, a range of from rest up to the norm of the motor, secured by cutting out the armature resistance step by ste higher range, up to twice normal speed, secured by inserting resistan shunt field of the motor.

In stopping, the controller handle can be brought back to the secon giving half speed, and then to the first point, which introduces the resis series with the armature and shunts the armature with the dynam resistance which is relatively low. In this way it is possible to give a sl ing speed of about 25 per cent of the normal speed and which does not v much with the load in the car. Moving the control handle to the off stops the car. It causes the motor to be disconnected from the circui same time applying the solenoid brake, which is actuated by a spring or The coil of the dynamic brake is connected to the motor armature so t circuit is kept closed in stopping until the motor comes practically to r the braking effect of the current generated in this local circuit is avai assist the mechanical brake.

Limit switches actuated by the elevator winding drum are provided the elevator at predetermined limits of travel. In addition to these, ov switches are also ordinarily provided in the elevator hatchway as a precaution. These switches are arranged to open the control circuit travel of the car. The first-named switches are generally connected after the car has been automatically stopped at either limit of travel, it is for the operator to start the car in the reverse direction only. When th way-limit switches open, it is, however, generally impossible for the ope reverse the car without first going to the elevator machine, thus insurin tion to the cause which made it necessary for the hatchway-limit sw operate the car.

An auxiliary switch which will automatically stop the motor in case t slackens from any cause, such as the breaking of the cable or the catchin cage, is also generally provided. It is mounted on one side of the windin and operated by a cross arm extending across the drum. Should the c come slack the movement of the cross arm will serve to trip the switch, the control system and stopping the elevator. The slack-cable switch

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after having tripped out must be reset by hand thus to go to the source of trouble before the elevator can

nt Control Equipment. — As with the direct-current types of controllers made for the alternating-current re those known as the full-magnet controllers, which and controlled from a car switch in the same manner

All controllers should be protected by a relay which n the line when the phase rotation in the supply cir- her reasons, reversed.

-current motors are preferably not to be used for minute. For higher elevator speeds the two-speed vator speed corresponding to the slowest motor speed 50 or 200 feet per minute.

current control equipment generally comprises a con- one or more limit switches, a slack cable switch and a noid brake is designed to be connected directly to the the circuit to the motor is closed the solenoid is en- tracted. Upon the opening of the main-line circuit, entionally in operating the elevator or is the result is deënergized and the brake is instantly applied. ed so as to permit of a gradual rather than an instanta- to avoid jarring the car by stopping it too suddenly. omplished by a number of alternating-current con- nnected as to cut a section out of each of the three simultaneously, and also to change the pole con- rate of acceleration or retardation being governed r of time limit relays.

— In all elevators, particularly in those electrically increases in proportion to the number of starts and result of the use of the electric motor, in which the is required for the process of acceleration, the next nechanical retardation, and a lesser amount for the a small proportion devoted to the continuous exci- refore follows that in this form of elevator, which is in part of the consumption of power is directly related nd starts which result from the number of persons results which have been reported from time to time urrent by electrical elevators may therefore be attrib- conditions. The results of a series of tests made upon ne traction elevator in a ten-story building as reported ., *1910*) are given in the table on the following page.

OR ELECTRIC ELEVATORS. — The following o assist in writing specifications. See also article on

elevator is to be situated. Purpose, i.e., whether for ice. Characteristics of current supply. Length of . Full running speed and number of feet traveled oiselessness outside of spaces occupied by machinery. per car mile. (This is often supplied by bidder for

hoisting machinery. Who supplies supports and fram- of drum and shaft materials, and minimum diameter.

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ter. meter.

ENERGY CONSUMED BY AN ELECTRIC ELEVATOR AT VA LOADS AND STOPS

Machine: One-to-one Electric Traction.
Total Weight of Car: 3956 pounds; Overbalance: 1060 pounds.
Capacity: 2500 pounds at a speed of 500 feet per minute.

Stops at floors No.												
	Up	1 and 9						1, 5 and 9				
	Down	9 and 1						9, 5 and 1				
Distance ..		101 ft. 6 in. one way or per trip = 52 trips per car mile										
Load, lb...		Oper-ator	666	1060	1360	2010	2360	2660	Oper-ator	666	1060	201
Kw-hr. per car mile..		2.345	2.075	1.945	1.87	2.15	2.495	3.22	3.09	2.855	2.52	2.91

Stops at floors No.								
	Up	1, 3, 5, 7 and 9				1, 2, 3, 4, 5, 6, 7, 8 a		
	Down	9, 7, 5, 3 and 1				9, 8, 7, 6, 5, 4, 3, 2 a		
Distance.....		101 ft. 6 in. one way or per trip = 52 trips per car m						
Load, lb.....		Operator	666	1060	2010	Operator	666	1060
Kw-hr. per car mile		4.91	4.185	3.975	4.25	7.285	6.75	6.7

(Drums are usually of gray cast iron and shaft of forged open-hearth Worm and gear details. The worm shall be of open-hearth steel and t of phosphor bronze. Motor details (*see articles on Motors.*) Method of up thrust of shaft and drum. Details of brake.

Safety Devices.—(a) Centrifugal governor: When the speed exceeds a speed, the car shall be gradually retarded. (b) Machine governor: When of car reaches a certain amount, greater than that at which the cent governor acts, and less than that required to throw the safety clutches car, the circuit breaker shall open. (c) Limit stops, upper and lower: the car approaches the limits, the controller circuit shall be automa opened, and the brake applied. (d) Circuit-breaker details.

Cables.—Description, diameter and minimum number. The number of shall be sufficient to prevent any slipping of the cables on the drum wh car is operated under maximum load and contract speed.

Switchboard and Wiring.—Details of switchboard. Details of con cable, which should be extra flexible and insulated with the best rubber.

Shaft Equipment.—Description of shaftway inclosures, with dra

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ion; whether elevator contractor will find it ready, achinery may be installed below the pit. Pent- whether elevator contractor will find it ready for ery may be installed outside or above penthouse rt of sheaves, guides, governors, bumpers, etc. Whether to be supplied by elevator contractor. ption. Counterweights, description; the material haftway fittings, including supports, oil buffers, material of sheaves (usually tough grey cast iron), e rails. The guide rails are usually steel tees of a details of their attachment to the shaft structure letails.

tion, including statement of sides where door or utch, details. Slack-cable device, details. Coun- ached to bottom of car to compensate for weight

ction, fireproofing, floor details, including finish of ighting, emergency door, etc. There shall be no safety devices operate. Operating equipment, cy switch, lighting switch, safety lever, annun- al system, etc.

ol mechanism, description. Number of speeds by release of lever. Controller shall be out of way tor to keep one hand on the gate while the other hall be made to operate the car from the switch- ked from within. If the operator reverses while l of direction shall be gradual and without shock operations shall be accomplished by controller: nd reverse motor without destructible arcing at . (b) Give easy acceleration of car independently ting without shock or jar. (c) Lift brake, cut and operate fields by successive steps in starting. special field resistance in series with armature in etardation of the car prior to the pressure of the lley. (e) Other control will be considered.

System.—Details of signaling system. Signals osition of the car whatever the motions of the shall give the operator in the car a clear signal nd whether passengers want to go up or down.

ils of test. Instruction by contractor in use of ation of the cars in the shaft and before its final ll install on the cars a 6-inch gong, which will ring and down the shaft as a warning signal. Lubri- ls. Tools to be supplied.

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ENDOSMOSE OR ELECTRIC OSMOSIS. — (*See also E istry, Principles of.*) If a current is passed along a film of water insulating surface, the water will be attracted to the negative Similarly an electric current flowing through a porous partition, o opening, filled with conducting liquid, causes a flow of the liquid t partition or opening. This phenomenon is known as endosmose osmosis. While various physicists have offered explanations of thi enon, none have received general acceptance.

The quantity of a given liquid which is carried through a given p phragm in a definite time varies directly with the current strength a pendent of the area and thickness of the diaphragm. The quantity the nature of the solution, being greater with liquids of high specific and high specific capacity. The direction of flow is generally from negative electrode, but under certain conditions the flow may be posite direction.

Applications of Endosmose. — Endosmose may be utilized water from wet substances. Thus if a wooden box be equipped forated metallic plates at opposite ends and be filled with wet tur rent circulated through the turf from one end to the other, wate out of the perforations of the cathode plate. Endosmose is utili ning processes to accelerate the passage of tanning fluids through and efforts are being made to utilize it for drying peat, extractin similar purposes.

Endosmose of Negative Feeders. — If electric conductors cove saturated braid or a number of such braids be made the cathode of a and say 110 volts applied between anode and cathode, the braid will few minutes and the blisters will finally burst, grounding the condu water. The same action goes on at lower voltages at a proportiona rate, but with equal certainty. No action is observable if the wire be anode instead of the cathode. The same phenomenon is said to be with rubber insulation, but the writer has tried several samples of American compounds made with 30 per cent of Para rubber and ol signs of endosmose after subjecting them for a week to a press volts. C. H. Wordingham (*Elec. Engineer, London, Vol. 26, 1900, p.* however, that certain makes of rubber insulation are porous and enter and eventually destroy the whole of the rubber on the neg ductors. For this reason insulation of low specific resistance shoul used on negative feeders. For the same reason it is not practicable t a negative contact rail on electric railways, below earth potent insulators soon become saturated with moisture and thereby be ductors. Thus S. B. Fortenbaugh, relating the experience of the ways in London, says:

1. That the difference of potential between the positive conductor is always normally considerably greater than the potential existing be negative conductor and earth.

2. That a reversal of polarity is always instantly accompanied by able increase in the normal leakage current between the positive an conductor.

3. The insulation of the negative conductor to earth cannot be i maintained.

Effect of Endosmose on Insulation Measurements. — Wh wires having insulation of low specific resistance, endosmose may fur the resistance if the wire is negative to the water bath.

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EQUATIONS. — (*See also Complex Numbers; Errors of Observation; rithms; Vectors.*) The subjects treated in this article are

Quadratic Equation
Cubic Equation
Simultaneous Equations
Determinants for solving simultaneous equations
Equations of Common Curves
Differential Equations

QUADRATIC EQUATION. — The solution of

$$ax^2 + bx + c = 0$$

is $$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = -\frac{b}{2a}\left[1 \pm \sqrt{1 - \frac{4ac}{b^2}}\right]$$

CUBIC EQUATION. — The solution of the general cubic equation form

$$ax^3 + 3bx^2 + 3cx + d = 0$$

is obtained as follows: Put

$$y = ax + b$$
$$H = b^2 - ac$$
$$G = a^2d - 3abc + 2b^3$$

then (1) becomes

$$y^3 - 3Hy + G = 0.$$

The nature of the roots of this equation depends upon the algebraic sig and the relative numerical magnitudes of G and H.

Case I. H positive and G numerically less than $2H\sqrt{H}$. (G r either positive or negative.) Put

$$\phi = \frac{1}{3}\sin^{-1}\left[\frac{G}{2H\sqrt{H}}\right]$$

then the three roots of (2) are

$$y_1 = 2\sqrt{H}\sin\phi$$
$$y_2 = 2\sqrt{H}\sin(\phi + 120)$$
$$y_3 = 2\sqrt{H}\sin(\phi - 120)$$

and all three roots are real.

Case II. H positive and G numerically greater than $2H\sqrt{H}$. Put

$$u = \frac{1}{3}\cosh^{-1}\left[\frac{\pm G}{2H\sqrt{H}}\right]$$

the plus sign to be used when G is positive, the negative sign when G is n thus making $\cosh 3u$ positive in either case.

Then the three roots of (2) are

$$y_1 = \mp 2\sqrt{H}\cosh u$$
$$y_2 = \pm\sqrt{H}\cosh u + \sqrt{-3H}\sinh u$$
$$y_3 = \pm\sqrt{H}\cosh u - \sqrt{-3H}\sinh u$$

ed when G is positive, the lower when G is negative.
e is real, the other two being complex quantities. See
tities and *Hyperbolic Functions*.

and G any value. Put

$$u = \frac{1}{3}\sinh^{-1}\left[\frac{\mp G}{2H\sqrt{-H}}\right]$$

used when G is positive, the positive sign when G is
h $3u$ positive in either case. Then the three roots of

$$= \mp 2\sqrt{-H}\sinh u$$
$$= \pm\sqrt{-H}\sinh u + \sqrt{3H}\cosh u \qquad (5)$$
$$= \pm\sqrt{-H}\sinh u - \sqrt{3H}\cosh u$$

when G is positive, the lower sign when G is negative.
is real, the other two complex quantities.
the sum of the three roots is zero. Also, in the special
the angle ϕ is 30°, and therefore from (3) the three
$-2\sqrt{H}$; this also follows from (4).

$$y^3 - 6y + 2 = 0.$$

$G = 2$ and is less than $2H\sqrt{H}$.

$$\phi = \frac{1}{3}\sin^{-1}\left[\frac{2}{4\sqrt{2}}\right] = 6.90°$$

0.3399; $y_2 = 2.2618$; $y_3 = -2.6018$.

$$y^3 - 3y + 4 = 0.$$

$G = 4$ and is greater than $2H\sqrt{H}$.

$$u = \frac{1}{3}\cosh^{-1} 2 = 0.439$$

$= 1.098 + 0.785\sqrt{-1}$; $y_3 = 1.098 - 0.785\sqrt{-1}$.

$$y^3 + 6y + 2 = 0.$$

$= -2$ and $G = 2$

$$= \frac{1}{3}\sinh^{-1}\frac{-2}{-4\sqrt{2}} = 0.1155$$

$= -0.3275$

$= 0.1638 + 2.467\sqrt{-1}$

$= 0.1638 - 2.467\sqrt{-1}$

QUATIONS. — Given n independent equations in
uations fix the values of each of the n unknowns.
nultaneous equations in x, y and z, say, solve each of

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the three equations for x in terms of y and z. Equating these three for x gives two equations in y and z. Solving each of these two equat y in terms of z and equating these two values of y gives a single equat The solution of this last equation then gives the value of z. Then su this value of z in either of the equations in y and z, and solve for y substitute these values of y and z in any one of the original equations a for x.

Determinants. — In the case of linear simultaneous equations (i.e x, y and z occur only to the first power), the equations may be solved b minants. This method is a considerable time saver when the numbe knowns is greater than three, but when the number of unknowns is less the straight substitution method is preferable.

The determinant of a set of simultaneous equations is formed by the equations one below the other with the same unknown in the same position in each. The block of numbers forming the coefficients of knowns is called the determinant. For example, the determinant of th tions

$$\begin{aligned} w + x + y + z &= 6 \\ w + \quad\; y + 3z &= 4 \\ w + 2x + 3y \quad\; &= 1 \\ w + 3x + \quad\; z &= 3 \end{aligned}$$

is

$$D = \begin{vmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 3 \\ 1 & 2 & 3 & 0 \\ 1 & 3 & 0 & 1 \end{vmatrix}$$

The values of any one of the unknowns, say y, is found by writing a determinant, D_y, exactly like the determinant D, except that the constant ing the right-hand members of these equations are substituted for the coe of y in the determinant, that is

$$D_y = \begin{vmatrix} 1 & 1 & 6 & 1 \\ 1 & 0 & 4 & 3 \\ 1 & 2 & 1 & 0 \\ 1 & 3 & 3 & 1 \end{vmatrix}$$

Then

$$y = \frac{D_y}{D}$$

and similarly for the other unknowns.

The value of any determinant is found by making use of the followin

(1) If a determinant has two equal rows or columns, it is equal to ze

(2) To any row or column one may add or subtract any number of tin other row or column without altering the value of the determinant.

(3) To multiply any row or column by a number is the same as mult the determinant by that number.

(4) If all the terms in a row or column except one are zero, the deter reduces to one of a lower order which may be obtained by striking out t and column which intersect at the term in question, and multiplying th by that term, changing the sign of this term, however, if it is removed odd number of terms from the principal diagonal. The principal diag

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t the upper left-hand corner and ending at the
us,

$$\begin{vmatrix} 2 & 8 & 5 \\ 4 & 6 & 9 \\ 3 & 0 & 0 \\ 7 & 4 & 3 \end{vmatrix} = -3 \begin{vmatrix} 1 & 8 & 5 \\ 3 & 6 & 9 \\ 6 & 4 & 3 \end{vmatrix},$$

at with the figures 1, 4, 0 and 3. It is immaterial
diagonal is counted along a row or a column.
ant of the second order is

$$\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix} = a_1 b_2 - a_2 b_1$$

nts is effected by altering the terms according to
r column is obtained in which all terms but one
uction of order to be effected in accordance with
nued until one of the second order is obtained.

(2), the determinant D given above may be
w being subtracted from each of the others.

$$\begin{vmatrix} 1 & 1 & 1 & 1 \\ 0 & -1 & 0 & 2 \\ 0 & 1 & 2 & -1 \\ 0 & 2 & -1 & 0 \end{vmatrix}$$

$$\begin{vmatrix} -1 & 0 & 2 \\ 1 & 2 & -1 \\ 2 & -1 & 0 \end{vmatrix}$$

en

$$\begin{vmatrix} -2 & 0 & 4 \\ 2 & 4 & -2 \\ 2 & -1 & 0 \end{vmatrix}$$

w to each of the others, this reduces to

$$\begin{vmatrix} -2 & 0 & 4 \\ 0 & 4 & 2 \\ 0 & -1 & 4 \end{vmatrix}$$

$$\begin{vmatrix} 4 & 2 \\ -1 & 4 \end{vmatrix}$$

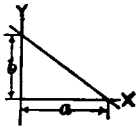
$= -\frac{1}{2}(4 \times 4 + 1 \times 2) = -9.$
$= 21$
$= -\frac{21}{9} = -2.333.$
3, $x = -2.667$, $z = -2.333.$

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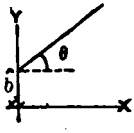
EQUATIONS OF COMMON CURVES.

Straight Line. —

$$\frac{x}{a} + \frac{y}{b} = 1$$

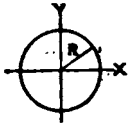


or $y = x \tan \theta + b.$



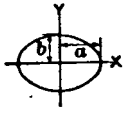
Circle. —

$$x^2 + y^2 = R^2.$$



Ellipse. —

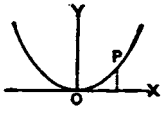
$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1.$$



Parabola (Vertical). —

$$y = kx^2$$

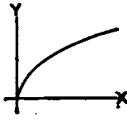
where k is a constant.



Parabola (Horizontal). —

$$y = k\sqrt{x}$$

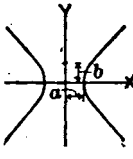
where k is a constant.



Hyperbola. —

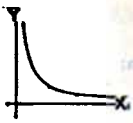
$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1 \text{ (Horizontal).}$$

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = -1 \text{ (Vertical).}$$



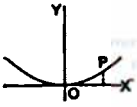
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ilateral



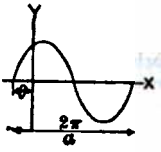
$kx - 1\Big]$

he length of arc



rbolic Functions.

$+\theta$).



ATIONS. — Differential equations of the following eory of alternating and transient currents.
used: $\epsilon = 2.7183 \ldots$ = base of natural system riables. A, ϕ, γ, and θ are integration constants. n constants.

$$\frac{dy}{dx} = ay. \qquad (1)$$

$$y = A\epsilon^{ax}.$$

$$\frac{dy}{dx} + ay = 0. \qquad (2)$$

$$y = A\epsilon^{-ax}.$$

$$\frac{dy}{dx} + ay = b. \qquad (3)$$

$$y = \frac{b}{a}\left[1 - A\epsilon^{-ax}\right].$$

$$\frac{d^2y}{dx^2} = -a^2y. \qquad (4)$$

$$y = A \sin (ax + \phi).$$

$$\frac{d^2y}{dx^2} = a^2y. \qquad (5)$$

$$y = A \sinh (ax + \phi).$$

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$$\frac{d^2y}{dx^2} + 2u\frac{dy}{dx} + (u^2 + a^2)\,y = 0.$$

Solution:

Case I. a^2 positive: —	$y = Ae^{-ux}\sin(ax + \phi)$.
Case II. a^2 negative: —	$y = Ae^{-ux}\sinh(ax + \phi)$.
Case III. $a^2 = 0$: —	$y = A(x + \phi)\,e^{-ux}$.

$$\frac{d^2y}{dx^2} + 2u\frac{dy}{dx} + (u^2 + a^2)\,y = B\sin(\omega x + \theta).$$

The complete solution of this equation consists of the solution of N the term

$$\left(\frac{B\sin\delta}{2u\omega}\right)\sin(\omega x + \theta - \delta),$$

where

$$\delta = \tan^{-1}\frac{2u\omega}{a^2 + u^2 - \omega^2}.$$

For each additional sine term added to the right-hand member of tion, there will be a corresponding term of the same form as (a) in the

---

$$\frac{d^ny}{dx^n} + a_{n-1}\frac{d^{n-1}y}{dx^{n-1}} + \ldots a_1\frac{dy}{dx} + a_0y = B\sin(\omega x + \theta).$$

Solution:

$$y = A_1e^{m_1x} + A_2e^{m_2x} + \ldots A_ne^{m_nx} + KB\sin(\omega x + \theta + \delta),$$

where m_1, m_2, etc., are the n roots of the equation

$$m^n + a_{n-1}m^{n-1} + \ldots a_1m + a_0 = 0,$$

and K and δ are found by substituting the $KB\sin(\omega x + \theta + \delta)$ by its given differential equation and equating the coefficients of $\sin(\omega x$ - $\cos(\omega x + \theta)$ respectively on the two sides of the resulting equation the second member of the differential equation is a constant, B, the sin the solution becomes simply $\frac{B}{a_0}$.

Note that all of the preceding equations are merely special cases of th equation (8).

$$\frac{d^2y}{dx^2} + 2u\frac{dy}{dx} + (u^2 - q^2)\,y = \frac{1}{c^2}\frac{d^2y}{dx^2}.$$

The complete solution of this equation contains an infinite number of the form

$$y = e^{-(u-s)x}[A_1e^{mx}\sin(\omega x + nz + \phi_1) + A_2e^{-mx}\sin(\omega x - nz + \phi_2)]$$

where A_1, ϕ_1, A_2, ϕ_2 and two of the four constants ω, s, m and n are in constants (fixed by the terminal conditions). The values of m and n of ω and s are

$$m = c\sqrt{ab}\cos\frac{\eta + \epsilon}{2},$$

$$n = c\sqrt{ab}\sin\frac{\eta + \epsilon}{2},$$

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$$\epsilon = \tan^{-1}\left(\frac{\omega}{s+q}\right),$$

$$\eta = \tan^{-1}\left(\frac{\omega}{s-q}\right).$$

s of m and n are

$$\omega = \frac{\sqrt{FG}}{c}\cos\frac{\alpha+\beta}{2},$$

$$s = \frac{\sqrt{FG}}{c}\sin\frac{\alpha+\beta}{2},$$

$$\alpha = \tan^{-1}\left(\frac{m}{n+cq}\right),$$

$$\beta = \tan^{-1}\left(\frac{m}{n-cq}\right).$$

) may also be written as a series of terms of the

$$\epsilon^{-(u-s)z}\sin(\omega x+\phi+\mu), \qquad \text{(b)}$$

$\cosh 2(nz+\gamma)+\cos 2(nz+\theta)$,

$z+\gamma)\tan(nz+\theta)$,

gration constants, and the relations between the are the same as above.

o, the solution of equation (9) is

$$[f_1(\omega x+nz)+f_2(\omega x-nz)], \qquad \text{(c)}$$

itrary functions and ω and n are connected by the

$$\frac{\omega}{n}=\frac{1}{c}.$$

$$\frac{d^2y}{dx^2}+\frac{1}{x}\frac{dy}{dx}=4a^2y. \qquad (10)$$

$$+\frac{(ax)^4}{2^2}+\frac{(ax)^6}{(3!)^2}+\frac{(ax)^8}{(4!)^2}+\ldots\Big]. \qquad \text{(a)}$$

ergent for all values of x, but for $ax>1$ the more convenient and sufficiently accurate.

$$+\frac{3^2}{2\,(16\,ax)^2}+\frac{3^2.5^2}{3!\,(16\,ax)^3}+\frac{3^2.5^2.7^2}{4!\,(16\,ax)^4}\Big]. \qquad \text{(b)}$$

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ERRORS OF OBSERVATION. — When a quantity is measure possible accuracy many times in succession, the numbers expressing t are found to differ by amounts, which, although generally small, are oc considerable in comparison with the quantity measured. Though th ences may be decreased by improved methods, better instruments skill, they can never be entirely removed. They are known as the observation. The following formulas, which are derived from the Least Squares, apply to such errors and not to errors which can be e by correcting mistakes of the observer or defects of instruments or m observation. *That is, they apply only to errors which may be either negative, the chance of a positive error occurring being exactly the same as of a negative error occurring.*

Weighted Observations. — Sometimes in spite of the care with servations are taken, there are reasons for believing that some obs are better than others. In this case the observations are given "weights" or numbers expressing their relative practical worth. A observation is an observation multiplied by its weight.

PROBABLE VALUE OF SEVERAL OBSERVATIONS. — probable value of a quantity which is observed directly several ti equal care is the arithmetical mean of the measurements.

Example. — The length of a room (in feet) is measured ten t the following results:

20.05	20.06	19.98	19.99	20.00
20.07	20.01	20.05	19.95	19.98

The arithmetical mean of these lengths is 20.01 feet, which is accord probable length of the room.

The most probable value of a quantity which is observed direct times, but where the observations have different weights, is equal to t the weighted observations divided by the sum of the weights.

Example. — In the above example if the fourth and fifth obs are twice as reliable as the others, and the seventh three times as reli most probable value would be the sum of 20.05, 20.06, 19.98, (19 (20.00 × 2), 20.07, (20.01 × 3), 20.05, 19.95 and 19.98, divided by 14, equal to 20.01, which happens in this instance to agree with the un average.

PROBABLE ERROR OF ANY ONE OF SEVERAL OB TIONS. — The probable error of a number of direct observations m equal care is found by the following formula:

$$r = 0.6745 \sqrt{\frac{\Sigma v^2}{n-1}},$$

where

n = number of observations.
r = probable error of a single observation.
v = residual found by subtracting the arithmetical mean fr measurement.

Example.—In the example cited above, $n = 10$. The value the order of the observations given above are as follows:

+ 0.04	+ 0.05	− 0.03	− 0.02	− 0.01
+ 0.06	0	+ 0.04	− 0.06	− 0.03

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these quantities is 0.0152. The probable error in ions is

$$= 0.6745 \sqrt{\frac{0.0152}{9}} = 0.0277.$$

ach of a number of direct observations, where the weight, is found by the following formula, in which an observation.

$$r_1 = 0.6745 \sqrt{\frac{\Sigma pv^2}{n-1}}.$$

example cited above for weighted observations, the the values of v in the preceding example. ollows:

025	0.0009	0.0008	0.0002
	0.0016	0.0036	0.0009

of a single observation

$$0.6745 \sqrt{\frac{0.0157}{9}} = 0.0282.$$

OF THE ARITHMETICAL MEAN. — If

of a single observation,
ervations,
of the arithmetical mean,

ations of equal weight, or

qual weight.

mple cited above for observations of equal weight,
$r_0 = 0.0277/\sqrt{10} = 0.0088.$
ve for observations of unequal weight,
nd $r_0 = 0.0282/\sqrt{14} = 0.0075.$
the probable error of the mean decreases inversely mber of observations.

robable error in making a single reading of a watt-comotive is 5 per cent, after all constant sources of If 25 locomotives are used, what will be the prob-gy consumption obtained, by adding the watt-hour one per cent.

$$r_0 = \frac{5}{\sqrt{25}} = 1.$$

IN A RESULT CALCULATED FROM THE OBSERVED QUANTITIES. — Let Z = a sum pendent quantities.
robable errors in these quantities. Then the prob-

$$\sqrt{r_1^2 + r_2^2 + r_3^2 + \text{etc}}$$

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Let $Z = As$, where s is an observed quantity, and A, a known num
be the probable error in s. Then the probable error in Z is Ar.

Let Z be the product of two independently observed quantities
whose probable errors are r_1 and r_2 respectively. Then the error in Z i

$$\sqrt{z_1^2 r_2^2 + z_2^2 r_1^2}.$$

Let Z be any function of the independently observed quantities z_1,
whose probable errors are r_1, r_2, r_3, etc. Then the probable error in Z i

$$\sqrt{\left(\frac{dZ}{dz_1}\right)^2 r_1^2 + \left(\frac{dZ}{dz_2}\right)^2 r_2^2 + \left(\frac{dZ}{dz_3}\right)^2 r_3^2 + \text{etc.}}$$

METHOD OF LEAST SQUARES. — A set of simultaneous
containing more equations than unknowns cannot have any exact solut
the superfluous equations are deducible from the others. They may,
have a most probable solution which is such that the sum of the errors
after corrections for the deduced values of the unknowns shall be a
This result is obtained as shown in the following example:

$$\begin{aligned} s - t + 2u &= 3, \\ 3s + 2t - 5u &= 5, \\ 4s + t + 4u &= 21, \\ -s + 3t + 3u &= 14. \end{aligned}$$

The coefficients of s are 1, 3, 4 and -1. Multiplying by these co

$$\begin{aligned} s - t + 2u &= 3, \\ 9s + 6t - 15u &= 15, \\ 16s + 4t + 16u &= 84, \\ s - 3t - 3u &= -14. \end{aligned}$$

Add these equations and obtain $27s + 6t = 88$.

The coefficients of t are -1, 2, 1 and 3. Multiply the original equ
these coefficients.

$$\begin{aligned} -s + t - 2u &= -3, \\ 6s + 4t - 10u &= 10, \\ 4s + t + 4u &= 21, \\ -3s + 9t + 9u &= 42. \end{aligned}$$

Add these equations and obtain $6s + 15t + u = 70$.

The coefficients of u are 2, -5, 4 and 3. Multiply the original
by these coefficients.

$$\begin{aligned} 2s - 2t + 4u &= 6, \\ -15s - 10t + 25u &= -25, \\ 16s + 4t + 16u &= 84, \\ -3s + 9t + 9u &= 42. \end{aligned}$$

Add these equations and obtain $t + 54u = 107$.

The equations

$$\begin{aligned} 27s + 6t &= 88, \\ 6s + 15t + u &= 70, \\ t + 54u &= 107, \end{aligned}$$

are then solved in the ordinary way, the solution being

$$s = 2.47, \quad t = 3.56, \quad \text{and} \quad u = 1.92.$$

BIBLIOGRAPHY. — The subject of error of observation is very fu
in *A Text Book on the Method of Least Squares*, by Mansfield Merrim

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ICTIONS. — (*See also Roots and Powers.*) When variable y and another variable x is such that x one or more terms, y is said to be an exponential ar importance in connection with electric circuits are ϵ^x and ϵ^{-x}, where ϵ is the base of the natural loga-

ctly from the table of common logarithms (*see Loga-* nat ϵ^x is equal to the number whose logarithm to the e exactly $0.4342945\,x$), which may be written sym-

$$\epsilon^x = \log_{10}{}^{-1}(0.4343\,x).$$

$$\epsilon^{-x} = \frac{1}{\log_{10}{}^{-1}(0.4343\,x)}.$$

the value of ϵ^{10}. We have $0.4343 \times 10 = 4.343$.

ver, the following table giving the value of ϵ^x and given. For larger values of x use the above rela- $x < 0.1$ (*see Series*).

th an error of less than 0.47 per cent,

th an error of less than 0.54 per cent,

$\frac{x^2}{2}$ with an error of less than 0.016 per cent,

$\frac{x^2}{2}$ with an error of less than 0.018 per cent.

TIONS ϵ^x AND ϵ^{-x} 0.00 - 0.89

	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
01	1.0202	1.0305	1.0408	1.0513	1.0618	1.0725	1.0833	1.0942
00	0.9802	0.9704	0.9608	0.9512	0.9418	0.9324	0.9231	0.9139
63	1.1275	1.1388	1.1503	1.1618	1.1735	1.1853	1.1972	1.2093
58	0.8869	0.8781	0.8694	0.8607	0.8521	0.8437	0.8353	0.8270
37	1.2461	1.2586	1.2712	1.2840	1.2969	1.3100	1.3231	1.3364
06	0.8025	0.7945	0.7866	0.7788	0.7711	0.7634	0.7558	0.7483
34	1.3771	1.3910	1.4049	1.4191	1.4333	1.4477	1.4623	1.4770
34	0.7261	0.7189	0.7118	0.7047	0.6977	0.6907	0.6839	0.6771
68	1.5220	1.5373	1.5527	1.5683	1.5841	1.6000	1.6161	1.6323
37	0.6570	0.6505	0.6440	0.6376	0.6313	0.6250	0.6188	0.6126
53	1.6820	1.6989	1.7160	1.7333	1.7507	1.7683	1.7860	1.8040
05	0.5945	0.5886	0.5827	0.5769	0.5712	0.5655	0.5599	0.5543
04	1.8589	1.8776	1.8965	1.9155	1.9348	1.9542	1.9739	1.9939
34	0.5379	0.5326	0.5273	0.5220	0.5169	0.5117	0.5066	0.5017
40	2.0544	2.0751	2.0959	2.1170	2.1383	2.1598	2.1815	2.2034
16	0.4868	0.4819	0.4771	0.4724	0.4677	0.4630	0.4584	0.4538
79	2.2705	2.2933	2.3164	2.3396	2.3632	2.3869	2.4109	2.4351
49	0.4404	0.4360	0.4317	0.4274	0.4232	0.4190	0.4148	0.4107

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EXPONENTIAL FUNCTIONS e^x AND e^{-x}

x	Function	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.0
0.9	e^x	2.4596	2.4843	2.5093	2.5345	2.5600	2.5857	2.6117	2.6379	2.6
	e^{-x}	0.4066	0.4025	0.3985	0.3946	0.3906	0.3867	0.3829	0.3791	0.3
1.0	e^x	2.7183	2.7456	2.7732	2.8011	2.8292	2.8577	2.8864	2.9154	2.9
	e^{-x}	0.3679	0.3642	0.3606	0.3570	0.3535	0.3499	0.3465	0.3430	0.3
1.1	e^x	3.0042	3.0344	3.0649	3.0957	3.1268	3.1582	3.1899	3.2220	3.2
	e^{-x}	0.3329	0.3296	0.3263	0.3230	0.3198	0.3166	0.3135	0.3104	0.3
1.2	e^x	3.3201	3.3535	3.3872	3.4212	3.4556	3.4903	3.5254	3.5609	3.5
	e^{-x}	0.3012	0.2982	0.2952	0.2923	0.2894	0.2865	0.2837	0.2808	0.2
1.3	e^x	3.6693	3.7062	3.7434	3.7810	3.8190	3.8574	3.8962	3.9354	3.97
	e^{-x}	0.2725	0.2698	0.2671	0.2645	0.2618	0.2592	0.2567	0.2541	0.2
1.4	e^x	4.0552	4.0960	4.1371	4.1787	4.2207	4.2631	4.3060	4.3492	4.3
	e^{-x}	0.2466	0.2441	0.2417	0.2393	0.2369	0.2346	0.2322	0.2299	0.2
1.5	e^x	4.4817	4.5267	4.5722	4.6182	4.6646	4.7115	4.7588	4.8066	4.8
	e^{-x}	0.2231	0.2209	0.2187	0.2165	0.2144	0.2122	0.2101	0.2080	0.2
1.6	e^x	4.9530	5.0028	5.0531	5.1039	5.1552	5.2070	5.2593	5.3122	5.3
	e^{-x}	0.2019	0.1999	0.1979	0.1959	0.1940	0.1920	0.1901	0.1882	0.1
1.7	e^x	5.4739	5.5290	5.5845	5.6407	5.6973	5.7546	5.8124	5.8709	5.9
	e^{-x}	0.1827	0.1809	0.1791	0.1773	0.1755	0.1738	0.1720	0.1703	0.1
1.8	e^x	6.0496	6.1104	6.1719	6.2339	6.2965	6.3598	6.4237	6.4883	6.5
	e^{-x}	0.1653	0.1637	0.1620	0.1604	0.1588	0.1572	0.1557	0.1541	0.1
1.9	e^x	6.6859	6.7531	6.8210	6.8895	6.9588	7.0287	7.0993	7.1707	7.2
	e^{-x}	0.1496	0.1481	0.1466	0.1451	0.1437	0.1423	0.1409	0.1395	0.1
2.0	e^x	7.3891	7.4633	7.5383	7.6141	7.6906	7.7679	7.8460	7.9248	8.0
	e^{-x}	0.1353	0.1340	0.1327	0.1313	0.1300	0.1287	0.1275	0.1262	0.1
2.1	e^x	8.1662	8.2482	8.3311	8.4149	8.4994	8.5849	8.6711	8.7583	8.8
	e^{-x}	0.1225	0.1212	0.1200	0.1188	0.1177	0.1165	0.1153	0.1142	0.1
2.2	e^x	9.0250	9.1157	9.2073	9.2999	9.3933	9.4877	9.5831	9.6794	9.7
	e^{-x}	0.1108	0.1097	0.1086	0.1075	0.1065	0.1054	0.1044	0.1033	0.1
2.3	e^x	9.9742	10.074	10.176	10.278	10.381	10.486	10.591	10.697	10.8
	e^{-x}	0.1003	0.0993	0.0983	0.0973	0.0963	0.0954	0.0944	0.0935	0.0
2.4	e^x	11.023	11.134	11.246	11.359	11.473	11.588	11.705	11.822	11
	e^{-x}	0.0907	0.0898	0.0889	0.0880	0.0872	0.0863	0.0854	0.0846	0.0
2.5	e^x	12.182	12.305	12.429	12.554	12.680	12.807	12.936	13.066	13
	e^{-x}	0.0821	0.0813	0.0805	0.0797	0.0789	0.0781	0.0773	0.0765	0.0
2.6	e^x	13.464	13.599	13.736	13.871	14.013	14.154	14.296	14.440	14.5
	e^{-x}	0.0743	0.0735	0.0728	0.0721	0.0714	0.0707	0.0699	0.0693	0.0
2.7	e^x	14.880	15.029	15.180	15.333	15.487	15.643	15.800	15.959	16
	e^{-x}	0.0672	0.0665	0.0659	0.0652	0.0646	0.0639	0.0633	0.0627	0.0
2.8	e^x	16.445	16.610	16.777	16.945	17.116	17.288	17.462	17.637	17.8
	e^{-x}	0.0608	0.0602	0.0596	0.0590	0.0584	0.0578	0.0573	0.0567	0.0
2.9	e^x	18.174	18.357	18.541	18.728	18.916	19.106	19.298	19.492	19.6
	e^{-x}	0.0550	0.0545	0.0539	0.0534	0.0529	0.0523	0.0518	0.0513	0.0
3.0	e^x	20.086	20.287	20.491	20.697	20.905	21.115	21.328	21.542	21.7
	e^{-x}	0.0498	0.0493	0.0488	0.0483	0.0478	0.0474	0.0469	0.0464	0.0

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	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
1	22.646	22.874	23.104	23.336	23.571	23.807	24.047	24.288
6	0.0442	0.0437	0.0433	0.0429	0.0424	0.0420	0.0416	0.0412
9	25.028	25.280	25.534	25.790	26.050	26.311	26.576	26.843
4	0.0400	0.0396	0.0392	0.0388	0.0384	0.0380	0.0376	0.0373
5	27.660	27.938	28.219	28.503	28.789	29.079	29.371	29.666
5	0.0362	0.0358	0.0354	0.0351	0.0347	0.0344	0.0340	0.0337
5	30.569	30.877	31.187	31.500	31.817	32.137	32.460	32.786
0	0.0327	0.0324	0.0321	0.0317	0.0314	0.0311	0.0308	0.0305
8	33.784	34.124	34.467	34.813	35.163	35.517	35.874	36.234
9	0.0296	0.0293	0.0290	0.0287	0.0284	0.0282	0.0279	0.0276
6	37.338	37.713	38.092	38.475	38.861	39.252	39.646	40.045
1	0.0268	0.0265	0.0263	0.0260	0.0257	0.0255	0.0252	0.0250
4	41.261	41.679	42.098	42.521	42.948	43.380	43.816	44.256
5	0.0242	0.0240	0.0238	0.0235	0.0233	0.0231	0.0228	0.0226
0	45.604	46.063	46.525	46.993	47.465	47.942	48.424	48.911
1	0.0219	0.0217	0.0215	0.0213	0.0211	0.0209	0.0207	0.0204
9	50.400	50.907	51.419	51.935	52.457	52.985	53.517	54.055
0	0.0198	0.0196	0.0195	0.0193	0.0191	0.0189	0.0187	0.0185
7	55.701	56.261	56.826	57.397	57.974	58.557	59.145	59.740
1	0.0180	0.0178	0.0176	0.0174	0.0172	0.0171	0.0169	0.0167
7	61.559	62.178	62.803	63.434	64.072	64.715	65.366	66.023
1	0.0162	0.0161	0.0159	0.0158	0.0156	0.0155	0.0153	0.0151
7	68.033	68.717	69.408	70.105	70.810	71.522	72.240	72.966
8	0.0147	0.0146	0.0144	0.0143	0.0141	0.0140	0.0138	0.0137
0	75.189	75.944	76.708	77.478	78.257	79.044	79.838	80.640
4	0.0133	0.0132	0.0130	0.0129	0.0128	0.0127	0.0125	0.0124
9	83.096	83.931	84.775	85.627	86.488	87.357	88.235	89.121
2	0.0120	0.0119	0.0118	0.0117	0.0116	0.0114	0.0113	0.0112
2	91.836	92.759	93.691	94.632	95.583	96.544	97.514	98.494
0	0.0109	0.0108	0.0107	0.0106	0.0105	0.0104	0.0103	0.0102
8	101.49	102.51	103.54	104.58	105.64	106.70	107.77	108.85
0	0.0099	0.0098	0.0097	0.0096	0.0095	0.0094	0.0093	0.0092
5	112.17	113.30	114.43	115.58	116.75	117.92	119.10	120.30
0	0.0089	0.0088	0.0087	0.0087	0.0086	0.0085	0.0084	0.0083
3	123.97	125.21	126.47	127.74	129.02	130.32	131.63	132.95
1	0.0081	0.0080	0.0079	0.0078	0.0078	0.0077	0.0076	0.0075
4	137.00	138.38	139.77	141.17	142.59	144.03	145.47	146.94
4	0.0073	0.0072	0.0072	0.0071	0.0070	0.0069	0.0069	0.0068
0	151.41	152.93	154.47	156.02	157.59	159.17	160.77	162.39
7	0.0066	0.0065	0.0065	0.0064	0.0063	0.0063	0.0062	0.0062
7	167.31	169.02	170.72	172.43	174.16	175.91	177.68	179.47
0	0.0060	0.0059	0.0059	0.0058	0.0057	0.0057	0.0056	0.0056
9	184.93	186.79	188.67	190.57	192.48	194.42	196.37	198.34
5	0.0051	0.0054	0.0053	0.0052	0.0052	0.0051	0.0051	0.0050

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EXPONENTIAL FUNCTIONS e^x AND e^{-x} 5.30-

x	Function	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.0
5.3	e^x	200.34	202.35	204.38	206.44	208.51	210.61	212.72	214.86	217.02	219
	e^{-x}	0.0050	0.0049	0.0049	0.0048	0.0048	0.0047	0.0047	0.0047	0.0046	0.0
5.4	e^x	221.41	223.63	225.88	228.15	230.44	232.76	235.10	237.46	239.85	242
	e^{-x}	0.0045	0.0045	0.0044	0.0044	0.0043	0.0043	0.0043	0.0042	0.0042	0.0
5.5	e^x	244.69	247.15	249.64	252.14	254.68	257.24	259.82	262.43	265.07	267
	e^{-x}	0.0041	0.0040	0.0040	0.0040	0.0039	0.0039	0.0038	0.0038	0.0038	0.0
5.6	e^x	270.43	273.14	275.89	278.66	281.46	284.29	287.15	290.03	292.95	295
	e^{-x}	0.0037	0.0037	0.0036	0.0036	0.0036	0.0035	0.0035	0.0034	0.0034	0.0
5.7	e^x	298.87	301.87	304.90	307.97	311.06	314.19	317.35	320.54	323.76	327
	e^{-x}	0.0033	0.0033	0.0033	0.0032	0.0032	0.0032	0.0032	0.0031	0.0031	0.0
5.8	e^x	330.30	333.62	336.97	340.36	343.78	347.23	350.72	354.25	357.81	361
	e^{-x}	0.0030	0.0030	0.0030	0.0029	0.0029	0.0029	0.0029	0.0028	0.0028	0.0
5.9	e^x	365.04	368.71	372.41	376.15	379.93	383.75	387.61	391.51	395.44	399
	e^{-x}	0.0027	0.0027	0.0027	0.0027	0.0026	0.0026	0.0026	0.0026	0.0025	0.0

A more complete table is given in the *Smithsonian Mathematical Tab*
Hyperbolic Functions (No. 1871), by G. F. Becker and C. E. Van Orstra
Washington, 1909. Semi-exponentials, i.e., values of $\frac{1}{2}e^x$ and $\log_{10}\frac{1}{2}e^x$,
iven in *Tables of Complex Hyperbolic and Circular Functions*, by A. E. K
elly, Cambridge, Mass., 1914.

FACTORIALS. — The multiple product represented by

$$n\,(n-1)\,(n-2)\,\ldots\,3\times 2\times 1$$

called "n factorial," and is represented either by the symbol $n!$ or $\underline{n}$. Th
llowing table gives the value of $n!$ up to $n = 10$.

$1! = 1.$	$6! = 720.$
$2! = 2.$	$7! = 5040.$
$3! = 6.$	$8! = 40320.$
$4! = 24.$	$9! = 362880.$
$5! = 120.$	$10! = 3628800.$

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and Compressors; Draft, Mechanical.) For ven- nd for producing mechanical draft, two kinds of l the centrifugal fan.

reversed, that is, driven by power applied to the r in large volume at low pressure, and it is then are in common use for blowing air into or out of tilation. Usually they consist simply of a rapidly r more nearly flat blades slightly inclined to the s these blades are given various curved forms for efficiency of the fan.

older form of centrifugal fan is that of a paddle ng from four to twelve radial arms, to which are planes. In modified forms the blades are bent ference to the direction of rotation, from an axial l fans up to 25 feet diameter and 10 feet width n of mines, and in many cases without an external asing is used, with a tangential discharge outlet, inlets, concentric with the shaft, one on each side nodification of the centrifugal fan known as the n, the number of blades is increased to from 30 to made relatively very long, axially, and narrow, o width being as much as 9 to 1; they are made ge tipped forward in the direction of rotation and e casing and the radial distance of the vanes from ed. The pressure produced by centrifugal fans e of the speed of the tips of the blades and with the es a maximum commercially of about 1 pound per s of centrifugal or multivane fans. Much higher obtained from special forms of fans built on the *see Blowers and Compressors*).

-In the article on *Blowers and Compressors* is l" work done by a blowing machine. Since an a pressure of more than 1 per cent of normal atmos- n the volume and static pressure of the air as it gibly small in comparison with the initial volume a for the theoretical horse power reduces to

$$\frac{}{000}\left[\frac{dQ^3}{2g\,(60A)^2}+144\,p_s Q\right],$$

pressure at discharge over the initial static pres- square inch,

ced per minute,

ne cubic foot of air at the barometric pressure B and at $f°$ F.,

tlet opening in square feet,

avity in feet per second ($= 32.2$),

ressure in pounds per square inch necessary to

ear velocity $V_a = \frac{Q}{A}$ feet per minute to the air.

called the "velocity" pressure.

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Useful or "Air Horse Power" of the fan may then be written

$$P = \frac{(p_v + p_s)\,Q}{229}.$$

The total pressure $p_v + p_s$ developed by the fan is called the "imp "dynamic" pressure. The pressures developed by a fan are usually e in inches of water column; hence putting H_v and H_s for the correspondi of water column required to balance p_v and p_s, the above formulas beco

$$H_v = 0.832 \times 10^{-4} \frac{d\,Q^2}{A^2},$$

$$P = \frac{(H_v + H_s)\,Q}{6360}.$$

When the discharge outlet is restricted (e.g., by partially closing the d valve), the cross section A refers to the area of the discharge pipe betw restriction and the fan, not to the cross section of the restricted openin

Actual Horse Power. — The actual horse power required to drive is equal to the value given by the last formula divided by the efficienc fan efficiency depends not only upon the design of the fan, but also u relative values of the velocity and static pressures. The maximum effi a centrifugal fan ranges from 40 to 70 per cent. The maximum efficienc fans usually ranges from 30 to 40 per cent. The table below, taken fro published by F. R. Still of the American Blower Co., in the *Jour. E Eng.*, 1902, is fairly representative of the performance of ordinary st centrifugal fans. For a given type of fan and given ratio of velocity within the casing on the outlet side to the static pressure, there is a fi tion between the linear velocity $V_a = \frac{Q}{A}$ of the air within the casing on let side and the peripheral velocity V_f of the fan; the ratio $\frac{V_a}{V_f}$, as ca from Still's curves, is also given in the table below.

$\frac{H_v}{H_s}$	Efficiency	$\frac{V_a}{V_f}$	$\frac{H_v}{H_s}$	Efficiency
0.00	0.00	0.00	0.4	0.38
0.05	0.30	0.22	0.5	0.37
0.10	0.43	0.30	1.0	0.32
0.15	0.43	0.35	1.5	0.30
0.20	0.42	0.39	2.0	0.28
0.30	0.41	0.42	∞	0.22

More recent fans of the multivane or "Sirocco" type, when prope portioned, have given efficiencies of 60 per cent and upwards.

THE VOLUME OF AIR DISCHARGED per minute is $Q = V_a$ V_a is the linear velocity of the air in feet per minute. When the speed constant and the outlet pipe is partially closed, the linear velocity o through the full cross section A of the outlet decreases and the power

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A fan running at constant speed requires maximum
outlet is wide open; the volume discharge is also a
tions.
e fan running at a given speed the maximum volume
an deliver is roughly $\frac{1}{3} DWV_f = \frac{\pi}{3} D^2WN$, where D
n feet, W its width (at periphery) in feet, V_f the
in feet per minute and N the velocity in revolutions

s working against very low resistances is directly
the circle inclosing the fan and to the number of
varies with the form and inclination of the vanes.
ller fan of diameter D feet will deliver $Q = KD^3N$
K ranges from 0.4 to 0.7 (depending on the design
nce is small, the delivery decreasing rapidly as the

PEED. — The full discharge outlet A of an ordinary
out two-thirds the product of the width W by the
is $A = \frac{2}{3} DW$. The width of the fan ranges from
meter. Using the latter figure, we have $D = \sqrt{3}\, A$.
able given above a rough estimate of the dimensions
may be made. For example, 20,000 cubic feet of
to be discharged against a static head of 1 inch of
approximate dimensions and speed of the fan and
te horse power required? The size of fan and the
depend upon the linear velocity of the air through
locity the smaller the fan and the greater the horse
s as defined above we have $Q = 20{,}000$, $H_s = 1$,
alue of the linear velocity V_a is 2000 feet per minute.
$= 2.74$, $H_v = 0.255$, $\frac{H_v}{H_s} = 0.255$, $\frac{V_a}{V_f} = 0.41$, $V_f =$
0.415, H.P. = 9.6. That is, the diameter of the
5 feet 6 inches, its width 2 feet 9 inches, its speed
wer will be required to operate it. If V_a is taken as
the required diameter will be approximately 3 feet
11 inches, its speed 650 r.p.m., and 20 horse power
t.
iving at the size of fan is extremely rough at best;
reader is referred to manufacturers' catalogues.

R FANS. — The following memoranda are intended
ations. See also article on *Blowers* and article on

n and service for which it is to be used. Rating,
under specified conditions of test. Whether exhaust
d. Whether fixed or oscillating. Details of motor,
quency, phases and voltage.

See also Motors, Industrial Applications of.) The
es as the speed rises and unless some sort of shutter-
ill be fully loaded when it comes up to speed. Shut-
starting conditions should be carefully considered-
r is intended for driving the fan. As the torque
usually small, a motor with low-resistance starting
out requiring a very heavy current. To keep the

current down, however, a low tap on the starting compensator mus and an intermediate step may be very desirable.

Fig. 1 shows the starting-torque curve of a shuttered centrifugal fan to full speed, and also a speed-torque and a speed-current curve of a sy motor with a squirrel-cage starting winding of fairly low resistance plotted for 50, 70 and 100 per cent of normal voltage. If the motor is started from the 50 per cent tap of the compensator it will bring the fan to about 80 per cent of full speed. If the motor is then thrown over to the full-line voltage it may exert an excessive torque, and the current, as shown by the current curve, will rise to a very high value. If an intermediate tap is provided — say a 70 per cent tap — the torque exerted will be less but still enough to bring the motor to about 95 per cent of synchronous speed and the current will be much less. Application of the field would then pull the machine into step after which it could be thrown over to the line with a very little rush of current. For a variable-speed service the synchronous motor is of course not suitable and a varying-speed brush-shifting motor or a phase-wound induction motor must be used.

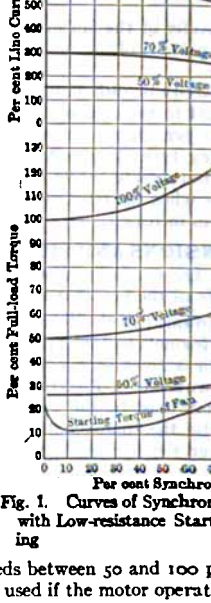


Fig. 1. Curves of Synchron with Low-resistance Start ing

For direct-current installations shunt motors are preferred, the speed adjustment being accomplished either by field control, armature control or a combination of the two. Field control is generally used where the motor operates for long intervals at speeds between 50 and 100 p maximum speed; the combination control is used if the motor operat intervals at speeds between 75 and 100 per cent of maximum speed, a sionally required to operate at speeds below 75 per cent; and armatu is used advantageously for motors operating at long intervals near but where occasionally a lower speed is required. Ventilating fans o the best applications for armature control because the torque a decreases with the cube of the speed.

With very large mine fans, having a high inertia, the time required f ation is comparatively long — one minute or more — and this must be when the starting resistances are selected. Starting resistances f driving such large fans should therefore as a rule be of a larger size t ordinarily be the case.

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TERS AND PURIFIERS. — (*See also Boilers; ctric.*) Impurities in the water supplied to a boiler ion of scale on the heating surface of the boiler, re- iler efficiency and overheating and consequent weak- lates; (2) the corrosion and consequent weakening (3) an increase in the amount of suspended moisture m from boiler to engine. Sulphates of lime and silica, iron and aluminum and suspended matter are purities. Acids, organic matter, magnesium chloride sion, while priming is induced by the presence of rbonate and other alkalies.

the feed water of various chemicals, as, for example, le-forming impurities may be changed into harmless between the impurities and the "boiler compounds" dhesion of the scale to the heating surfaces may be tion into the feed water or boiler of such substances led matter, such as sand, mud, insoluble organic inated by mechanical filtration or by allowing the tanks. Organic impurities usually float on top of is making steam and may be blown out through a cipitated matter may be ejected by frequent blowing rm a crust. Scale, when it has once formed, can be the tubes with some form of scraper. Very hard be softened so as to be more easily scraped, by dis- ntity, say 50 to 100 pounds, of caustic soda in the it at atmospheric pressure for from 12 to 24 hours. nagnesia, two of the chief scale-forming impurities, ly precipitated by raising the temperature of the g point for a pressure of about 60 pounds absolute).

EHEATING FEED WATER. — Although the heat- g or settling of the feed water results in the elimina- purities, the primary object of preheating the feed l consumption. The heat required to raise the tem- ed water 11° F. is approximately 1 per cent of the nvert the water into saturated steam at ordinary y 11° F. the temperature of the feed water is raised which would otherwise be wasted, a saving of approx- e effected in the amount of coal required. Let H = the given pressure, h_0 = heat of the water entering water leaving the heater, then the saving, expressed t that would be required by a boiler without a super-

$$S = 100 \frac{h - h_0}{H - h_0}.$$

may be taken from steam tables (*see Steam*). This ing in fuel, provided the boiler efficiency is the same water heater. However, if the boiler is overdriven, ater heater will effect a greater saving than that given n the work to be done by the boiler is reduced the ncrease.

ATER HEATERS. — The heat used for preheating ived: (1) from the exhaust steam; (2) from the flue

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gases, in which case the heater is usually called a "fuel economizer" live steam taken directly from the boilers, in which case the primar of the heater is to purify the feed water, and it is therefore usuall "live-steam purifier." The heat may be transmitted from the ste water either (1) by allowing the steam to mingle with the wate up its heat by condensation, or (2) by passing the water and stea separate chambers arranged so that the heat is conducted to the wat the walls of the chambers. These two types of heaters are referred tively as "open" and "closed" heaters. Closed heaters may be eit water-tube or steam-tube type; in the former the steam surround tubes through which the water is passed, while in the latter the stean through a set of tubes surrounded by water. A closed heater in steam pressure is less than atmospheric is called a "vacuum" or " heater; such heaters are frequently used in the exhaust of condensin "Atmospheric" or "secondary" heaters are those in which the stea is that corresponding to the back pressure of the engines or pumps. in which the steam pressure is the same as that in the boiler is called a " heater.

Open Heaters. — The essential parts of an open heater are: (1) a taining (2) a set of trays or pans to catch the scale-forming elen cipitated from the water; (3) a filter to take out suspended impur (4) an oil separator to extract the oil from the steam before it superheater.

Dimensions. — C. L. Hubbard (*Practical Engineer, Jan. 1, 1* the following:

Exhaust heaters should be proportioned according to the quality of to be used, the size being increased with the amount of mud or sca ing properties which the water contains, regardless of the quantity o be heated. The general proportions of an open heater will depend upon the arrangement of the trays or pans, but an approximation o of shell for a cylindrical heater is as follows: $A = H + aL$; $L = H$ which A = sectional area of shell in square feet; L = length of shell feet; H = total weight of water to be heated per hour divided by t of steam used per horse power per hour by the engine; $a = 2.15$ for ve water, 6.0 for slightly muddy water, and 8.0 for clear water.

The pan or tray surface varies according to the quality of the wate regards the amount of mud and the scale-making ingredients. Th in square feet for each 1000 pounds of water heated per hour may be follows, for the vertical and horizontal types respectively:

Very bad water	8.5 an
Medium muddy water	6 an
Clear and little scale	2 an

The space between the pans is made not less than 0.1 of the rectangular and 0.25 of the diameter for round pans. Under ordinar stances it is not customary to use more than six pans in a tier, in obtain a low velocity over each pan. The size of the storage or settling in the horizontal type varies from 0.25 to 0.4 of the volume of the shell ing on the quality of the water; 0.33 is about the average. In th vertical heaters, this varies from 0.4 to 0.6 of the volume of the shell occupy from 10 to 15 per cent of the volume of the shell in the horizo and from 15 to 20 per cent in the vertical.

Temperature Elevation of Feed Water. — Let H = tota steam in B.t.u. above 32° F. at the pressure of the steam in the hea

ter entering the heater; F = final temperature of K = ratio of weight of exhaust steam condensed ight of the feed water per hour; then, neglecting

$$= \frac{I + K(H + 32)}{1 + K}.$$

. *Hepburn, Power, April, 1902.*) Let W = pounds ft. of heating surface between steam and water; n; I = initial temperature of the water; F = final = B.t.u. transmitted per sq. ft. per hr. per deg. ween the steam and the water; then

$$= \frac{2.30\,W}{U} \log_{10} \frac{T_s - I}{T_s - F}.$$

according to the condition of the surface and with d also depends upon whether the heater is of the pe. Gebhardt gives the following values of U: ers, 250 for plain copper or brass tubes and 300 for er velocity of 50 feet per minute; for single-flow plain brass with a water velocity of 12.5 feet per eaters, 300 for copper tubes with a water velocity team-tube heaters, 120 for iron tubes.

zers for boiler plants are usually made of vertical a long rectangular chamber of brickwork. The f tubes at one end, while the hot gases enter the nd travel in the opposite direction to the water. ron because it is more non-corrosive than wrought o gases of combustion at low temperatures. An usually provided for the purpose of removing dust tubes.

n plants operating with steady load in which little The annual maintenance usually amounts to 10 or cost.

fuel that may be made by an economizer varies nditions of operation. With a given quantity of through it, its economy will be greater (1) the hese gases; (2) the lower the temperature of the e greater the amount of its heating surface.

el which may be made by the use of an economizer t are working with reasonable economy is about are not working with fair economy on account of aving made by the addition of an economizer may ports the following results of economizer tests:

are feet	1,894	1,058	5,592	3,126
, square feet	1,600	1,920	1,290	1,600
g boiler, degrees F	376	361	403	435
economizer, degrees F	231	254	299	279
r entering economizer,				
	95	79	111	84
entering boiler, degrees F.	175	145	169	196
duced by economizer, %	10.5	7	9.3	12.8

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and W. R. Roney (*Transactions A.S.M.E., Vol. 15*), reports:

Plant tested	1	2	3	4	5	6	7
Gases entering economizer, degrees F	610	505	550	522	505	465	49
Gases leaving economizer, degrees F	340	212	205	320	320	250	29
Water entering economizer, degrees F	110	84	185	155	190	180	16
Water leaving economizer, degrees F	287	276	305	300	300	295	28
Gain in temperature of water, degrees F	117	192	120	145	110	115	11
Fuel, saving, per cent	16.7	17.1	11.7	13.8	10.7	11.2	11.

Temperature Elevation of Feed Water. — Let A = squ economizer heating surface per boiler horse power, T_1 = temperatu heit) of flue gases entering economizer (ranges from about 450 I = temperature of feed water entering economizer; F = temperat water leaving economizer; W = pounds feed water per boiler hors hour; G = pounds flue gas per pound coal; C = pounds coal per b power hour; S = specific heat of flue gases; U = B.t.u. transmitte per hr. per deg. difference of temperature between flue gas and wat

$$F - I = \frac{A\,(T_1 - I)}{\frac{W}{U} + \frac{(W + CGS)\,A}{2\,CGS}}.$$

A varies from 3.5 to 5, and U from 2.25 to 3.3, depending upon the of operation. Putting $W = 30$, $S = 0.2$ and $U = 3.3$, the above form to

$$F - I = \frac{A\,(T_1 - I)}{9.1 + \frac{(5\,W + GC)\,A}{2\,GC}},$$

which is the formula advocated by the Green Economizer Co.

Rating and Cost (Pre-war cost figures). — The ordinary ec has from ⅓ to ½ square feet of heating surface for each boiler horse costs from 75 cents to $1 per horsepower. Economizers are sometime tubes, the usual area per tube being 15 square feet. From 3.5 to 5 s are usually installed per boiler horsepower. Economizers cost appr $1.25 per square foot of heating surface, this figure including erection setting.

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ELEGRAPH. — (*See also Telegraph Instruments and Systems; Wiring of Buildings for Miscellaneous Devices.*)
n telegraph systems is to notify the fire-fighting forces
ptly of the existence and location of a fire, and also to
mmunication between the various branches of the fire-
hether at a fire or in quarters.
f fire-alarm system is shown in Fig. 1, where several fire
ed in series in the alarm or "box" circuit extending from
rters throughout the district covered by the boxes. These
h a clockwork mechanism, so that when the box is started
rson sending the alarm, a break wheel, carrying notches

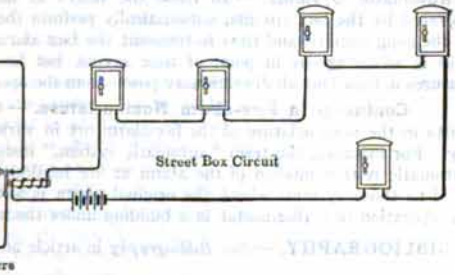


Fig. 1. Fire-Alarm System

ode number of the box, is caused to revolve, thus making
it in accordance with the code. These makes and breaks
f the relay at headquarters and by means of a local
s the alarm at headquarters. As many gongs as may be
ted by the same relay, these being placed in the engine-
or wherever else it is desired to give the alarm.

—The placing of a number of boxes on the same circuit
bility of confusion, due to two or more boxes being pulled
lled "interference." A box which makes no provision
is called an "interfering box." A common type of box,
fering box," is so arranged that if two or more boxes on
pulled at once the signal of the first box to be started
thout interference from the others, but the signals of the
smitted. In a later development, and one that is largely
is such that if any number of boxes up to four on the
ltaneously pulled, no interference and no loss of signals
box securing possession of the line in succession, the
g their turn, so that the signals of all the boxes will be
onfusion. These are called "non-interference succession

In fire departments which have a number of engine and
s, it is customary to establish a single fire-alarm head-
box circuits center. From this headquarters other cir-
circuits," extend to the apparatus houses. An alarm
rcuit may be transmitted to the gong circuits either man-

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Manual Systems. — In manual systems the box alarm is received
quarters and then is set up on a transmitter, which, when started, a
cally repeats the alarm over the desired gong circuits. The manual
this operation may consist in placing a disc, notched on its periphery t
with the desired box number, in the transmitter, and then starting the
ism, the notches on the disc effecting the desired makes and break
gong circuits. This method is employed in the fire-alarm systen
Borough of Manhattan, New York.

Another manual method of transmission is to set up the desired box nu
a dial transmitter, which, when set in motion, transmits the alarm to
circuits. Still another method is to actually re-transmit the box numbe
ally by means of a Morse key.

Automatic Systems. — In these the relays at headquarters, w
operated by the box circuits, automatically perform the making and
of the gong circuits, and thus re-transmit the box alarm to the gong
This is advantageous in point of time saving, but has certain obje
features in removing all discretionary power from the operators at head

Confusion in Fire-alarm Nomenclature. — Considerable c
exists in the nomenclature of the fire-alarm art in various parts of t
try. For instance, the term "automatic system," instead of applyin
automatic re-transmission of the alarm at fire headquarters, is freque
plied to those systems where the original alarm is automatically se
the operation of a thermostat in a building under the influence of unc

BIBLIOGRAPHY. — See *Bibliography* in article on *Telegraph Sys*

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(*See also Galvanometers.*) The Grassot fluxmeter is essen-
vanometer, the suspension fiber of which is designed to
orsional force on the moving system when the latter is

g. 1 is a diagram showing its construction. The coil *C*
air gap between the pole pieces *NS* of a permanent mag-
co e *A*. . The system is sup-
single cocoon fiber, the upper
attached to a flat spiral spring
fect of shocks. The torsional
fiber is extremely small. *S* and
strips, serving to lead the cur-
coil *C*. These strips are in the
ich, however, are extremely
rt but a small theoretically in-
orce on the coil. An index or
the instrument, this pointer
rated scale. The fluxmeter is
irror in addition to the pointer
d in conjunction with a lamp
escope and scale.

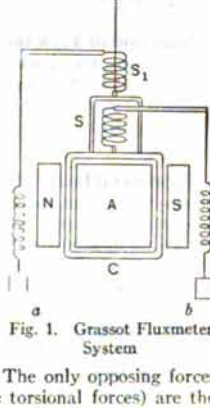


Fig. 1. Grassot Fluxmeter System

ion. — When a given quantity
rged through the moving coil,
ing the flux threading an ex-
to the terminals *a* and *b*, a
the coil tending to deflect it. The only opposing forces
and theoretically inappreciable torsional forces) are the
motion and the back e.m.f. induced in the coil due to its
ld of the permanent magnet. The latter is proportional
velocity of the coil, and the frictional force is also ap-
nal to this velocity. If both forces are directly propor-
when a given quantity of electricity is discharged through
mes to rest at a definite point, depending only upon its
on and the total quantity discharged through it. As the
discharged through an exploring coil, when the magnetic
anged, depends solely upon the change in flux and the
nd the rest of the circuit in series with it, the instrument
read directly the change in the flux density produced in
the coil. In practice the friction is not exactly propor-
nd the fiber and leading in springs usually exert an ap-
oil. The instrument therefore has not proved altogether

motor or in dynamo work an exploring coil, consisting
of wire, may be fixed or wound in position and the
uction observed on exciting the field magnet. Even in
e some minutes may be taken to reach the limit of mag-
thus introduced. The fluxmeter can also be used for the
etic field strength, pole strength and the distribution of
nets. It is also adapted to the measurement of perme-
eresis (q.v.).

gures). — A direct reading fluxmeter with one exploring
Additional exploring coils cost from $8 to $10 each.

— V. Karapetoff, *Experimental Electrical Engineering*,

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FLYWHEELS FOR LOAD EQUALIZATION. — (*See also Motors, Industrial Application of; Steel Mills, Electric Drive of.*) There methods in general use for equalizing a fluctuating load, the storage and the flywheel. The former is mostly used in connection with a ce vice where the peaks are of considerable duration and for which se flywheel is entirely unsuitable. For short fluctuating loads, such as service, mine hoists, etc., the flywheel is particularly suitable, and it applied either to the driving motor direct or to an intermediate moto tor equalizing set, depending on the operating conditions.

Selection of Flywheel. — The problem of selecting a flywheel for service is not an easy one, and each case must be treated separately. Th problem is to determine what effect a flywheel will have on smoothing load fluctuations; what effect it will have on the motor and supply whether a flywheel is warranted; and what size flywheel will result in r economy.

Flywheel Effect. — The effectiveness of a flywheel, rotating at a given of revolutions per minute, in equalizing the load, depends not only weight but also upon the square of its radius of gyration (q.v.). The p the weight of a flywheel by the square of its radius of gyration is common the "flywheel effect"; it is proportional to the moment of inertia of the A factor which limits the usefulness of a given flywheel is the allowable in speed, as the energy which a flywheel is able to give up is proportion difference between the squares of the initial and final speeds. Another be considered is the fact that a flywheel is not an inexhaustible source o The time during which it can supply a certain number of horse-power i and it can, with a given drop of speed, only supply a given number power seconds. A certain flywheel, for example, may easily take care amounting to 100 per cent overload for one second, but it may be en adequate to handle a 50 per cent overload lasting for five seconds.

Induction Motor with Flywheel. — Let the motor at any instant oping a torque T, and let the opposing torque of the load at this insta

Then $T = T_1 + \frac{I}{32.2}\frac{dw}{dt}$, where I is the moment of inertia of all the r

parts and w their angular velocity. In the case of an induction motor th T is practically proportional to the slip (*see Motors, Induction*). By maki this relation and the above equation the following working formula i deduced for the change in the torque developed by an induction moto interval during which the opposing torque of the load remains constant

T_0 = torque, in pound-feet, developed by motor at a given instant.
T = torque, in pound-feet, developed by motor *t seconds later.*
T_1 = opposing torque, in pound-feet, due to the load, *assumed constan*
R = ratio of torque (in pound-feet) to slip (expressed as a decimal for the given motor, obtained from characteristic curves of th
N = synchronous speed of motor, in r.p.m.
k = radius of gyration of flywheel, in feet (the inertia of the other parts is usually negligible in comparison with that of flywheel)
W = weight of flywheel in pounds.

Calculate the constant

$$A = \frac{308\,R}{k^2WN}.$$

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he motor t seconds from the time that its torque

$$T = T_1 - \frac{T_1 - T_0}{\epsilon^{At}},$$

system of logarithms (*see Exponential Functions*).
he load torque suddenly increases from the value
then the torque developed by the motor does not
builds up to this value at a rate depending upon
The smaller A the more slowly does the torque of
ently small and the load represented by the torque
torque of the motor may increase only a relatively
rops back to its original value. The constant A
ng a flywheel with a large flywheel effect; (2) by
by designing the motor so that for a given torque
secondary resistance.

her & Riker, *Relation of Flywheel and Motor* Elec. Jour., 1912, Vol. 9, p. 270; Gaske, F. G., *otors*, A.I.E.E., 1910, Vol. 29, p. 1385; Cheney, *n Rolling Mills*, G. E. Rev., 1911, Vol. 15, p. 411; *wheel*, Pow. and Eng., 1908, Vol. 28, p. 1043; *Safe* Pow. and Eng., 1910, Vol. 32, p. 162; Haar, S., , G. E. Rev., 1912, Vol. 15, p. 255; Motter & , A.I.E.E., 1911, Vol. 30, p. 729; Doherty, R. E., *Motors*, G. E. Rev., Aug., 1920; Clewell, C. E., *tor Operation*, Elec. W., Feb., 23, 1918; Pearce, wer, Jan. 16, 1917.

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FREQUENCY CHANGERS.— (*See also Generators; Motor Motors.*) Frequency changers are motor-generator sets in which bot are designed for operation with alternating current, but for two d quencies, thus a 25-cycle motor may drive a 60-cycle generator. Th for three general classes of work which may be typified as follows:

(a) To supply 60-cycle current for lighting from a 25-cycle po The 60-cycle current is much more satisfactory for lighting than is current.

(b) To supply 25- or 15-cycle current for single phase railway fr 60-cycle power system.

(c) To tie together two large power stations which started indepen different frequencies and as a result of growth and changed economi or ownership, find it desirable to be able to exchange energy either of evening up the demand or to meet the emergency of an accident erators of one of them. Most of the large power stations in a given ne even when owned by different corporations, are tied together to help out in case of trouble in one of them. For this type of service it that the frequency changers be "reversible," that is, either mach the driving motor.

While several types have been proposed and discussed on pape types have attained, or are likely to attain, any great commercial These are the "Induction-synchronous" and the "Synchronous-sy types. The former is not ordinarily reversible while the latter is re

INDUCTION-SYNCHRONOUS TYPE. — An induction m connected to a synchronous alternating-current generator (either sin three-phase at either end or any combination thereof) may be d choosing a suitable relation between the number of poles on each receive power at any frequency and deliver power at any other Thus a 10-pole motor operating on a 25-cycle circuit driving a 24-pol at 300 r.p.m. will deliver approximately 60 cycles. This combinati disadvantage that an increasing load causes decreasing speed an decreasing frequency in the load circuit. This can be taken care cases by choosing a ratio of poles which will give a nominal ratio of cycles for instance, and by added resistance in the secondary of th motor, regulate the speed at all loads so that the generator gives Where the secondary system or load is an independent circuit wit generators there is no objection to allowing the frequency to vary sli the nominal value.

If there are to be two frequency changers in parallel supplying t adjustment of the division of load may be accomplished either designing the resistances of the secondary of the two induction mot they have the same slip, or by having an adjustable resistance co these secondary circuits of the motors. The great advantage of the synchronous type is that, due to the characteristics of the inductio variation of one or two per cent in the frequency of either of the two s not cause a serious overload on the set, as is the case with the sy synchronous type.

SYNCHRONOUS-SYNCHRONOUS TYPE. — This consists chronous motor driving a synchronous alternating-current gener constant speed characteristic of a synchronous motor makes it p suited as the driving motor of a frequency changer, as this insures ratio of frequencies irrespective of the load on the set.

Such sets are more generally used than any other type, particular

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whose frequencies are fixed by the presence of other
considerable variation in the frequency of one system
erload on the set and may cause it to pull out of step.
ble that the capacity of the set be not too small in
of the system. The synchronous motor usually has
cage winding in its pole faces in order to assure good
duce hunting (*see Motors, Synchronous*). This type
will transfer energy either way between the systems
he reversal of the flow of energy is accomplished by
ry armatures in its cradle as described under parallel

ous-synchronous set may operate properly in parallel
rtionately with other synchronous apparatus on the
motor and generator are respectively connected, the
otor and generator must be carefully chosen. Thus
ycles per second, the highest speed which allows an
quency is 300 rev. per min., and this requires 10 poles
d 24 poles on the 60-cycle machine.
pensive sets it is frequently the custom to use a speed
4-pole machine on the 25-cycle circuit and a 10-pole
5 cycles for the other circuit. All the other machines
then operate at 62.5 cycles. Other combinations of
us combinations of frequencies can be readily calcu-
al relation between poles, speed and frequency; see
rent, and attached tables. High-speed sets with
ause they are smaller and less expensive for a given
nerator set must be provided with direct current for
n a direct-connected exciter or from a special exciter

Synchronous Sets. — The parallel operation of two
nvolves certain complicated considerations. In the
he load depends not only upon the voltage regulation
constituting a set, but upon the mechanical position
haft. Two sets built apparently the same may not
cause of inaccuracy in the placing of the key-ways,
it is customary to mount the stationary member of
ovable in a cradle, so that the angular phase position
e stationary armature) with respect to the base, may
to be operated in parallel are loaded, and the station-
ne is rotated in the cradle until the load on the two

ncy Changers. — The synchronizing of such sets is
plicated conditions must be satisfied. The theory is
ssed at length in a paper by J. B. Taylor on *Parallel*
., *Vol. 25, p. 113*, from which the attached table is
uirement is that it is necessary to synchronize not
upply circuit, but also the generator with its load
otor has been synchronized properly, it may be found
egrees out of phase with the load circuit. To bring
is necessary to cause the motor to "slip" one or more
generator comes into proper phase; this can be done
motor one or more times depending upon the number
nd on the motor. The necessity for more than one
hat with a large number of poles on both motor and

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generator there are only a few combinations in which the poles of the
the generator of one set match up with the poles of motor and ge
another set. Thus with a 10-pole motor and 24-pole generator (the
mon arrangement) when the motor slips one pole or 180 electrical deg
circuit, the generator slips $\frac{5}{12} \times 180$ or 432 electrical degrees of its
is necessary to make the motor slip 5 poles or 5×180 degrees to mak
erator slip the first even multiple of 360, that is $5 \times 432 = 2160$ o
degrees. In this case it might be necessary to make the motor slip 4 p
getting the right combination. Five reversals would reproduce the ori
ditions and, after that, more reversals would repeat the cycle of pos
binations. The table shows the possible combinations for various
used sets.

In practice, this difficulty is overcome by the use of a special syn
indicator (*see Synchronizers*) having two hands on the same dial; one h
the phase relation of each member of the set with respect to its particul
circuit. It is necessary to synchronize the set when both hands are
stationary but point to the zero position. If only the motor were
synchronized it would be found that both hands were stationary,
hand pointing to zero but the generator hand pointing to some other

POSSIBLE COMBINATIONS FOR SYNCHRONOUS-SYNCHR
FREQUENCY CHANGERS

Cycles		Poles		Speed	Kw.	Chances of correct Synch.	Field re switc
Motor	Gen.	Motor	Gen.	R. P.M.	Capacity		Motor
25	60	10	24	300	Max.	1 in 5	Yes
25	62.5	4	10	750	600	1 in 2	....
25	62.5	8	20	375	Max.	1 in 2	....
40	60	4	6	1200	150	1 in 2	....
40	60	8	12	600	3000	1 in 2	....
40	60	12	18	400	Max.	1 in 2	....
25	50	4	8	750	600	Certain	....
25	50	8	16	375	Max.	Certain	....
33.3	60	10	18	400	Max.	1 in 10	Yes
30	60	6	12	600	1000	Certain	....
30	60	8	16	450	Max.	Certain	....

Explanation of Table. — The first two columns show the fr
of the two circuits to be tied together, the third and fourth columns, the
of poles on motor and generator respectively, the fifth column, the spe
set. The sixth column, the maximum capacity in kw. in which such
available in commercial practice ("max." means as large as desire
seventh column states the chances of the set coming in right the first
indicates the maximum number of trials that might be necessary b
right combination is found; thus in the first line, four trials might h
made to secure proper synchronizing. The last two columns tell whe
necessary to have field reversing switches on each member. These ar
make the motor slip a pole and to reverse the polarity of the generator.

both members of a set reduces the number of trials
ynchronizing.
ous sets are started by means of a squirrel-cage winding
akes the motor start (at a reduced voltage) as an induc-
step without synchronizing.
pacity in the motor, particularly in field copper, these
er-factor correction of the motor circuit by over-excita-

sets is quite high, but is of course the product of the
chines. The machines may be wound for high voltage,
d of transformers for voltages of 13,000 or less. Two-
e quite popular in order to economize in space and in

FREQUENCY CHANGERS. — When the stator
excited from a supply circuit having a frequency of f_1
e rotor of this motor is driven by another motor in the
t in which it would rotate due to the currents in its
ency of the current induced in the rotor winding is

$$f_2 = \frac{N_0 + N}{N_0} \cdot f_1,$$

s speed of the motor and N = actual speed at which its
mbination of two motors (the driven motor really acts
therefore be used as a frequency changer.
n the driven motor, the electrical input into its stator is

× (output of set at frequency f_2)

ut of the driving motor is

× (output of set at frequency f_2).

n is less expensive than the usual motor-generator set,
of poor regulation, as every change in the potential of
nsmitted to the receiving circuit; it is therefore but

EQUENCY CHANGERS. — See article on *Radio*

— Taylor, J. B., *Parallel Operation of Frequency*
E., Vol. 25, p. 113; Funk, N. E., *Operation of Frequency*
E., Vol. 32, p. 1713; Harris and Bonnett, *Frequency*
c., 1913; Townsend, R., *Frequency Changers*, Br. I.E.E.,

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FREQUENCY INDICATORS. — The frequency of the current by a generator may be determined directly from its speed, N revolut minute, and number of poles p, from the formula

$$f = \frac{Np}{120}.$$

The same formula also applies to a synchronous motor, N and p being and number of poles of the motor. The speed may be measured by a r counter and stop watch or by means of a tachometer, or speed indicat latter may be calibrated to read the frequency directly for a given gen motor.

By the term Frequency Indicator or Meter is to be understood an ins the indications of which are determined directly by the frequency of t connected to its windings, as distinguished from an electrical Tacho Speed Indicator which generally consists of a D.C. Voltmeter opera permanent field generator, the scale being calibrated to read "cycle permanent field generator, or so-called magneto, is directly driven from of the A.C. generator, the frequency of which it is desired to measure in

INDICATING FREQUENCY METERS. — Indicating frequenc are made in a variety of types, the most common being (1) the moving moving-coil type, (2) the induction type, and (3) those operating on ciple of the mechanical resonance of an iron reed acted upon by the field produced by a current from the given source.

Other types, less common, consist of a synchronous motor with an att for indicating its speed on a scale which is calibrated in frequency.

A wave meter is a type of frequency meter used for measuring radio fre which are much higher in value than the frequencies used in power wo description, see *Wave Meters*.

Moving-vane Type of Frequency Indicator. — A common form quency indicator of this type consists of a moving vane, with pointer att mounted that it is acted upon by two coils set at right angles to each oth coil is connected in series with a non-inductive resistance and the other with a comparatively large inductance. The vane tends to set itself in t tion of the resultant field due to the currents in two coils, there being trolling spring, and consequently for a fixed ratio of these currents the va up a definite position irrespective of the values of these currents. circuits are so connected to the source of supply that when the volta the mains varies, the voltages across the two circuits of the instrum proportionally to each other, and therefore the position of the vane and is unaffected by voltage variations. An increase in the frequency, decreases the current through the inductive circuit relative to that thr non-inductive circuit, and consequently causes a deflection of the v pointer; similarly a decrease in the frequency increases the current thr inductive circuit, producing a deflection in the opposite direction. Th ance and inductance of each circuit is so adjusted that for the stand quency, e.g., 60 cycles, the pointer stands in the middle of the scale. instrument is suitable for a range of frequency generally from about 25 below, to 25 per cent above normal frequency.

Effect of Wave Form. — Such instruments are affected to a ve extent by the wave form of the voltage on the mains to which they are co

This is readily understood by considering that wave forms differing fro sine are the equivalent to a superimposed higher frequency harmoni affects the frequency meter in the same way as would a higher frequenc

umerous expedients have been devised to overcome
ibinations of resistive and inductive circuits, and by
ble resistance in series with the inductance, this resist-
nd with the wave form on which the instrument is to

Frequency Indicator. — This type is similar to the
that two moving coils, rigidly fastened together, con-
t and the stationary element is a single coil.

Frequency Indicator. — A form of instrument of
nsitiveness is greatly increased, is described by *Pratt*
E., 1912, Vol. 31, p. 1505. The two moving coils or
in series with suitable resistances, inductances and
hat the two circuits are nearly in electrical resonance
with the impressed frequency. A 6-inch deflection of
of the instrument is readily obtained for a change of
ycles per second, and by changing the constants of the
n can also be obtained for a change of frequency from
. This instrument shows only a trace of variation due
temperature

ency Indicator (see Fig. 1) — In these instruments a
rque in opposite directions by two small shaded pole
ction
n in-
e cir-
s in-
other
ve, *H*
ating
n one
the
disk
lative
The
on in
nced,
nd on
the
e cur-
ment
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asure

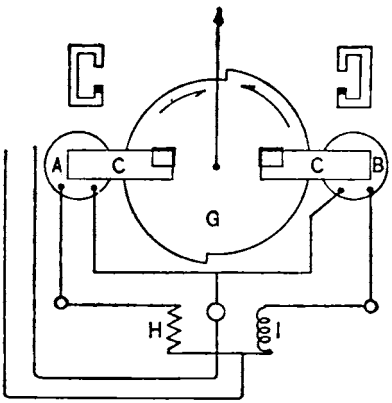


Fig. 1.

om the above that the moving vane, moving arm, and
meters do not operate with a control force such as a
oltmeters, etc. The introduction of such a mechanical
er the instruments sensitive to changes of voltage and
ould vary the electrical torque without changing the
e, thus producing an error. Therefore, all these fre-
ements and pointers which will remain at rest at any
aced when not connected to the circuit. When coils
ment assumes a position at which the differentially-

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Vibrating-reed Type of Frequency Indicator. — In these instru series of vibrating reeds is provided, each tuned to vibrate at a frequenc sponding to a certain number of cycles per second, or sometimes the t done for differences as small as ¼ cycle per second or less. Some arra is provided by means of which the frequency of the alternating circuit municated to these vibrating reeds. In one arrangement all of the r mounted on a common support which is vibrated by a single electr through which the alternating current whose frequency is to be measure In another arrangement the reeds are attached to a rigid support but structed of magnetic materials and acted on by one or more electro directly. These instruments are quite accurate in service if the voltag varied beyond that for which the instruments are intended, in which wrong reed may be made responsive.

The frequency of modern power circuits varies but little and the rate tion is slow. Thus the pointers of the usual frequency meters are g either at rest or moving very slowly, introducing a personal element of c the part of the observer as to operativeness. The argument in favo vibrating reed frequency meter is that the indicator is in motion cor showing that the instrument is operating. On the other hand, frequency indicating by means of pointers and graduated dials in the same way meters and ammeters, are generally preferred, being more easily read.

Miscellaneous Indicators. — Graphic recording frequency meters on the same principles and have movements similar to those of movi moving coil, or induction-indicating instruments, to which are added cloc paper charts and pens for recording the frequency variations at different

Cycle counters can be considered as a variety of frequency meters a not intended primarily to measure frequency. They consist of a cloc the escapement of which is controlled by a vibrator oscillated by an magnet connected to an alternating current circuit. The dials oper the clock train indicate the number of alternations elapsed or occurrir connected to the circuit. Conversely, if allowed to be connected to an cuit of unknown frequency for a fixed length of time, as for example, 10 s the frequency may be determined. The principal use of cycle counte timing relays, etc., instead of using stop watches, as much greater acc possible than with the stop watch. The frequency of the circuit sh either known or can be readily determined by operating the cycle count period of time which can be readily measured by ordinary means, suc seconds. Then, intervals of time as short as 1 cycle can be readily m within an error equal to 1 alternation, which is obviously an impossibili stop watches. By the use of cycle counters, chronographs or oscillogra avoided for timing purposes, unless time intervals within an error of le one alternation are to be determined.

COST OF FREQUENCY INDICATORS. — Switchboard fr meters of the moving-vane induction or moving-coil type (not tuned), co $45 to $65. The tuned, or electrical resonance, switchboard type cost fr to $85. Vibrating-reed frequency indicators for switchboard service co $35 to $95; portable indicators of this type cost from $110 to $125 included in both cases. The various types are made for standard freque 25, 40 and 60 cycles per second and for circuits of 110 or 220 volts. Fo voltages potential transformers should be used.

BIBLIOGRAPHY. — Jansky, C. M., *Electrical Meters*, N. Y., 1913 and Rice, *Resonant Circuit Frequency Indicator*, Trans. A.I.E.E., 1912, p. 1595; Bulletins of Manufacturers.

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Automobiles, Electric; Bearings; Belts and Belting; ns; Friction Drive; Gears and Gearing; Hydraulics, nd Lubrication; Pipes and Piping; Railways, Energy nd Rope Drive; Valves; also under name of machine

he tangential force set up whenever an external force g to move it, or actually moving it, over the surface distinct types of friction, namely, "sliding friction" gain, the force required to start a body sliding or another body (in addition to the force required to he first body) is in general greater than the force r rolling at slow speed after it is once started. The dy is called the "static friction" or the "friction of l to keep it in motion is called the "kinetic friction" ." There is evidence to indicate that there is no e of the friction from rest to motion, but that the , varying rapidly with the speed at low speeds. At with the speed, at moderate speeds it is nearly con- increases rapidly with the speed. Air friction must at very high speeds.

LIDING FRICTION (*f*) AND ANGLE OF RE-

ent of sliding friction is defined as the ratio of the body along a horizontal plane surface to the normal ssing the body against this surface. If the body is e and the force normal to this plane is due only to e angle of inclination of this plane to the horizontal is called the angle of repose. The tangent of this ient of static friction, i.e.,

$$f = \tan \theta.$$

is a special case of sliding friction (*see Bearings*).

Coefficient of Sliding Friction. — For a given unit area perpendicular to surface of contact) the proximately independent of the area of contact, all ame, except in the case of fibrous materials, in which s with extent of surface.

n, however, is as a rule materially affected by the moothness of the surfaces in contact, the condition dry, moist, greasy or oily), temperature in case of

inst Solids. — Thurston states that for all fluids, the resistance is: (1) independent of the pressure act; (2) directly proportional to the area of rubbing- the square of the relative velocity at moderate and locity nearly at low speeds; (4) independent of the he solid against which the stream may flow, but de- pon their degree of roughness; (5) proportional to d related in some way to its viscosity (*see Pipes and ples of*).

Surfaces approximates more closely the laws of roughly the surface is lubricated (*see also Bearings;*).

ent of Sliding Friction. — Due to the numerous fficient of friction, the values of this coefficient given

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by various authorities are found to differ widely. The table below to indicate the order of magnitude of the coefficient in the cases sta should be kept in mind that these values are only rough approxim *also Belts and Belting, Brakes and Braking Systems; Ropes and Rope*

COEFFICIENT OF STATIC FRICTION BETWEEN DRY, SM SURFACES

Materials	Pressure, lb. per sq. in.	*f*	Autho
Wrought iron on wrought iron	187–560	0.25–0.41	Rennie.
Wrought iron on cast iron	187–672	0.28–0.38	Rennie.
Steel on cast iron	187–672	0.30–0.40	Rennie.
Brass on cast iron	187–784	0.21–0.23	Rennie.
Yellow pine on yellow pine	100–1500	0.25–0.32	Messiter a
Spruce on spruce	100–800	0.18–0.53	Messiter a
Metals on metals	.....	0.15–0.25	Rankine.

COEFFICIENT OF STATIC FRICTION AND ANGLES OF F OF BUILDING MATERIALS

Materials	Angle of repose, degrees	*f*	A
Dry masonry and brickwork	31–35	0.6–0.7	
Masonry and brickwork with damp mortar	36.5	0.74	
Masonry on dry clay	27	0.51	
Masonry on moist clay	18.25	0.33	
Timber on stone	22	0.4	
Timber on timber	11.3–26.5	0.2–0.5	
Timber on metals	11.3–31	0.2–0.6	
Iron on stone	16.7–35	0.3–0.7	
Earth on earth	14–45	0.25–1.0	

COEFFICIENT OF KINETIC FRICTION (*Rankine*

Materials	Dry surface	Wet surface	Soapy surface
Wood on wood	0.25–0.5	.....	0.04–0.2
Metals on oak	0.5–0.6	0.24–0.26	0.2
Metals on elm	0.2–0.25	.....	.....
Metals on metals	0.15–0.2	0.3	.....
Hemp on oak	0.53	0.33	.....
Leather on oak	0.27–0.38	.....	.....
Leather on metals	0.56	0.36	0.15–0.23
Bronze on lignum vitæ	.....	0.05	.....

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lding Friction. — Let

n,
ormal to surface of contact,
second,

$$\text{oot-pounds per second} = \frac{fWv}{550} \text{ h.p.}$$

ROLLING FRICTION. — Let

ounds tangent to circumference of wheel,
eet,
unds,

g friction (f) is defined by the relation

$$F = \frac{fW}{r}.$$

epends upon the unit in which r is expressed. If r is
of feet f will be 12 times as great.

Coefficient of Rolling Friction. — Rolling friction
regularities of form and the roughness of surface of
other. Its laws are not yet definitely established in
ainty which exists in experiment as to how much of
ghness of surface, how much to original and permanent
how much to distortion under the load. See also
Resistance to Rolling of a Hard Body Over a Plastic
pp. 478 and 555, Aug. and Sept., 1915.

lction. — The following are some reported values of
expressed in feet,

oak track	0.0016
ck	0.0027
steel rail	0.0015–0.002
el on soft soil	0.065
el on smooth hard road	0.02
el on wood	0.0185
el on asphalt	0.012

olling Friction. — Let

on, in feet,
on wheel, in pounds,
feet,
ons of wheel per second,
per second,
tion is

$= 6.28 fWn$ foot-pounds per second

$$= \frac{fWn}{87.5} \text{ h.p.}$$

Numerous references will be found in *Kent's Mechani-*

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FRICTION DRIVE. — (*Adapted from paper by W. F. M. Go*
A.S.M.E., 1907.) A friction drive consists of a fibrous or somewha
driving wheel working in rolling contact with a metallic driven wh
a drive may consist of a pair of plain cylinder wheels mounted upo
shafts, or a pair of beveled wheels, or of any other arrangement
serve in the transmission of motion by rolling contact.

Suitable fibrous materials for the driving wheel are straw fiber, lea
tarred fiber, sulphite fiber, or leather; suitable materials for the dri
are iron, aluminum and type metal. See also P. L. Weston, *Magn*
band Drive, El. Rev. 81, p. 383, Oct. 19, 1917.

Crushing Strength and Safe Load for Fiber Wheels. — The
strength of each fibrous material, as determined by finding the lo
which the wheel failed before 15,000 revolutions had been made, is
the following table, together with the safe working load, taken as one

Material	Crushing load, lb. per in. width	Sa lb.
Straw fiber.....	750	
Leather fiber.....	1200	
Tarred fiber.....	1200	
Sulphite fiber.....	700	
Leather.....	750	

Coefficient of Friction. — The coefficients of friction between the various fibrous materials and the three metals are given in the table below, these being maximum values, corresponding to a slip of about 2 per cent. The friction at constant slip was found to be practically independent of the pressure between the limits of 150 and 400 pounds per inch width of face in contact.

Horse-power Transmitted. — Goss gives the following formula
maximum horse-power which can be safely transmitted by a friction d

$$P = \frac{\pi d}{12} \times \frac{WPN \times 0.6f}{33{,}000} = kdWN,$$

in which d = diameter of driving wheel in inches, W = width of face
P = safe working pressure in pounds per inch of width, N = revolu
minute, f = coefficient of friction, 0.6 a factor for the decrease of the
in service and for the loss in journal friction, k a coefficient including
the numerical constants.

COEFFICIENTS OF FRICTION AND HORSE-POWER OF FRI
DRIVES

Surface of Driving Pulley	On iron		On aluminum		On type m	
	f	k	f	k	f	
Straw fiber.....	0.255	0.00030	0.273	0.00033	0.186	0.0
Leather fiber.....	0.309	0.00059	0.297	0.00057	0.183	0.0
Tarred fiber.....	0.150	0.00029	0.183	0.00035	0.165	0.0
Sulphite fiber.....	0.330	0.00037	0.318	0.00035	0.309	0.0
Leather.....	0.135	0.00016	0.216	0.00026	0.246	0.0

BIBLIOGRAPHY. — Additional data on friction drive will be
Kent's *Mechanical Engineers' Pocket-Book*.

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s; Calorimeters, Fuel; Gas; Gas Producers; Power
s are wood, peat, coal, charcoal, coke, petroleum
e raw state all contain carbon and hydrogen as
, together with oxygen, nitrogen, sulphur, earthy
are undesirable and detract from the value of the
f sulphide of iron, which frequently exists in coal,
combustion.

he production of large amounts of energy. Peat,
iarshes by the partial decomposition or destructive
erials, is unsuitable for fuel until dried. Although
for both heating and power purposes, its use
gone beyond the experimental stage. Charcoal
fter evaporating the major portion of the volatile
at, or other vegetable matter. Coke is similarly
er evaporating the volatile ingredients of coal.
, with slightly metallic luster, porous, brittle and
e., absorbs and retains moisture when exposed to
al yields from 0.35 to 0.90 pound of dry coke,
coal from which it is made. Coke is used chiefly
ries; its high cost prevents its use for the pro-

used are coal, oil and gas. Coal and oil will be
a discussion of gas see the article on *Gas*.

n a fuel is heated to red heat in a non-oxidizing
the solid residue is called "fixed carbon." The
eous compounds which distil off are called "vola-
burns or oxidizes, the solid mineral matter left is
state also contain a certain amount of water or
rbon and volatile matter together are called the
nitrogen and oxygen in the volatile matter are not
determination of the fixed carbon, volatile matter,
is called the "proximate analysis." The deter-
nd ash of the fuel and the constituent elements of
rbon, hydrogen, oxygen, nitrogen and sulphur, is
s." The "heating" or "calorific" value of a fuel
eat energy developed as the result of the complete
t (or mass) of the fuel. In this country and in
s expressed in British thermal units, abbreviated
-lb. = 0.2928 watt-hour = 3.927×10^{-4} hp.-hr.)
1 pound. The heating or calorific value should
t.u. per pound of *combustible*, although it is some-
ound of *dry fuel* or per pound of *fuel as fired* (in-

S. — The analyses of the solid fuels given above
Wood when freshly felled contains on an average
ure, varying with different species. After eight to
e open air, the moisture is reduced to 20 or 25 per
greater dryness, it will, on exposure to the atmos-
n, and the percentage it will then contain will vary
ss of the air; that is, wood is hygroscopic.
be surface moisture, received from rain while being
d which may be dried out on exposure to the atmos-
ure, contained inside of the lumps, which cannot be

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dried out without subjecting the coal for some time to a temperatu
ably above 212° F. The anthracite, the semi-bituminous coals an
minous coals of the Appalachian coal field seldom contain hygroscop
in excess of 1 or 2 per cent, but it is a characteristic of the western
coals and lignites that the hygroscopic moisture is much higher; th
Illinois coals it is as high as 14 per cent. When this moisture is dr
coal will again absorb it on being exposed to the atmosphere. So
contain as much as 40 per cent moisture.

ULTIMATE ANALYSES OF VARIOUS FUELS. — Typic
analyses of various fuels together with the percentage of ash are g
the analyses are for fuels from which all moisture has been expelled

	C	H	O	N	S
Wood	50	6	41	1	..
Peat	59	6	30	1	..
Lignite	69	5	16	1	1
Bituminous coal	76	5	10	1	1
Semi-bituminous coal	86.5	4.5	3	1	0.
Semi-anthracite	78.5	3.5	2	1	2
Anthracite	77	2.5	2	1	1
Charcoal	82	2	..	1	..
Coke	89	..	..	..	1
Petroleum (Texas)	84.5	11	3	..	1.
Natural gas	70	25	1	4	..

In the progression from wood to anthracite, the chief change in ch
stitution, as shown in the above table, is a decrease in the oxygen from
to 2 per cent. The hydrogen also decreases, but less rapidly. In all t
of coal, the ash is exceedingly variable, ranging from as low as 2 per
25 per cent or more. Coals high in ash are usually also high in sul
ash and sulphur may be removed to a considerable extent by c
washing.

AIR REQUIRED FOR COMBUSTION. — The theoretical w
A required for complete combustion of 1 lb. of fuel may be deter
the formula,

$$A = 0.115\,C + 0.346\left(H - \frac{O}{8}\right) + 0.043\,S,$$

where C, H, O and S are the percentages (by weight) of carbon,
oxygen and sulphur in the fuel. This gives about 12 lb. of air pe
combustible. In the best boiler practice, the weight of air required is
20 lb. per pound of coal, but in actual practice, the air supplied vari
much wider limits. See article on *Boilers*.

COAL. — **The proximate analysis** of coal is made by separatin
by successive heatings at different temperatures, into moisture, volat
fixed carbon and ash. For the determination of moisture, a r
sample, say 2 ounces or 60 grams, should be taken, crushed to ab
size, and heated for two hours to 140° C. (284° F.) or until the coa
decrease in weight. If a finely crushed small sample is taken, m
moisture may be lost by air-drying while crushing and weighing

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constituents, a sample of about 1 gram of finely
or an hour at 105° C. (221° F.) and weighed, then
covered crucible until all the volatile matter is
ith a blast lamp to a white heat, the cover being
carbon is burned away, leaving the ash, which is
d be reported as in the example below, the per-
weight.

	Moist coal	Dry coal	Combustible
.....	10.0	.....	.....
.....	30.0	33.33	57.14
.....	40.0	44.45	42.86
.....	20.0	22.22	.....
	100.0	100.0	100.0

Proper sampling of coal is difficult. So much
be properly done. For instructions in this field,
Mines and Reports of Committee D-5, A.S.T.M.

The percentages of fixed carbon and volatile mat-
sh a means of classifying different kinds of coal.
ows:

	Fixed carbon	Volatile matter	Heating value per lb. of combustible, B.t.u.
....	97 to 90	3 to 10	14,600 to 15,000
....	90 to 85	10 to 15	14,700 to 15,500
....	85 to 75	15 to 25	15,500 to 16,000
....	75 to 60	25 to 40	14,800 to 15,500
....	65 to 50	35 to 50	13,500 to 14,800
....	Under 50	Over 50	11,000 to 13,500

ey classifies coals into six groups, as follows: (1)
cite; (3) semi-bituminous; (4) bituminous; (5)
ite; and (6) lignite.

iny, burns with little or no smoke, is slow to ignite,
small pieces when rapidly heated. Anthracite is
e lumps separated into different sizes by passing
bars.

imilar to anthracite, but is less hard, less shiny
t can usually be distinguished by its tendency to
thracite does not.

al is softer than semi-anthracite. The combustible
coals is very uniform in composition. The volatile
22 per cent of the combustible matter. Such fuels

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are usually low in moisture, ash and sulphur and rank among the best st coals in the world.

The ash content runs from 3 to 8 per cent and for the higher grade heating value is in the neighborhood of 14,500 B.t.u. or better, per po dry coal.

Bituminous coal is also a soft coal. It is distinguished by hig centage of volatile matter, which causes it to give off dense volumes of when heated. It requires careful firing and furnaces especially adapte to prevent smoke. There is a wide variation in its physical properties.

Sub-bituminous coal is commonly known as "black lignite." generally black and shining, closely resembling bituminous coal, "weathers" or disintegrates more rapidly on exposure and lacks the pri structure of bituminous coal. Its calorific value is generally less than bituminous coal.

Lignite, or "brown coal," is intermediate between coal and pe usually has a woody structure and is distinctly brown in color, even on fracture. It carries a higher percentage of moisture than any other c coals, its mine samples showing from 30 to 40 per cent of moisture. fragile and rapidly splits into fine pieces upon exposure to air.

The following analyses of representative coals of the six classes are gi Prof. N. W. Lord:

Class 1. Anthracite Culm. Penn.
Class 2. Semi-anthracite. Arkansas.
Class 3. Semi-bituminous. W. Va.
Class 4(*a*). Bituminous coking. Connellsville, Pa.
Class 4(*b*). Bituminous non-coking. Hocking Valley, Ohio.
Class 5. Sub-bituminous. Wyoming, black lignite.
Class 6. Lignite. Texas.

COMPOSITION OF ILLUSTRATIVE COALS—CARLOAD SAMPL

Proximate Analysis of "Air-dried" Sample

Class	1	2	3	4a	4b	5	
Moisture	2.08	1.28	0.65	0.97	7.55	8.68	9
Vol. comb.	7.27	12.82	18.80	29.09	34.03	41.31	3
Fixed carbon	74.32	73.69	75.92	60.85	52.57	46.49	4
Ash	16.33	12.21	4.63	9.09	5.85	3.52	1
Loss on air-drying	3.40	1.10	1.10	4.20	Undet.	11.30	2

Ultimate Analysis of Coal Dried at 105° C.

Hydrogen	2.63	3.63	4.54	4.57	5.06	5.31	4
Carbon	76.86	78.32	86.47	77.10	75.82	73.31	6
Oxygen	2.27	2.25	2.68	6.67	10.47	15.72	1
Nitrogen	0.82	1.41	1.08	1.58	1.50	1.21	1
Sulphur	0.78	2.03	0.57	0.90	0.82	0.60	1
Ash	16.64	12.36	4.66	9.18	6.33	3.85	1

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OF ILLUSTRATIVE COALS — *Continued.*

ed to an Ash and Moisture Free Basis						
	2	3	4a	4b	5	6
1	14.82	19.85	32.34	39.30	47.05	45.31
)	85.18	80.15	67.66	60.70	52.95	54.69
Ultimate Analysis						
5	4.14	4.76	5.03	5.41	5.50	5.05
)	89.36	90.70	84.89	80.93	76.35	73.21
1	2.57	2.81	7.34	11.18	16.28	18.65
3	1.61	1.13	1.74	1.61	1.25	1.47
)	2.32	0.60	1.00	0.87	0.62	1.62
er pound of Combustible by Dulong's Formula						
?	13,406	15,190	13,951	12,510	11,620	10,288
)	15,496	16,037	15,511	14,446	13,235	12,889

— The heating value of coal depends on its percent-
nd on the heating value per pound of that com-
in different districts and bears a relation to the
r as shown by the above table.
tile matter is less than 40 per cent of the combustible,
of combustible may be approximately determined
means of the following table. When the volatile
ent, the figures in the table may have a plus or minus
cent, since the coals high in volatile matter differ
xygen.

Volatile matter, per cent of combustible	Heating value, B.t.u. per pound of combustible	Volatile matter, per cent of combustible	Heating value, B.t.u. per pound of combustible
28	15,660	43	14,220
32	15,480	45	13,860
37	15,120	47	13,320
40	14,760	49	12,420

und of combustible of all the semi-bituminous coals,
cent of volatile matter in the combustible, is within
u. per pound. This is within the limits of error of
sis or of calorimetric determination.

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The heating value of any coal may also be calculated from t analysis by means of Dulong's formula,

$$\text{B.t.u. per pound} = 146\,C + 620\left(H - \frac{O}{8}\right) + 40\,S,$$

in which C, H, O and S are respectively the percentages by weig hydrogen, oxygen and sulphur. The probable error of this formula 2 per cent for any coal containing less than 40 per cent volatile m combustible. For coals higher in volatile matter, the error is somet When the percentages are expressed as percentages of the various the *combustible*, the formula gives the B.t.u. per pound of combus the percentages are percentages of the various elements in a give **coal**, the formula gives the B.t.u. per pound of coal, which is, of cour the B.t.u. per pound of combustible in proportion to the per cent and ash present. In general, if K be the per cent of combustible sample, and H the heating value per pound of combustible, the he per pound of coal is $\frac{KH}{100}$.

For the direct determination of the heating value of coal or othe a bomb calorimeter, in which the fuel is burned in an atmosphere of oxygen, is the most accurate instrument. (*See Calorimeters, Fuel.*)

Average Heating Values. — The following figures give t commercial heating values of the principal power plant fuels, otl and gas.

	B.t.u
Anthracite	11
Semi-anthracite	
Semi-bituminous coal	14
Bituminous	11
Lignite (as fired)	
Lignite (dry)	
Coke	
Charcoal	11
Peat (as fired)	4
Peat (dry)	5
Wood (dry)	6
Bagasse (45 to 55 per cent water)	
Tan bark (65 per cent water)	
Tan bark (dry)	6
Straw	5

The Commercial Value of a Coal is not always in direct p its heating value. Excessive moisture causes a reduction in its ter combustion, which reduction, in steam boiler practice, decreases th excessive ash tends to obstruct the draft and thus cause imperfect High percentages of volatile matter tend to cause smoke and soot, the use of special furnaces.

Specifications for Coal. — For the reasons just stated, contracts chase of coal on specifications of quality should penalize excess of m and volatile matter above certain stated percentages. For a full d purchase of coal by specification and specifications used by the U see latest Bulletins of the U. S. Bureau of Mines relating to this subj specifications are as follows:

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l-anthracite. — **The standard is a coal containing** not over 2 per cent moisture and not over 10 per 5 per cent on the price will be given for each per 5 per cent up to and including 15 per cent, and a e price will be made for each 1 per cent of moisture

nd Eastern Bituminous. — The standard is a ning not over 20 per cent volatile matter, 2 per t ash. A reduction of 1 per cent in the price will of volatile matter in excess of 25 per cent, and of t of ash and moisture in excess of the standard.

or western coals in which the volatile matter differs xygen, the above specification based on proximate tly accurate, and it is well to introduce the heat- her by a calorimeter or by calculation from the

ntaining not over 6 per cent moisture and 10 per ple, and having a heating value of 14,500 B.t.u. free from moisture and ash). For lower heating l, the price shall be reduced proportionally, and e in ash or moisture above the specified figures, be deducted.

ge. — **The space occupied by a ton of coal depends** e coal and the size of the lumps. A ton of 2240 size, or smaller, occupies a space of from 36 to 45 ounds of bituminous coal occupies a space of from nating the space required for storage, 45 cubic feet lly assumed.

nthracite coal when exposed to the weather under- xcept the oxidation of the sulphur content, which ntains a larger percentage of sulphur, the oxidation ent amount, may develop sufficient heat to cause me lignites are rapidly disintegrated when exposed carload lots of Illinois coal (*F. W. Wheeler, Trans.* the screenings and 3-inch nut coal lost 1.3 per cent nonth, and 2 per cent in six months. Pillar coal round twenty-two to twenty-seven years, showed lue than the fresh face coal from the same mine.

of coal delivered to any power plant depends not coal and the size of the lumps, but also upon the ailroad or water facilities for delivering the coal, affecting the cost of mining. In making an esti- al, one should obtain quotations from the dealers me under consideration.

lso Boilers; Gas Engines.) Crude petroleum and eum, such as gasoline, kerosene, etc., are largely eir use in any locality depending chiefly on their ith coal. In Texas, California, Russia and other d where coal is relatively expensive, petroleum a fuel for steam boilers. Gasoline, kerosene and ely used in various types of internal combustion s composed chiefly of hydrocarbons, which distil at

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different temperatures, the lightest vapors being driven off as low as and heavier vapors and oils at temperatures rising to 600°, above wh and residuum are formed. The crude oil contains small percentage sulphur and oxygen as impurities. The specific gravity, weight an value of California oil are given as follows by J. N. LeConte (*Jour. Aug., 1911*):

CALIFORNIA OIL

Degree Baumé	Specific gravity	Weight per barrel, pounds	B.t.u. per pound	B.t.u. p (42 g
10	1.000	350	18,280	6,39
12	0.986	345	18,400	6,34
14	0.972	340	18,520	6,30
16	0.959	336	18,640	6,25
18	0.946	331	18,760	6,21
20	0.933	327	18,880	6,16
22	0.921	322	19,000	6,12
24	0.909	318	19,120	6,08
25	0 903	316	19,180	6,06

Oils from other sources have different densities and heating va Lima, O., crude is reported to have a sp. gr. of 0.792; Beaumont (sp. gr. 0.92, B.t.u. per pound 19,060; Pennsylvania heavy crude, sp. B.t.u. 20,736; Caucasian light crude, sp. gr. 0.884, B.t.u. 22,027. oil, six lots, used in a boiler test at Redondo, Cal., contained moist 2.70 per cent; sulphur 2.17 to 2.607; B.t.u. per pound 17,717 to 17,96

The following table shows the relative heating values of crude petr coal, based on oil of sp. gr. 0.885; B.t.u. per pound 20,000; 1 barrel, = 310 pounds.

Coal B.t.u. per pound	1 pound oil = pounds coal	1 barrel oil = pounds coal	1 ton (22 coal = b
10,000	2	620	3
11,000	1.818	564	3
12,000	1.667	517	4
13,000	1.538	477	4
14,000	1.429	443	5
15,000	1.333	413	5

Advantages of Liquid Fuel. —

1. Reduction in number of firemen in proportion of 5 or 6 to 1.
2. Easy lighting of fires and more regular supply of heat.
3. Fires readily regulated to suit demand for steam, and can be extinguished.
4. Small proportion of refuse and its easy disposal.
5. Storage tanks can be located to best advantage, while coal bin near the boilers.

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no loss by banking.

ld Fuel. —

ited by some city ordinances.
prohibited by some cities.
mixture with air.

nable roaring noise.
become coated with residue.
creep by valves and leak.
apparatus to start oil fire or maintain it or both.

Oil Fuel. — Although boiler efficiencies as high as orted with oil-burning furnaces, the average is prob-., the efficiency with oil is about 2 per cent higher

nd Alcohol. — The following is taken from the (1914):

	Spec. grav. at 15° C.	Cal. per gram	B.t.u. per lb.
	0.684–0.694	12,210–12,220	21,980–22,000
	0.710–0.730	11,100–11,400	19,980–20,520
	0.790–0.800	11,000–11,200	19,800–20,160
	0.8196–0.8202	6,440– 6,470	11,590–11,650

ee articles on *Gas and Gas Engines*.

Steam, published by the Babcock & Wilcox Co.; *Economy*; numerous Bulletins and Technical Papers logical Survey and the Bureau of Mines. A list of ned from the Bureau of Mines, Washington, D. C.; *neering of Power Plants;* Moore, Elwood S., *Coal;* Univ. of Ill., Bulletin 116, 1920; Muhlfeld, J. E., *ves*, A.S.M.E., Trans. Vol. 38, p. 1043; Lewis, V. D., Putsch, A., *Gas and Coal Dust Firing;* Moore, *nternal Combustion Engines;* Ellis and Meigs, *Gaso-* Herington, C. F., *Powdered Coal as a Fuel.*

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FURNACES, ELECTRIC, AND ELECTRIC FURNAC UCTS. — (*See also Electrochemical Processes, Industrial.*) Elect may be classified as follows:

Arc furnaces.
Induction furnaces.
Resistance furnaces.
a. Current conducted by the materials heated:
1. With electrolysis.
2. Without electrolysis.
b. Current conducted by a special resistor.

In the arc furnace the heat is produced by an electric arc (*see A* usually between carbon electrodes. The induction furnace is e static transformer (*see Transformers*) with the low-tension "windi by the material to be heated. In the resistance furnace the cur plied to the material to be heated (i.e., to the furnace "charge", special resistor, by connecting the charge or resistor directly to the s current supply. The heat developed in both the induction and res naces arises from the passage of the current through the resistanc the charge or special resistor.

The arc furnace may be considered a resistance furnace in which is a gas. Since the resistance of a gas at atmospheric pressure is g that of any solid resistor of the same dimensions as the arc, the amo that can be produced in a small space will be greatest with an arc f

TEMPERATURE AND DISTRIBUTION OF HEAT. — tage in electric heating is that a higher temperature can be produ using fuel, that the heat is produced inside the furnace where it is that the heat can be easily and accurately regulated. In the arc part of the positive carbon is estimated to be between 3900° C. a absolute. (*Waidner and Burgess, Bull. Bureau Stds., Vol. 1, p.* The temperature of the arc itself increases with the current. (*Ka buch der Spektroscopie, Vol. 1, pp. 154–160, 1900.*)

The electric energy delivered to the furnace as heat is used as to heat the charge to the desired temperature, which involves the furnace walls, if cold at the start. This energy is equal to the charge times the temperature rise times the specific heat. If t melted or vaporized in the furnace, additional heat must also This item may be reduced by delivering the charge to the furnace as in steel refining. (2) To supply the energy needed for the r energy so required cannot be reduced. (3) To supply the loss duction and radiation through the walls and electrodes, and the hea by hot gases. A part of the heat carried off by hot gases may be heating water in boilers, so that it is not a complete loss.

MAXIMUM SIZE OF ELECTRIC FURNACES. — The l able capacity of an open-arc single hearth with a compact bundle has been found in practice to be from 2500 to 3000 kilowatts at fro 40,000 amperes and from 75 to 90 volts. These large sizes are with the three-phase system, so that the maximum total power abs furnace is from 7500 to 9000 kilowatts. In carbide furnaces double furnaces are used with six electrodes, in place of three, in the sam the power absorbed is from 15,000 to 18,000 kilowatts. Great progr made in electric-furnace construction, by closing the furnace at the having special means of feeding in the charge, thereby avoiding t sance and protecting the workmen from the heat, as well as dist

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ussig, VII Int. Cong. App. Chem., Sec. 10, p. 24, ol. 5, p. 254, 1909; VIII Int. Cong. App. Chem.,

WALLS. — To reduce the conduction of heat les to a minimum amount, these must be properly ough the walls of three different shapes may be low. In all cases

of the walls, at the mean temperature $(t_1 + t_2)/2$. ay be expressed in any convenient unit, e.g., gram ter cube per second per °C., or watts per inch rticle on *Heat and Thermal Properties* for values. er second through the walls.
ide surface of the wall.
side surface of the wall.

lle!opiped. —

$$\left(+ 0.54\,\Sigma l + 0.15\,n\vartheta\right) k(t_2 - t_1),$$

ix inner surfaces, ϑ = thickness of wall, Σl = the edges, n = the number of corners. This applies ions are greater than $\frac{1}{8}\vartheta$. (Langmuir, Adams, *rochem. Soc., Vol. 14, p. 53, 1914.*)

$$H = \frac{\pi k D d\,(t_2 - t_1)}{l},$$

of sphere, d = inside diameter, l = thickness of

$$\frac{kL\,(t_2 - t_1)}{.3 \log_{10} \frac{D}{d}} + \frac{\pi k D d\,(t_2 - t_1)}{2l},$$

ner and outer walls, D = outside diameter, d = ness of top and bottom walls, all in the same unit. of heat through the cylindrical walls, the second top and bottom. (Hering, *Trans. Am. Electroch.*

Walls. — The most refractory substances do not luctivities. Consequently, it is advantageous to nce only for the inner part or lining of the walls, hat the drop in temperature will be sufficient to ance of a lower conductivity being used for the next ral layers may be employed. See Ray and Kreisin- *nce Walls*, Bull. No. 8, Dept. of the Interior, 1912.

Walls. — The most refractory substance is carbon, t conductor. Some of the products of the electric siloxicon (a substance containing varying amounts stand next to carbon as refractories, and do not vities. (*See* Fitzgerald, *Electrochem. Ind., Vol. 2,* l values of heat conductivities of refractories at for only a few substances and then only approxi- *and Thermal Properties;* also article by Hering in p. 625, 1911, and *the table below for graphite and* tivity see article on *Resistance and Conductance.*

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DESIGN OF ELECTRODES FOR ELECTRIC FURNAC electrodes of an electric furnace should be so designed that the ene carried into the furnace with a minimum energy loss. The loss electrical resistance is directly proportional to the electrode's length; therefore be made as short as convenient. The loss due to electrica will be smaller the greater the cross-section of the electrode, but th from the furnace through the electrode will be directly proportic cross-section. It is therefore possible to find a cross-section of a giv which will give a minimum total loss for a given length. The cross-s would give the minimum loss on certain assumptions, only approxin is found from the equation

$$S = 0.346\, LI \sqrt{\frac{r}{k(t_2 - t_1)}},$$

and the loss itself, watts, is

$$h = 2.89\, I \sqrt{kr\,(t_2 - t_1)},$$

where S = cross-section of electrode, L = its length, I = the curr peres carried by the electrode, t_2 and t_1 the temperatures, in ° C., and cold ends of the electrode respectively, r = its mean electrica in ohms per unit cube and k = its mean heat conductivity for the perature $(t_1 + t_2)/2$. If S and L are in centimeters, r and k must b if S and L are in inches, r and k must be per in.^{2}.

The values of k and r for carbon and graphite are not known ac high temperatures. The following values have been computed fro ments of Hering (*Trans. Am. Electroch. Soc., Vol. 17, p. 166, 1910*).

Material	Temperature °C.		Thermal cond. g-cal. per cm.^{2} per °C. per sec.	E r ohn
	Hot end	Cold end		
Carbon.....	300	40	0.0891	
	701	50	0.124	
	902	60	0.130	
Graphite.....	355	66	0.399	
	516	70	0.325	
	707	87	0.309	

SMALL LABORATORY FURNACES. — A great variety of e naces have been devised. A few typical laboratory furnaces will b in this section. Some industrial furnaces are described in the next s

Moissan's Furnace (Fig. 1). — Moissan's work was carried out in consisting of two horizontal electrodes, mounted so that the distan the two ends could be adjusted longitudinally by a screw thread. An arc was formed between these electrodes in a cavity formed by some refractory material, such as lime. The substance to be heated was placed in a crucible under the arc as shown in Fig. 1. When the substance was not to be exposed to the gases of the arc, a furnace was made with a carbon tube passing through it at right angles to the electrodes and in below the arc. The substance to be heated was placed inside this tu

). — A type of furnace due to Borchers consists in wo larger electrodes. The charge is either packed ced under it. This type of temperature below that of the

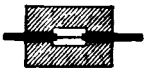


Fig. 2.

). — A furnace that takes its n a crucible with one or more above the crucible. The crucible is represented n an iron container. Graphite crucibles may be ectrodes. The charge in the crucible is usually etween the crucible and the table resistance in series with s melted the electrode may be In case it is desired to melt a ut the use of an arc, a smaller ced between the crucible and furnace. If after the substance has been melted it through the bath itself, as, for example, in case he upper electrode may be raised, the thin rod s and the electrode then lowered into the bath. ng this operation.

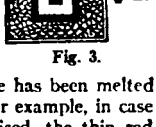


Fig. 3.

– It frequently happens in the laboratory that it e to a high temperature in a vacuum or in some or nitrogen. A his purpose has *ans. Am. Elec-*), and has been rch work. This m the General an one size. A Fig. 4. It con-er *B* made of a e at the joint. k, forms an air- fastened down tube *J* through n the furnace is e window *E* is .005 inch thick s *F*. s tubing which . The clamps e copper. The graphite, which te electrode and own. Metallic he lower end of

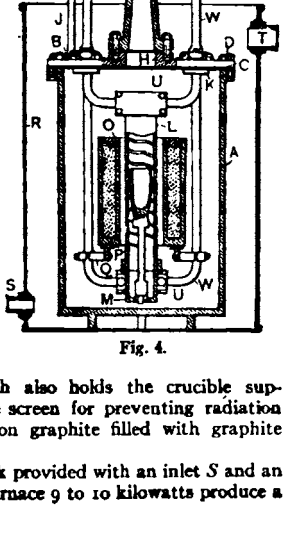


Fig. 4.

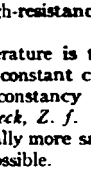
phite cup which also holds the crucible sup- lava ring. The screen for preventing radiation box of Acheson graphite filled with graphite

anized-iron tank provided with an inlet *S* and an small size of furnace 9 to 10 kilowatts produce a

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High-pressure Furnaces. — The Arsem furnace may be of course the internal pressure above an atmosphere, but it is not designed for sures. A furnace for working up to 200 atmospheres has been de Hutton and Petavel. (*Phil. Trans., Series A, Vol. 207, p. 421, 1908, trochem. and Met. Ind., Vol. 6, p. 97.*) For a modified form see *Pring a* (*VIII Int. Cong. App. Chem., Vol. 21, p. 79, 1912*). For a furnace fo scopic work on gases at pressures up to 200 atmospheres, see *King, A. physical Journal, Vol. 28, p. 300, 1908.*

Heræus Furnace (Fig. 5). — A very useful type of furnace is c firm of Heræus. This consists in a tube wound in its middle portio electrical resistor. The ends of the tube are cooled by the air, or may be cooled by a coil of copper pipe through which water flows. The tube may be of some non-conducting substance, such as porcelain, in which case a ribbon of metal may be wound directly on the tube. Furnace tubes with grooves for winding with wire are now made by the Norton Company of Worcester, Mass., from fused alumina. These, however, and cannot be used for a vacuum furnace. Glazed German porcela heated up to 1180° C. and a vacuum maintained. At temperatures h this the glazing melts and air leaks into the tube. A nickel tube ma for higher temperatures.



Fig

The metallic winding for carrying the current may be of platinu nichrome, tungsten, molybdenum or any other suitable high-resistanc (*see Wires, Resistance*).

These furnaces are particularly useful when the temperature is t constant over a long period of time. For most purposes a constant c keep the temperature sufficiently constant. For greater constancy of regulator must be used (*see Bodenstein and Kranendieck, Z. f. Vol. 18, p. 417, 1912*). The Heræus type of furnace is usually more sa when homemade, as a greater choice of materials is then possible.

Hoskins Furnace. — A convenient furnace for heating rather large or masses of material is made by the Hoskins Manufacturing Co Detroit, Michigan. The heater consists of two rows of narrow, th plates which extend over two sides of the cavity which receives the su be heated. The contact resistance between the plates may be varied by This furnace of course requires a very large current at a low voltage.

Granular Carbon Furnace (Fig. 6). — A carbon or graphit may be easily heated by placing it in a trough surrounded by gra carbon; this conducts better than coke. The current is passed through the trough, into which it is conducted by carbon rods. Clay crucibles should not be used in this way for temperatures over 1000° C., as at a high temperature they are attacked by the carbon.



Fig

ELECTRIC-FURNACE PRODUCTS AND INDUSTRIAL FURNACES. — Some typical industrial furnaces and their products are described below.

Calcium Carbide. — Willson and Horry Furnaces. Calcium ca first made on a large scale by Willson in 1892 at Spray, N. C., by he and carbon in an arc furnace. The reaction that takes place is

$$CaO + 3\,C = CaC_2 + CO.$$

The furnace consisted of a carbon plate 3 by 2.5 feet with a carbon suspended above it. The whole was surrounded by brick walls. similar to this were at first used at Niagara Falls, with the lower

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s removed when filled with an ingot of carbide.
ace was used (*U. S. Pat. 656,156*). The Carbide
eir present furnace secret. In Europe the Willson
ide may be either formed in an ingot in the crucible
solid, or it may be drawn off in the liquid state.
has been found better to have the current flow
ended over the crucible, in place of having the
(*Conrad, Electrochem. and Met. Ind., Vol. 6, p. 397,*
bide is in the neighborhood of 80 per cent. The
about 5 kilograms per 24 kilowatt hours.

n Process. — Silicon carbide or carborundum was
Acheson. It is produced from quartz and carbon
eated in an electric-resistance furnace, according

$_2 + 3\,C = CSi + 2\,CO$.

rbon core around which the charge, consisting of
sodium chloride, is packed. The latest furnaces
meters wide, and absorb 1600 kilowatts. The
n. Industry, Vol. 16, p. 155, 1907; Vol. 17, p. 112,
on a 750-kilowatt furnace it was found that the
. and decomposes when heated above 2240° C.
h. Soc., Vol. 21, p. 425, 1912.) The yield is about
arbide for 8.5 kilowatt hours. Silicon carbide is
ce linings and as a substitute for ferro-silicon in
itzgerald, Carborundum, Vol. 13, in the Engelhardt
e Elektrochemie.) For description of Norton Com-
let. and Chem. Eng., Vol. 10, pp. 519–521 (1912).
e for silicon carbide made by exposing hot carbon
rods are used for electric heating. (*J. Eng. Chem.,*

e incomplete reduction of silica, and may be repre-
though compounds with varying proportions of
loxicon is used for crucible linings. It is made by
ent quantity of carbon for complete reduction of

of about the same composition as siloxicon, made
pany, by heating silica and carbon in a closed arc
listillate in a large chamber. It is used for heat

urnace from coke and sand. At the high temper-
mpletely reduced and the melted metal is drawn
600 to 800 pounds. It varies from 90 to 97 per
trochem. and Met. Ind., Vol. 7, p. 102, 1900; Min.
).
n. de Chem. et de phys., Series 4, Vol. 10, p. 303,
t allotropic form of carbon which when oxidized
werful oxidizing agents (potassium chlorate and
de. Arsem suggests as a definition for graphite
f carbon whose density lies betewen 2.25 and 2.26.
ol. 20, p. 105, 1911.)
g carbon, containing a small amount of impurity,
electric resistance furnace. Anthracite coal is
s and crucibles are also graphitized after moulding.

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Acheson's theory of the formation of graphite is that the carbon first carbide, which decomposes at a higher temperature, leaving the carbo form of graphite. This theory is not confirmed by Arsem's experiment *Fitzgerald, Kunstlicher Graphit, Vol. 15 of the Engelhardt Monograph angewandte Electrochemie.*)

Carbon Bisulphide is made in a specially designed furnace by together sulphur and carbon. Most of the disagreeable features encoun the manufacture of this substance are thus avoided. (*Taylor, Tra Electroch. Soc., Vol. 1, p. 115, 1902; Vol. 2, p. 185, 1902.*)

Phosphorus is a substance the production of which the use of the furnace has much simplified. It is made in the Readman-Parker furnace ing to Wöhler's process:

$$Ca_3(PO_4)_2 + 3\ SiO_2 + 5\ C = 3\ CaSiO_3 + 5\ CO + 2\ P.$$

(*Min. Industry, Vol. 6, p. 537, 1897; Vol. 7, p. 557, 1898.*)

Alundum is the trade name of fused aluminum oxide, which is mad Norton Company of Worcester. Aluminum oxide is fused in an arc (*Min. Industry, Vol. 19, p. 28, 1910.*) Fused alumina is used as an a as a refractory substance for furnace linings, and porous crucibles of t stance are used in analytical laboratories.

Aluminum. — Hall and Héroult Processes. — Aluminum is now p by the electrolysis of a solution of alumina in fused cryolite ($AlF_3.3$ which other fluorides, such as those of aluminum and of sodium, are added factories. The aluminum sinks to the bottom of the crucible and is dr This process was discovered nearly simultaneously by C. M. Hall and The heat developed by the current in passing through the solution is s to keep the bath melted. The cathode is an iron trough lined with carb the anode consists of a number of carbon rods suspended over the crucibl Aluminum Company of America uses as anode for one crucible 48 carb 3 inches in diameter and 15 inches long. The electromotive force ap each crucible is 5.5 volts; the current is 10,000 amperes. The yield pounds of aluminum per horse-power day. For further information s *Industry, Vols. 6, 14, 15, 17, 20.*

Sodium, Potassium. — Castner Process. — Sodium and potassi obtained by the electrolysis of their fused hydrates, usually in the cell c by Castner (*U. S. Pat. 453,030, filed 1890; see also Becker, Die Elektromet der Alkalimetalle*). At Holcomb's Rock, Va., sodium is made by the elec of fused sodium chloride. (*Mineral Ind., Vol. 19, p. 614, 1910.*)

Calcium is made by the electrolysis of fused calcium chloride, to which fluoride is added to lower its melting point. Calcium is made at Ho Rock, Va., probably in a cell devised by Seward and Von Kügelgen (*U. 880,760, 1908; Min. Industry, Vol. 16, p. 131, 1907; Vol. 17, p. 99, 190* abroad by the method of Rathenau (*Z. f. Elektroch., Vol. 10, p. 508, 190* the Ratheneau method the cathode is an iron rod which just touches the of the melted calcium chloride. The calcium solidifies when deposited cathode by electrolysis. As the calcium grows the rod is withdrawn s rod of calcium is produced. (*Trans. Am. Electrochem. Soc., Apr., 1920.*

Zinc may be made by the electrolysis of fused zinc chloride. In th burne–Ashcroft process sodium chloride is added to zinc chloride in suc tity that the resulting mixture contains 28 per cent zinc. The cell is lined, sheet-iron vessel. The anode is carbon, the cathode, melted zinc vat takes 4.5 volts, with a cathode current density of 400 amperes pe The temperature of the fused salt is 450° C. (*Electroch. and Met. Ind., p. 65, 1905.*)

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ne electrolysis of fused carnallite ($MgCl_2.KCl.6H_2O$)
ne salt, which is, of course, anhydrous when melted.
nagnesium chloride may be used, which is dried in
hloride ($1NH_4Cl$ to $1MgCl_2$) to prevent decomposi-
ride is then removed by volatilization and con-

y electrolyzing fused cerium chloride ($CeCl_3$). Its
and is used in gas lighters.

S IN METALLURGY. — Under special local
plentiful, where coke is expensive and where power
ion of iron ore is carried out commercially, as at
Sweden, and at Héroult, California. The furnaces
ast furnace, with a crucible at the base into which
anting position. (*For detailed accounts, see volumes*
More recently it has been found better to have
ssig, VIII Int. Congress App. Chem., Vol. 21, p. 105,

been tried on a commercial scale with apparent
., Vol. 9, p. 453, 1911) as well as the smelting of
Chem. Eng., Vol. 11, p. 22, 1913), and zinc (*see*
Eng.). The use of electric furnaces in steel refining
ro-alloys is much more extensive for in this case
cheap as in the reduction of iron ore.
the steel which is refined in electric furnaces is
ters or open-hearth furnaces and poured directly
he advantages of the electric furnaces are (*Walker,*
, p. 371, 1912):
oxygen,
sed by additions, such as silicon manganese,
steel ingots of 8 tons and less that are practically
on,
to 0.005 per cent if desired,
rus to 0.005 per cent as in the basic open-hearth
mplete removal of oxygen.
l refining furnaces in use was increased greatly by

ectric steel refining consists in an improvement
a reduction of costs. While in 1911 it was con-
elt and refine steel scrap in six hours at 750 kilo-
e operation is now carried out in four hours with
t, VIII Int. Cong. of App. Chem., Vol. 21, p. 50,

ces used in steel refining are the following:
(Fig. 7). — This furnace consists of a closed
es connected to a three-phase system above the
as to stir all of the metal. This furnace is used
tle-on-Tyne (*Met. and Chem. Eng., Vol. 10, p. 66,*

Fig. 8). — This furnace consists of a crucible lined
rbon electrodes project into it through the roof.
current passes from each electrode into the slag.
electrical automatic regulator which moves the
quired.

Girod Steel Furnace. — This furnace consists of a crucible w soft-steel rods projecting through the base. These form one electrode;

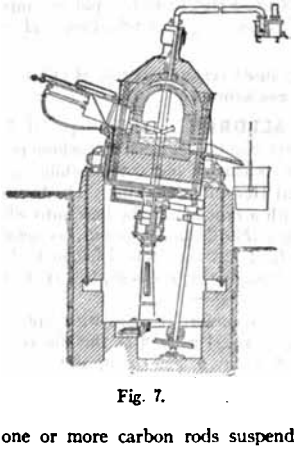


Fig. 7.

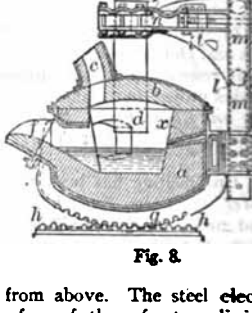


Fig. 8.

is one or more carbon rods suspended from above. The steel elec course melt several inches below the surface of the refractory lini crucible. The furnaces are sold by C. W. Leavitt and Co., 30 Ch New York, from whom the following data have been obtained.

These furnaces require from 65 to 70 volts at frequencies from 25 to The power factor is about 80 per cent and the duration of heat when is charged in the melted state is 1½ to 2½ hours. The number of are from 1 to 3, according to the capacity of the furnace. For a furnace 12 tons capacity, the maximum power required is 1200 kilowatts at the terminals of the electric generator; the energy consumption metal is charged cold is 900 kilowatt hours per ton of steel; with a melte from 150 to 250 kilowatt hours. The electrodes are so designed that th does not exceed 5 amperes per square inch of cross-section. The n consecutive heats possible without repairs is:

	Linings	Cover	Ele
With cold charge	30 to 40	20 to 30	
With melted charge	60 to 90	40 to 50	

To handle the furnace 6 persons are necessary: a melter, 2 assistant 2 workmen and a boy.

Other Arc Furnaces more or less similar to the Héroult furnace Keller furnace (*Trans. Am. Electroch. Soc., Vol. 15, p. 96, 1909*), the N furnace (*Met. and Chem. Eng., Vol. 10, p. 227, 1912*) and the Snyder (*Trans. Am. Electroch. Soc., Vol. 28, pp. 221–230, 1915*).

Induction Furnaces. — Induction furnaces are transformers in melted ring of steel is the secondary. The Kjellin furnace, Fig. 9, con single deep ring of metal. It has only a small area of contact between t and slag, and the slag is not easily heated. The use of this furnace is

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Kjellin, *Trans. Am. Electroch. Soc., Vol. 15, p. 175,*

ction furnace
ser furnace.
ar rings com-
gure 8. The
currents in-
ll as a current
extra second-
sses through
hich has suf-
t.
as another
rick furnace,
s and Halske,
by Dr. G. K.
rk. Another
e is due to
h. Soc., Vol.

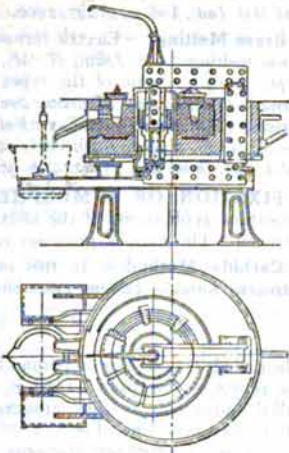


Fig. 9.

uction Fur-
the current
a trough of
the so-called
lectroch. Soc.,
a account of
t elements for each other, a compressing force is
auses a decrease in the cross-section at some point.
e metal may be entirely separated and the circuit

ace. — This is an induction furnace designed for
20,000 cycles per second or more. No iron core is
g merely surrounding the crucible which contains
The crucible itself or the metal which it contains
e high frequency is obtained from the discharge of
ary, the capacity of the condenser and the induct-
g so chosen as to give the desired frequency. (*See*
.) The condenser is charged through a step-up
volts and is short-circuited through the primary
ondenser is made up in units of 0.07 microfarad
+ 16 × 13 inches. One unit is required for each
rnace. The efficiency of this furnace is from 50 to
exceeding 1600° C. are readily obtained. This
the Pyroelectric Instrument Co., Trenton, N. J.
19, p. 155, 1918.)

oys were originally made from iron ore, the oxide
flux, but on account of impurities, scrap iron and
in place of iron ore (*Met. and Chem. Eng., Vol. 8,*
ance furnaces similar to those used for steel refining
rmation see Keeney, *Bull. Am. Inst. Mining Eng.*
.

nost important of the ferro-alloys. It is made from
At the Keller-Leleux works at Livet it has been
20 tons of 30 per cent ferro-silicon with 4000 horse-

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power during a day. (*See preceding reference.*) For an account of t the other ferro-alloys, see *Electrochem. Ind., Vol. 1, p. 583, 1903; E and Met. Ind., Vol. 4, p. 247, 1906.*

Brass Melting. — Electric furnaces are now used to a considerable brass melting. (*St. John., H. M., Electric Brass Melting, Elec. J Sept.*, 1919.) Some of the types of furnaces used are the Booth furnace (*Trans. Am. Electroch. Soc., Vol. 33, p. 247, 1918*); the furnace (*Met. and Chem. Eng., Vol. 12, p. 275, 1914; Trans. Am. Soc., Vol. 29, p. 407, 1916; Vol. 31, p. 87, 1917*); and the Helberg (*Met. and Chem. Eng., Vol. 12, p. 644, 1914*).

FIXATION OF ATMOSPHERIC NITROGEN. — One of important applications of the electric furnace is the fixation of at nitrogen. The various processes employed are described below.

Carbide Method. — In this method calcium carbide is heate nitrogen, forming calcium cyanamide according to the reversible rea

$$CaC_2 + N_2 \rightleftarrows CaCN_2 + C.$$

The carbide is heated in iron drums by a thin carbon conductor runnin the center of the drum. Heat is evolved by the reaction. The called "nitro-lime" or "lime-nitrogen," and contains 12 to 15 per cent (*Met. and Chem. Eng., Vol. 5, p. 78, 1907.*) It is used directly as a or may be converted into ammonia by superheated steam. The yiel gen by the carbide method is about 51.6 grams per kilowatt hour, incl manufacture of the carbide.

Direct-Oxidation Method. — In this method the nitrogen an in air are caused to combine in a high-voltage arc according to the reaction

$$N_2 + O_2 \rightleftarrows 2\,NO.$$

On cooling the NO is further oxidized to nitric dioxide. The nitric treatment with water gives nitric and nitrous acids:

$$2\,NO_2 + H_2O = HNO_3 + HNO_2.$$

Only about 1 to 3 per cent of the air treated is oxidized. The yield in land-Eyde furnace is 12.7 grams of nitrogen fixed per kilowatt hour. *Faraday Soc., Vol. 2, p. 98, 1906.*) Furnaces of three different de now in operation for oxidizing nitrogen: that of Birkeland and Eyd Schönherr, and that of H. and G. Pauling.

Direct Synthesis of Ammonia. — In this method, due to Haber, is formed directly from a mixture of nitrogen and hydrogen by passi catalyzer between 500° C. and 700° C. at 200 atmospheres, accordi reversible reaction

$$\tfrac{1}{2}\,N_2 + 3\tfrac{1}{2}\,H_2 \rightleftarrows NH_3.$$

(*Zeit. f. Elektroch., Vol. 16, p. 244, 1910; Vol. 19, p. 53, 1913.*) The of this process has not been made public.

Bucher Process. — This process was discovered in 1846 by Lewis (Bucher, *Am. Inst. Chem. Eng., Vol. 9, p. 335, 1916*) and is represent following reaction:

$$Na_2CO_3 + 5C + N_2 = 2NaCN + 3CO$$

which requires metallic iron as catalyzer. The temperature is betw and 1050° C. Many attempts have been made to use this process, but

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on. A plant was built at Saltville, Va., to make
its. The furnaces were 8-inch iron tubes heated
he reacting mixture is finely ground, briquetted hot
n treated with nitrogen. See also Ferguson and
Chem., Vol. 11, p. 946, 1919; Posnjak and Merwin,
Vol. 9, p. 28, 1919.

his process aluminum nitride is made by heating
nd nitrogen together. On heating the aluminum
and aluminum hydrate are formed. The product
said to contain 20 to 24 per cent of nitrogen, and
of nitrogen is said to be only one-half of that used
nod. (*Bull. de la Soc. ind. de Mulhouse, Vol. 79,*
,032, 1911.)

rchers, *Electric Smelting and Refining;* Kershaw,
n and Cooper, *Electrometallurgy;* Alfred Stansfield,
hauser, Schoenawa and Vom Baur, *Electric Furnaces*
y; Department of the Interior Bulletins: No. 77,
The Electric Furnace in Metallurgical Work, 1916;
Electric Furnaces for Making Iron and Steel, 1916;
The Smelting of Copper Ores in the Electric Furnace,
text above, and bibliography in article on *Electro-*
l.

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FUSES. — (*See also Circuit Breakers; Wiring of Buildings.*) Meta wires which open electric circuits by melting or fusing when the curre a predetermined value are called fuses. They were used in the earlie plants to furnish automatic protection for feeder and generator circuit use is now confined largely to low-voltage distribution circuits ar protection of small pieces of apparatus such as motors and smal transformers.

All fuses have an inherent time-element feature due to the fact current must heat the fuse metal up to its melting temperature. This varies with the size and type of fuse, the large ones in general taking reach their fusing temperature than the smaller sizes, due to thei capacities. There are three designs of fuses in general use, namely, or link, the expulsion, and the enclosed or cartridge types. The choic depends upon the service for which the fuse is intended.

RATING OF A FUSE. — The rating of a fuse depends somewh type and general design. Fuses will, as a rule, carry their normal rate indefinitely but will blow at a certain overload varying from 10 per c enclosed fuse to about 80 per cent in an open fuse if the overload co sufficient length of time. For greater overloads the length of time re blowing diminishes rapidly.

OPEN OR LINK FUSES were the original type of automatic p The early ones were small copper wires and had the drawback of formi globules and of possessing a high fusion temperature. In order to r temperature of the molten metal there were employed alloys of low fus made of lead, tin, or other metals. These fuses were soft and w damaged when tightening up the contact nuts. The next step was to fuses with copper tips, and these are still used to some extent.

As the price of aluminum was reduced this material was used l fuses as it has a high conductivity (thus reducing the amount of m fused), a fairly low melting point and almost complete vaporization of fused. By using wide strips of aluminum cut to form two or mor fairly reliable open fuses can be made up to 1200 amperes capacity.

Any metal strip which is exposed to drafts is apt to be very err behavior as a fuse. To protect link fuses from drafts, and also t the danger from molten metal which may be thrown at the time of b is desirable to install them in porcelain fuse boxes.

EXPULSION FUSES consist essentially of open fuse wires or stri in a holder, so designed that the expulsion of the gases formed by th of the fuse blows out the arc. The earliest designs of this type co removable fuse holder of lignum vitæ or similar tough, close-grain equipped with terminals which fitted into suitable blocks. Later ty the fuse placed in a fiber tube and arranged to blow out through on a bomb.

The fuses used for the protection of distributing transformers mo poles or houses are usually of the expulsion type. For such outdoor combination fuse and disconnecting switch is frequently used. Mod of the expulsion-type fuse were formerly used to advantage in railwa but in recent car equipments circuit breakers have practically repla and cut-outs.

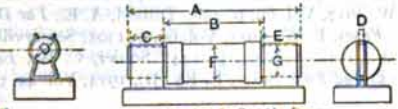
INCLOSED OR CARTRIDGE FUSE. — This type of fuse consi tially of a fusible wire, strip or sets of wires and strips inclosed with or cartridge usually of fiber. The tube is filled with a material to ex

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ng of the circuit when the fuse blows by absorbing
out the arc. Suitable terminals are provided so
ed in a fuse block.

Fuses. — When inclosed fuses were first put on
r developed his own spacings and designs of termi-
niformity and the fuse of one manufacturer could
of another manufacturer. To avoid this confusion
e builders and the National Board of Fire Under-
andard dimensions and types of contacts given in
to 60 amperes ferrule type contacts (i.e., cylindrical
m 61 to 600 amperes knife-blade contacts are em-
ns are used for fuses up to 250 volts and another
Fuses that correspond to the accepted dimensions
nents agreed on are known as National Electrical
re interchangeable. Fuses are made for higher
larger currents then 600 amperes, but they have
National Board of Fire Underwriters.

OF N. E. C. CARTRIDGE FUSES



Style of Terminal for Cartridge Fuses
61-600 Amperes

B	C	D	E	F	G
contact clips	Width of contact clips	Diameter of ferrules or thickness of terminal blades	Min. length of ferrules or of terminal blades outside of tube	Diameter of tube	Width of terminal blades
ches	Inches	Inches	Inches	Inches	Inches
1	½	9/16	½	½	...
1¾	⅝	13/16	⅝	¾	...
4	⅞	⅛	1	1	¾
4½	1¼	5/16	1⅜	1½	1¼
5	1¾	¼	1⅞	2	1⅝
6	2¼	¼	2¼	2½	2
4	½	13/16	½	¾	...
4¼	⅝	1 1/16	⅝	1	...
6	⅞	⅛	1	1¼	¾
7	1¼	5/16	1⅜	1¾	1⅛
8	1¾	¼	1⅞	2½	1⅝
9	2¼	¼	2¼	3	2

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Cost of N. E. C. Fuses. — In moderate quantities of stan ages the price of 30-ampere 250-volt fuses is about 21 cents each, ampere 600-volt fuses about $4.65 each. The others fall between t

Plug Fuses. — A plug fuse is a fuse mounted in a plug of th Edison-lamp base dimensions. They are in common use on lighting circuits up to 30 amperes capacity. The outer face of the plug us mica covering which is discolored by the blowing of the fuse. A l also sometimes used as a cover.

RENEWABLE FUSES. — The standard enclosed fuse when i blown has usually to be returned to its manufacturer for refillin fuses have been designed that fit in the standard N. E. C. fuse l arranged so that the fuse elements can be readily renewed. Thes been accepted by the National Board of Fire Underwriters.

For high voltage work fuses have been made using carbon tetra some similar liquid to extinguish the arc when the fuse blows.

SPECIFICATIONS FOR FUSES. — The following memora tended to assist in writing specifications. See also articles on *Spec*

Open or inclosed. Wire or ribbon. Current to blow fuse in a spe To blow without violence at a stated current. Voltage of circuit ab

BIBLIOGRAPHY. — Arthur, W., *Characteristics of Standard Enc* E. W. 1917, Vol. 69, p. 456; Dillard, A. E., *The Design and Operatio Gap Fuses*, E. W., 1915, Vol. 66, p. 1305; Somerville, A. A., *Electric F* E. W., 1913, Vol. 61, p. 144; Squier, C. W., *Equipment Defects, Blocks and Fuse Boxes*, E. Ry. Jr., 1914, Vol. 44, p. 219.

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ETAL. — (*See also Copper; Gages, Wire; Iron,*
re two principal gages for sheet iron and steel used in
tablished by Act of Congress in 1893 and the other
committee of the American Society of Mechanical
an Railway Master Mechanics Association.

. — The former gage, which is known as the U. S.
on the fact that a cubic foot of iron weighs 480 pounds.
been arranged so that each gage number represents
s in weight, or an equal number of 64oths of an inch
used for determining duties and taxes levied on sheet
nd in its application a variation of 2½ per cent either

latter gage, which is known as the Decimal Gage, is
but upon the thickness of the metal. Each number
of thousandths of an inch of thickness. This gage
by the Association of American Steel Manufacturers,
laster Mechanics' Association, and by most of the
United States, Canada and Mexico. The decimal
mmended by the American Institute of Mining Engi-
merican Society of Mechanical Engineers in 1895.

ge. — Copper and brass plates are rated by the Brown
te thicknesses on this gage correspond to the diameters
ge. (*See Gages, Wire.*)
e the dimensions and weights of sheet metal accord-
ve.

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U. S. STANDARD GAGE FOR SHEET AND PLATE, IRON AND

No. of gage	Approximate thickness in decimal parts of an inch	Approximate thickness in millimeters	Weight per square foot in pounds avoirdupois	Weight square in kilog
0000000	0.5000	12.7000	20.00	97.6
000000	0.4687	11.9062	18.75	91.5
00000	0.4375	11.1125	17.50	85.4
0000	0.4062	10.3187	16.25	79.3
000	0.3750	9.5250	15.00	73.2
00	0.3437	8.7312	13.75	67.1
0	0.3125	7.9375	12.50	61.0
1	0.2812	7.1437	11.25	54.9
2	0.2656	6.7469	10.62	51.8
3	0.2500	6.3500	10.00	48.8
4	0.2344	5.9531	9.375	45.7
5	0.2187	5.5562	8.750	42.7
6	0.2031	5.1594	8.125	39.6
7	0.1875	4.7625	7.500	36.6
8	0.1719	4.3656	6.875	33.5
9	0.1562	3.9687	6.250	30.5
10	0.1406	3.5719	5.625	27.4
11	0.1250.	3.1750	5.000	24.4
12	0.1094	2.7781	4.375	21.3
13	0.0937	2.3812	3.750	18.3
14	0.07812	1.9844	3.125	15.2
15	0.07031	1.7859	2.812	13.7
16	0.06250	1.5875	2.500	12.2
17	0.05625	1.4287	2.250	10.9
18	0.05000	1.2700	2.000	9.7
19	0.04375	1.1112	1.750	8.5
20	0.03750	0.9525	1.500	7.3
21	0.03437	0.8731	1.375	6.7
22	0.03125	0.7937	1.250	6.1
23	0.02812	0.7144	1.125	5.4
24	0.02500	0.6350	1.000	4.8
25	0.02187	0.5556	0.875	4.2
26	0.01875	0.4762	0.750	3.6
27	0.01719	0.4366	0.687	3.3
28	0.01562	0.3969	0.625	3.0
29	0.01406	0.3572	0.5625	2.7
30	0.01250	0.3175	0.5000	2.4
31	0.01094	0.2778	0.4375	2.1
32	0.01016	0.2580	0.4062	1.9
33	0.009375	0.2381	0.3750	1.8
34	0.008594	0.2183	0.3437	1.6
36	0.007031	0.1786	0.2812	1.3
38	0.006250	0.1587	0.2500	1.2

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SHEET AND PLATE IRON
EEL

Weights per square foot in pounds avoirdupois	
Iron, Basis: 480 pounds per cubic foot	Steel, Basis: 489.6 pounds per cubic foot
0.08	0.0816
0.16	0.1632
0.24	0.2448
0.32	0.3264
0.40	0.4080
0.48	0.4896
0.56	0.5712
0.64	0.6528
0.72	0.7344
0.80	0.8160
0.88	0.8976
1.00	1.0200
1.12	1.1424
1.28	1.3056
1.44	1.4688
1.60	1.6320
1.80	1.8360
2.00	2.0400
2.20	2.2440
2.40	2.4480
2.60	2.6520
2.80	2.8560
3.00	3.0600
3.20	3.2640
3.40	3.4680
3.60	3.6720
3.80	3.8760
4.00	4.0800
4.40	4.4880
5.00	5.1000
5.40	5.5080
6.00	6.1200
6.60	6.7320
7.20	7.3440
8.00	8.1600
8.80	8.9760
9.60	9.7920
10.00	10.2000

The sizes of wires having a
of certain arbitrary scales
l wire refers to the cross-
size or gage number of a
onstituent wires, irrespec-
usually described in terms
mil is the area of a circle
cular mils is equal to the
rsion Factors.
al ones being the following.

IRE GAGE. — This gage
or copper, aluminum and
the abbreviations A. W. G.

diameter of wires having
f $\sqrt[39]{92}$ (= 1.1229 approx.)
No. 35 A. W. G., therefore,
until No. 0000 is reached,

ich is 1.1225. This circum-
f regular gage size with an
er regular gage size.
l:

stance 25 per cent.
stance 60 per cent.
stance 100 per cent.
stance 10 times.

approximate characteristics:

..... 1
..... 10,000
..... 32

wing approximate character-

..... 1.6
..... 10,000
..... 9.5

pproximate size, resistance,
. 12 A.W.G. copper wire has
000 feet approximately. Its

50 circular mils; its diameter

20 pounds per 1000 feet.

known also as the "Wash-
and Wire Co.'s" gage, is
steel and iron wire. It is
confusion with the British
eviated "Stl. W. G." or "A.

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BROWN AND SHARPE GAGE FOR COPPER AND BRASS PLATES

B. & S. Gage No.	Thickness, inches	Weight, pounds per sq. ft.	
		Copper	Brass
0000	0.4600	21.30	10.20
000	0.4096	18.90	18.20
00	0.3648	16.90	16.00
0	0.3249	15.00	14.30
1	0.2893	13.40	12.70
2	0.2576	11.90	11.30
3	0.2294	10.60	10.10
4	0.2043	9.45	8.96
5	0.1819	8.41	7.98
6	0.1620	7.49	7.11
7	0.1443	6.67	6.33
8	0.1285	5.94	5.64
9	0.1144	5.29	5.02
10	0.1019	4.71	4.47
11	0.09071	4.20	3.98
12	0.08081	3.74	3.54
13	0.07196	3.33	3.16
14	0.06408	2.96	2.81
15	0.05707	2.64	2.50
16	0.05082	2.35	2.23
17	0.04526	2.09	1.99
18	0.04030	1.86	1.77
19	0.03589	1.66	1.57
20	0.03196	1.48	1.40
21	0.02846	1.32	1.25
22	0.02535	1.17	1.11
23	0.02257	1.04	0.99
24	0.02010	0.93	0.88
25	0.01790	0.83	0.79
26	0.05194	0.74	0.70
27	0.01420	0.66	0.62
28	0.02164	0.58	0.55
29	0.01126	0.52	0.49
30	0.01003	0.46	0.44
31	0.008928	0.41	0.39
32	0.007950	0.37	0.35
33	0.007080	0.33	0.31
34	0.006304	0.29	0.28
36	0.005000	0.23	0.22
38	0.003965	0.18	0.17
40	0.003145	0.15	0.14

* The specific gravity of copper plate is taken as 8.89 and of brass plate as 8.4

BIBLIOGRAPHY. — *Report of Committee on Standard Thickness Gage Metals*, Trans. A.S.M.E., 1895, Vol. 16, p. 641; *Report of Committee on Sta ard Gages*, Proc. Am. Ry. Master Mech. Assn., 1895, p. 149.

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(*See also Gages, Sheet Metal.*) The sizes of wires having a ch are usually stated in terms of certain arbitrary scales ze or gage number of a solid wire refers to the cross- pendicular to its length; the size or gage number of a he total cross-section of the constituent wires, irrespec- spiraling. Larger wires are usually described in terms in circular mils. A circular mil is the area of a circle the area of any circle in circular mils is equal to the n mils. See *Units and Conversion Factors.*

f wire gages in use, the principal ones being the following.

ROWN AND SHARPE WIRE GAGE. — This gage used in the United States for copper, aluminum and age is designated by either of the abbreviations A. W. G.

G. or B. & S. Gage. — The diameter of wires having this gage are in the ratio of $\sqrt[39]{92}$ (= 1.1229 approx.) e has a diameter of 5 mils. No. 35 A. W. G., therefore, .1229 = 5.61 mils and so on until No. 0000 is reached, o mils.

roximately equal to $\sqrt[9]{2}$, which is 1.1225. This circum- e to have a group of wires of regular gage size with an nately equal to that of another regular gage size. imate relations are also useful:

he number increases the resistance 25 per cent.
he number increases the resistance 60 per cent.
he number increases the resistance 100 per cent.
he number increases the resistance 10 times.

pper wire has the following approximate characteristics:

et	1
	10,000
er 1000 feet	32

luminum wire has the following approximate character-

et	1.6
	10,000
er 1000 feet	9.5

ules it is easy to find the approximate size, resistance, e wire. For example, a No. 12 A.W.G. copper wire has per cent = 1.6 ohms per 1000 feet approximately. Its

ts resistance, is $\frac{10,000}{1.6}$ = 6250 circular mils; its diameter

) mils and its weight, $\frac{32}{1.6}$ = 20 pounds per 1000 feet.

E GAGE. — This gage, known also as the "Wash- ebling," "American Steel and Wire Co.'s" gage, is ed in the United States for steel and iron wire. It is "S. W. G.," but to avoid confusion with the British *e below*) it should be abbreviated "Stl. W. G." or "A.

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BIRMINGHAM (OR STUBS') WIRE GAGE. — This gage used in the United States for some purposes, e.g., to designate the size wire, and is also employed to a limited extent in Great Britain. It is abbreviated "B. W. G." It is sometimes referred to as the "Stubs' but it should not be confused with the Stubs' Steel Wire Gage.

BRITISH STANDARD WIRE GAGE. — This gage, usually simply the "Standard Wire Gage," and abbreviated "S. W. G.," is also as the "New British Standard" (abbreviated "N. B. S."), the Englis Standard, or the Imperial Wire Gage, and is the legal standard of Great for all wires, as fixed by order in Council, August 23, 1883. It was con by modifying the Birmingham Wire Gage, so that the differences betwee sive diameters were the same for short ranges, i.e., so that a graph repr the diameters consists of a series of a few straight lines.

EDISON WIRE GAGE. — The size of a wire on this gage is its cross-sectional area in circular mils divided by 1000. For example wire 0.2 inch in diameter has the number $(200)^2/1000 = 40$. This gag rarely used.

OTHER GAGES. — In addition wire sizes are sometimes specified of the "Old English Wire Gage," known also as the "London Gage," "Stubs' Steel Wire Gage."

COMPARISON OF WIRE GAGES. — A comparison of the gages, in terms of the diameters (in mils or thousandths of an inch) wires corresponding to the various numbers, is given below. The cross in circular mils is the square of the diameter in mils.

COMPARISON OF WIRE GAGES

Diameters in Mils

(*Bureau of Standards. Circular No. 31*)

Gage No.	American wire gage (B. & S.)	Steel wire gage	Birmingham wire gage (Stubs')	Old English wire gage (London)	Stubs' steel wire gage	(British) Standard wire gage
7-0	.....	490.0	...	.....	...	500
6-0	.....	461.5	...	.....	...	464
5-0	.....	430.5	...	.....	...	432
4-0	460	393.8	454	454	...	400
3-0	410	362.5	425	425	...	372
2-0	365	331.0	380	380	...	348
0	325	306.5	340	340	...	324
1	289	283.0	300	300	227	300
2	258	262.5	284	284	219	276
3	229	243.7	259	259	212	252
4	204	225.3	238	238	207	232
5	182	207.0	220	220	204	212
6	162	192.0	203	203	201	192
7	144	177.0	180	180	199	176
8	128	162.0	165	165	197	160
9	114	148.3	148	148	194	144

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ARISON OF WIRE GAGES — *Continued*

Diameter in Mils

Bureau of Standards, Circular No. 31)

teel ire age	Birmingham wire gage (Stubs')	Old English wire gage (London)	Stubs' steel wire gage	(British) Standard wire gage	Gage No.
135.0	134	134	191	128	10
120.5	120	120	188	116	11
105.5	109	109	185	104	12
91.5	95	95	182	92	13
80.0	83	83	180	80	14
72.0	72	72	178	72	15
62.5	65	65	175	64	16
54.0	58	58	172	56	17
47.5	49	49	168	48	18
41.0	42	40	164	40	19
34.8	35	35	161	36	20
31.7	32	31.5	157	32	21
28.6	28	29.5	155	28	22
25.8	25	27.0	153	24	23
23.0	22	25.0	151	22	24
20.4	20	23.0	148	20	25
18.1	18	20.5	146	18	26
17.3	16	18.75	143	16.4	27
16.2	14	16.50	139	14.8	28
15.0	13	15.50	134	13.6	29
14.0	12	13.75	127	12.4	30
13.2	10	12.25	120	11.6	31
12.8	9	11.25	115	10.8	32
11.8	8	10.25	112	10.0	33
10.4	7	9.50	110	9.2	34
9.5	5	9.00	108	8.4	35
9.0	4	7.50	106	7.6	36
8.5	...	6.50	103	6.8	37
8.0	...	5.75	101	6.0	38
7.5	...	5.00	99	5.2	39
7.0	...	4.50	97	4.8	40
6.6	...	.....	95	4.4	41
6.2	...	.....	92	4.0	42
6.0	...	.....	88	3.6	43
5.8	...	.....	85	3.2	44
5.5	...	.....	81	2.8	45
5.2	...	.....	79	2.4	46
5.0	...	.....	77	2.0	47
4.8	...	.....	75	1.6	48
4.6	...	.....	72	1.2	49
4.4	...	.....	69	1.0	50

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GALVANIZING FOR IRON OR STEEL, Specification for A
ance Test. — These specifications give in detail the test to be app
galvanized material, as recommended by the Electric Railway Engi
Association, the National Electric Light Association, etc. All specime
be capable of withstanding these tests.

(a) **Coating.** — The galvanizing shall consist of a continuous coating
zinc of uniform thickness, and so applied that it adheres firmly to the
of the iron or steel. The finished product shall be smooth.

(b) **Cleaning.** — The samples shall be cleaned before testing, firs
carbona, benzine or turpentine, and cotton waste (not with a brush), a
thoroughly rinsed in clean water and wiped dry with clean cotton waste.
The sample shall be clean and dry before each immersion in the solutio

(c) **Solution.** — The standard solution of copper sulphate shall co
commercial copper sulphate crystals dissolved in cold water, about in t
portion of 36 parts, by weight, of crystals to 100 parts, by weight, of
The solution shall be neutralized by the addition of an excess of che
pure cupric oxide (CuO). The presence of an excess of cupric oxide
shown by the sediment of this reagent at the bottom of the containing v
The neutralized solution shall be filtered before using by passing
filter paper. The filtered solution shall have a specific gravity of 1
65° F. (reading the scale at the level of the solution) at the beginning
test. In case the filtered solution is high in specific gravity, clean wat
be added to reduce the specific gravity to 1.186 at 65° F. In case the
solution is low in specific gravity, filtered solution of a higher specific
shall be added to make the specific gravity 1.186 at 65° F.
As soon as the stronger solution is taken from the vessel containing
filtered neutralized stock solution, additional crystals and water must be
to the stock solution. An excess of cupric oxide shall always be kept
unfiltered stock solution.

(d) **Quantity of Solution.** — Wire samples shall be tested in a glass j
least two (2) inches inside diameter. The jar without the wire samples
filled with standard solution to a depth of at least four (4) inches. Ha
samples shall be tested in a glass or earthenware jar containing at least
(½) pint of standard solution for each hardware sample. Solution sh
be used for more than one series of four immersions.

(e) **Samples.** — Not more than seven wires shall be simultaneously im
and not more than one sample of galvanized material other than wire
immersed in the specified quantity of solution.
The samples shall not be grouped or twisted together, but shall be we
rated so as to permit the action of the solution to be uniform upon all im
portions of the samples.

(f) **Test.** — Clean and dry samples shall be immersed in the required
tity of standard solution in accordance with the following cycle of imm
The temperature of the solution shall be maintained between 62° and
at all times during the following test.

First. Immerse for one minute, wash and wipe dry.
Second. Immerse for one minute, wash and wipe dry.
Third. Immerse for one minute, wash and wipe dry.
Fourth. Immerse for one minute, wash and wipe dry.

After each immersion the samples shall be immediately washed i
water having a temperature between 62° and 68° F., and wiped dry with
waste.

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4 galvanized iron or steel wire, the time of the fourth
ced to one-half minute.

after the test described in section "f" there should be
r deposit upon the samples, the lot represented by the
l.

inc or within one inch of the cut end shall not be con-
ion.

re of only one wire in a group of seven wires immersed
a reasonable doubt as to the copper deposit, two check
these seven wires and the lot reported in accordance
e sets of tests.

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GALVANOMETERS. — (*See also Ammeters; Electrodynamomet meter; Voltmeters.*) The essential parts of a galvanometer are a p magnet (electromagnet in Einthoven String Galvanometer, see belo coil or wire designed to carry an electric current, the magnet and so mounted that the passage of the current through the coil causes tion of either the coil or the magnet, as a result of the mechan with which the current and magnet act on each other. See *Elect Magnetism, Principles of.* Ordinary direct-current ammeters and are operated on the same principle, but the term galvanometer is usuall for instruments designed for measuring relatively small currents, the being read either by means of a telescope and scale or by means of a scale. In portable test set galvanometers the deflection of a pointer

Moving-needle versus Moving-coil Galvanometers. — Galv in which the moving element is the permanent magnet, in the form needle, are called needle galvanometers, whereas those in which th element is the coil are called moving-coil galvanometers. The forme galvanometer is required when extreme sensitiveness is desired, but a rule be used in a commercial laboratory, on account of the disturb ences of the magnetic fields due to the lighting and power circuits in ratory and in neighboring buildings. Railway circuits, even though more away, may produce a disturbing field sufficient to render impo use of a sensitive needle galvanometer. For ordinary laboratory work, the moving-coil galvanometer can be made sufficiently sensitive, and permanent magnets used to produce the controlling field can be m strong, the effect of stray fields can be rendered relatively negligible.

Astatic Galvanometer. — The disturbing effect of stray magnetic a needle galvanometer can be partially prevented by the use of tw stationary coils and two needles, or the equivalent, the two needles arranged that any external field will produce opposing torques, and so connected that their torques are additive. The Broca galvanomete described below, is a modern type of astatic instrument.

Damping and Logarithmic Decrement. — Due to the mechanic to motion and the induced currents set up in the adjacent metal or co instrument as a result of the motion of the moving element, successi of the moving element when it is once set in motion decrease in a This effect is known as damping. Successive swings from the zero o rium position decrease approximately in geometric ratio. Hence of the logarithm of one swing to the logarithm of the next swing, to side of the zero, is approximately a constant. This constant, which is a of the damping, is called the logarithmic decrement of the instrument.

Ballistic Galvanometer. — A ballistic galvanometer is one in w moving element has a relatively long period and small damping. shown that when a quantity of electricity Q is discharged through su vanometer in an interval of time *very short* compared with the period o vanometer, then the first throw or swing of the moving element is appro proportional to the quantity of electricity Q. Such an instrument serves as a very convenient means of measuring the capacity of a (*see Capacity and Charging Current; Condensers, Electric*) as well as fo ing the quantity of electricity discharged through a circuit by transien electromotive forces (*see Magnetic Testing*).

Effect of External Resistance on Damping. — Since the da a galvanometer is due in part to the currents induced in the coils of th ment by the motion of the moving element, and since these currents dep

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ith these coils, it follows that the damping depends
rnal circuit. In particular, a low-resistance shunt
inals may increase the damping very considerably.
ements involving the comparison of initial throws
nents, care must be taken that the same external
nal circuit, or that a universal shunt (*see Shunts*)
iplying power (100 or more) be used.

rs. — When the damping of a galvanometer is
the moving element ceases to be periodic, and for
gh the coils the moving element swings out to its
rest without oscillation. Such an instrument is
dead-beat feature is very desirable when steady
d; it may be obtained mechanically by mounting
oving element, or by placing a solid piece of metal
o that the motion of the latter will induce currents

. — When the damping is *just sufficient* to render
e galvanometer is said to be aperiodic.

anometers. — The ordinary type of galvanometer
g alternating currents, since the twisting moment
of the current. An ordinary galvanometer may,
by connecting in series with it a thermo-couple,
oil carrying the alternating current to be measured;
dell's thermo-galvanometer. The "twisted-strip"
flection is caused by the untwisting of a strip, due
rrent, has also been used as an alternating-current
nents, however, are both decidedly inferior to the
nometer (Fig. 3) described below.

nometers are of historical interest only, and need

ometers. — The sensitiveness or deflectional con-
y be defined as the scale deflection in millimeters
e micro-ampere passing through the galvanometer
meter distance from the mirror; this is called the
strument has a scale attached, the current sensi-
est scale divisions per micro-ampere. It may also
otential difference in mico-volts, which must be
he galvanometer to produce unit deflection, or as
at meter distance of scale, per mico-volt on the
oltage, or *e.m.f.*, *sensitivity*. The sensitiveness of a
panied by good *zero-keeping quality*.
a galvanometer is the number of megohms which
ontaining an e.m.f. of 1 volt in order to obtain a
nm., the scale being at a distance of 1 meter from
, numerically, as the current sensitivity.

LVANOMETERS. — Only a few typical forms
be described here.

r. — This galvanometer is one of the best of the
s its sensitiveness and freedom from disturbance
to the unique construction of its system. This
sists of two vertical steel wires placed side by side
equent poles at their centers.
system that is very astatic and though magnets of

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considerable size are used, they are placed so close together that the
a very small moment of inertia. A small mirror is located below t
system and below this an aluminum damping vane that moves in a
the size of which can be varied, thus changing the damping. The wh
is suspended by a quartz fiber which serves as a control for the system
the main control is obtained by a movable permanent magnet on the
instrument. The stationary coils are made interchangeable and
and vary in resistance from 10 ohms to 1000 ohms per pair.

Either lamp and scale or telescope and scale can be used to read the
of this galvanometer. In the latter case the scale must be brilliantly ill
owing to the small size of the mirror.

The resistance of this galvanometer can be varied by connecting
coils in parallel or series or by substituting coils of different resista
vary the damping two rods on either side of the instrument case are

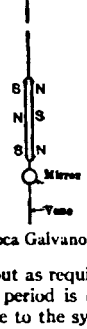


Fig. 1. Broca Galvanometer System



Fig. 2. D'Arsonval Galva

or pulled out as required, to increase or decrease the size of the damp
ber. The period is changed by changing the position of the contr
in reference to the system.

In the following table is given the sensitiveness of the instrument f
periods and resistances.

Resistance of coils in series in ohms	Period in seconds	Deflection in mm. at 1 m.	
		For 1 micro-ampere	For 1 micro-volt
10.9	8	218	19.9
107	12	1190	11.1
935	11	2450	2.62

D'Arsonval Galvanometers. — For the great majority of electrica
ments requiring galvanometers the D'Arsonval types, of which there
forms, are the most satisfactory. Fig. 2 shows a typical form of co
suitable either for mounting on the wall or on a tripod. This gal
has for its frame an iron casting which also serves as the permanen
and to hold the upper suspension tube. In the wall type this magn
is attached to a backboard holding the telescope and scale and th
core.

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ith copper wire, free from iron and suspended from of phosphor bronze, silver or steel, which also serves coil. The other terminal is in the form of a spiral of er strip brought off from the bottom of the coil. The or and the entire moving system is visible through a al plate that covers the front of the magnet casting, novable. The deflection is read by a telescope and so that the scale reading will be closely proportional

ves the approximate sensitiveness of galvanometers of il resistance and period.

METERS PER MICRO-AMPERE

	Galvanometer resistance		
ams	300 ohms	500 ohms	1000 ohms
	150	200	300
	300	450	600
	500	650	800

ters of a slightly different form, having a sensitiveness he above, are on the market. Portable galvanometers, sitiveness (0.5 to 10 micro-amperes per smallest scale n connection with thermo-couples and for measuring

alvanometer. — The Einthoven string galvanometer, which is shown in Fig. 3, is essentially a moving-coil e conductor which moves is *NS* are the poles of a power- he fine conducting "string" ow air gap between the poles t. When a current is passed string, it deflects at right electromagnet as indicated is deflection is observed by r by projecting an enlarged creen by means of a projection lantern, or the deflection otographic plate.

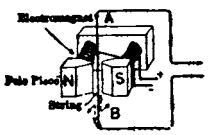


Fig. 3. Einthoven String Galvanometer

relatively large and the pole faces are so shaped that density is secured in the narrow air gap in which the magnetic circuit is always fully saturated so that small current do not affect the flux density in the air gap. be an extremely fine silver wire or a silvered quartz sion, which is adjustable by means of a micrometer nay vary from 5 ohms to 10,000 ohms, depending on . The period depends on the tension on the string and han 0.01 second or may be increased to 8 or 10 seconds ase in sensibility.

ves the characteristics of some Einthoven string gal- Cambridge Scientific Instrument Company, when used

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CHARACTERISTICS OF EINTHOVEN STRING GALVANOM

Material of string	Diameter of string	Resistance in ohms	Period in seconds	Magnifying power of microscope	Deflect mm
					Per microamp.
Silver wire.....	0.02 mm.	4.7	.....	500	4.4
Silvered quartz fiber.....	0.002 mm.	20,000	.....	500	62,500
	0.003 mm.	6,600	.....	650	333.000
	0.002 mm.	5,800	0.008	750	30
	0.002 mm.	3,890	0.005	750	9.7

* These are apparent deflections as observed through the microscope. Fo in the case of the galvanometer having the constants given in the third line, deflection is 333000/650 = 512 mm. per micro-ampere. An apparent deflectio ⅛ mm. can be detected by the eye, consequently with this particular galva current of $10^{-6}/3 \times 333000 = 10^{-12}$ amperes, approximately, may be detected

Vibration Galvanometer. — The Einthoven galvanometer may al as a vibration galvanometer for detecting an alternating current. I nating current is sent through the string and the tension on the latter i so that the free period of the string is the same as the period of the cur the string will be set in vibration, the amplitude of the vibration depen the strength of the current. Consequently when the instrument is th it may be used as a detector of extremely minute alternating current thus used the instrument is capable of detecting an alternating curren amperes, effective value.

A moving coil galvanometer may also be used as a vibration galv by providing means for adjusting the free period of the moving element to resonance with the period of the current to be measured. Fig. 4 shows such a galvanometer, the free period being adjusted by moving the movable bridge up or down.



Fig. 4. Vibrat nomet

Marine Galvanometers. — Any galvanometer that will give deflections that are not affected by the rolling of a ship and consequently can be used on shipboard may be called a marine galvanometer. A common form of marine galvonmeter is of the D'Arsonval type with the coil held by suspensions, both above and below, that are stretched under considerable tension.

The moving system of the galvanometer is carefully balanced, so that a 30-degree inclination will not cause a deflection of more than 3 mm. with the scale at 1 meter distance. It has a very stable zero and a sensitivity of 10 to 20 millimeters per micro-ampere with a 3-second period.

USE AND CALIBRATION OF GALVANOMETERS. — G eters, other than ballistic, are used in engineering work primarily a *detectors* in various bridge (q.v.) and potentiometer (q.v.) measurem

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is usually unnecessary. In order to determine uch measurements, however, the sensitiveness of known. This may be determined by connecting own e.m.f. a fairly high resistance, and connecting er across a known small fraction of this resistance. ice is known or previously measured, the current be calculated by Kirchhoff's laws (*see Electricity f*), and consequently the millimeters deflection d. If the sensitiveness of the galvanometer is too surement, it may be reduced by properly shunting

Galvanometer. — The ballistic galvanometer is measurements and for the determination of the nples of iron or steel (*see Magnetic Testing*). One charge a standard condenser to a known voltage, galvanometer, noting the deflection, and repeating voltages. As the capacity of ordinary standard on the time of charging (*see Condensers, Electric*), rate.

olenoid. — A better method is to use a standard should have a length about 50 times its diameter. er of experiments conducted under the auspices of ttee of the American Society for Testing Materials 18 A.W.G. double-cotton-covered copper wire care- upon a cylindrical core of red fiber approximately in diameter. (A convenient way of winding such shallow thread in the core of such a pitch that the ve between the threads will lie up snug.) A second- 36 A.W.G. double-silk-covered wire was wound in nches, at the middle of this coil.

of this solenoid in series with an adjustable resist- source of constant e.m.f. Connect the secondary ometer. Let

er inch length of the primary coil,
rrent in amperes in the primary coil,
in the secondary coil,
ohms of the secondary coil, galvanometer and any ich may be in the secondary circuit,
hes of the mean cross-section of the primary coil.

rimary coil is reversed a quantity of electricity

$$\frac{4\times 8\pi}{10^9}\frac{n_1 I_1 A N_2}{R} \quad \text{coulombs}$$

$$.638\,\frac{n_1 I_1 A N_2}{R} \quad \text{microcoulombs}$$

lvanometer. Hence, by calculating Q and noting hen currents of various strengths are reversed in n be plotted giving the quantity of electricity cor- any value; such a curve will be approximately a

s). — A Broca galvanometer costs from $40 to $50 ness. A D'Arsonval galvanometer costs from $18 and scale. An Einthoven galvanometer costs from

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$400 to $500. Vibration galvanometer (type shown in Fig. 4) cos
about $110.

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Nov. 2, 1917.

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Combustion Engines; Gas Producers.) The word
means a substance which is capable of indefinite
o used in a restricted sense to mean any mixture
ation or for fuel. It is in this sense that the word

thousands of cubic feet, at 60° F. and at a pressure
he term " permanent " or " fixed " gas is used to
t precipitate any of its constituents when cooled.

addition to natural gas, which exists in limited
alities (in this country, chiefly in western Penn-
io, Indiana, Kansas, Texas and California), there
red gas. These various types all contain the same
ferent proportions, depending upon the process of
om which they are made. Gas may be made from
or liquid fuel, but coal is the fuel usually employed.

s given to the mixture of permanent gases resulting
l retorts of the volatile matter in coal. The heavy
mpurities are extracted by cooling and " washing "
gh purifiers containing hydrated lime or sesquioxide
n the retorts is coke; the condensed hydrocarbons
ulphur compounds and cyanogen are absorbed in
all these by-products are of value.
illumination, but in this country carburetted water-
tensively employed for this purpose. Coal-gas is
oses on account of its high manufacturing cost as
(see below), which, though unsuitable for illumina-
ory fuel for gas engines.

e is given to the mixture of permanent gases result-
take place when steam is passed through a body of
l to redness or beyond, the hot gas being condensed
me manner as coal-gas. The chief reaction in the
decomposition of the steam by the heated carbon,
monoxide, the reaction being $C + H_2O = CO + 2H$.
rocess, hence the production of water-gas is inter-
stages: (1) the " blowing up " or heating the fuel
ir into it, producing CO_2 by the reaction $C + 2O =$
of water-gas by blowing steam through the fuel,
een shut off. Water-gas is generally made from
not only hydrogen and carbon monoxide, but also
nitrogen and light hydrocarbons. Pure water-gas
ion, since it is deficient in the heavy hydrocarbons
od illuminant. This defect is readily supplied by
water-gas as it comes from the producer and super-
med; the naphtha vapor and the superheated steam
anent gases of the hydrocarbon group. Water-gas
etted water-gas " and forms an excellent illuminant.
reater proportion of illuminating gas is carburetted
or carburetted, is seldom used for power purposes,

ame is given to the mixture of permanent gases
reactions which take place when air is blown or
al. At the bottom of the bed, where the air is in
his is reduced on passing through the upper part of

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the bed to CO by the reaction $CO_2 + C = 2\,CO$. The resulting gas al hydrogen, resulting from the reaction between the moisture in the co hot carbon, this reaction being the same as in the production of water- nitrogen of the air is also present in the gas, forming more than half i thereby making a very dilute or "lean" gas. This process has b seded by the producer-gas process described below.

Producer Gas. — This name is given to the mixture of perma resulting from the chemical reactions which take place when both ste are blown through a bed of hot coals. The gas is essentially a mixtur gas and Siemens gas. The process is a continuous one, enough air beir with the steam to maintain the producer bed at the proper tempera eliminating the "blowing up" operation in the water-gas process; a the presence of the steam and the reactions which take place between carbon, the proportion of hydrogen is increased and the proportion decreased, thus making a gas "richer" than Siemens gas. The exac tion of producer gas depends upon the kind of fuel used and the type o of which there are numerous forms (*see Gas Producers*). The gas m particular form of producer is frequently called by the name or type ducer, for example, "Mond gas," "Dowson gas," etc. Producer gas power plants employing large gas engines; it is also used for firing cer and metallurgical furnaces, and, to a limited extent, for firing steam

The thoroughness with which the gas must be cleaned depends upo pose for which it is to be used. For gas-engine work, it is particularly that no tar should be present. On this account, anthracite coal is used for the production of the gas for this purpose, in spite of the rela cost of such coal.

On the basis of the average figures from both the Bureau of Min Station and commercial plants, the following gas yield and heating va expected per ton (2000 pounds) of fuel as fired.

Fuel	Cubic feet of gas per ton of fuel as fired	B.t.u. per cubic foot of gas	B.t.u. per t as
Charcoal	160,000	135	21,
Anthracite	140,000	135	18,
Bituminous coal	135,000	150	20,
Lignite	72,000	155	11,
Peat	60,000	175	10,

Other Kinds of Gas. — "Oil-gas" is a mixture of gases resulting vaporization of crude oil and superheating the vapor; it is used to in illuminating qualities of water-gas. "Coke-oven gas" is the gas fo by-product in coke ovens. Its properties are intermediate betwee coal-gas and Siemens gas; the composition of the gas, however, varie kind of coal and with the time, changing from the beginning to the process. "Oil-water gas" is produced by the chemical reactions betw and oil heated to a high temperature in closed retorts. The cost of ma is low where oil is cheap. "Blast-furnace gas" is a waste produc furnaces, and is a mixture of CO, CO_2 and N, the latter being the la stituent. The relative proportions of CO and CO_2 vary with the of the furnace. An average analysis of blast-furnace gas cooled to at

), 10 per cent CO_2, 65 per cent N. Coke-oven gas, e gas are all suitable for use in gas engines.

NG VALUE. — The calorific or heating value (*see* of a given quantity of gas is the heat energy devel- tion. In this country, the calorific value of a gas per cubic foot, the volume being measured at 60° F. s of mercury. The total heating value of the gas ity of coal is less than that of the coal (or other In the case of coal-gas, the fixed carbon in the herefore, its calorific value contributes nothing to of water-gas and producer-gas, the carbon in the monoxide, but the heating value of carbon mon- carbon in it, since this carbon is already partially so required to distil the hydrocarbons in the coal sses due to radiation. The calorific value of pro- quantity of coal varies from 55 to 85 per cent of rom which it is made, depending upon the character oducer and the manner of operating it.

HEATING VALUE. — The discharge from a gas nsiderably greater than the boiling point of water, t heat of condensation of the water vapor in the ot available for the production of power, whereas on of the heating value of a gas this latent heat of he difference between the heating value, as deter- urement and the latent heat of condensation of ucts of combustion, is called the effective or net The net (or low) heating value of producer-gas is ver than the gross (or high) heating value. The n generally adopted in this country in reporting

FFERENT KINDS OF GAS. — The following nsidered the average composition (percentage by value of the different types of gases used for illumi- uld be noted, however, that the characteristics of considerably from the figures given in the table, of the coal used and the size and type of producer.

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COMPARISONS OF DIFFERENT KINDS OF GASES

Item	Natural gas	Coal-gas	Water-gas	Up-draft producer gas					
				Anthracite	Bituminous	Lignite	Peat	Wood	Oil
CO.....	0.50	6.0	45.0	22.7	18.28	18.72	21.00	13.6	10
H.....	2.18	46.0	45.0	15.5	12.90	13.74	18.50	4.0	10
CH_4.....	92.6	40.0	2.0	0.0	3.12	3.44	2.20	8.0	6
C_2H_4.....	0.31	4.0	.....	0.0	0.18	0.17	0.40	0.0	3
CO_2.....	0.26	0.5	4.0	5.5	9.84	10.55	12.40	12.9	6
N.....	3.61	1.5	2.0	56.0	55.64	53.22	45.50	61.7	63
O.....	0.34	0.5	0.5	0.3	0.04	0.16	0.00	0.0	0
Average B.t.u. per cu. ft...	1000	730	320	135	150	155	175	135	21

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ee also Gas; Gas Producers; Illumination, Laws of.)
l in terms of "calorific value," expressed in B.t.u.'s
minating power," or the candle-power of a standard
s most efficient state, consuming 5 cubic feet of the
urements of volume are reduced to standard condi-
ssure, viz., 60° F., and a 30-inch barometric height.
s stated in atmospheres and in pounds per square
y the inches of water manometer column which the
pheric pressure (*see Units and Conversion Factors*).
rom 1.5 to 4 inches in low-pressure systems and from
ure systems. Most of the gas systems in the United
ire type, but high-pressure systems are common in
ercial varieties of gas and their more important

distillation from bituminous coal, consists chiefly of
er hydrocarbons. It varies greatly in quality with
age of distillation. Values of 16 candle-power and
ve of the usual commercial supply. The use of coal

y the reaction of steam and incandescent coal or
rogen and carbon monoxide, and is usually enriched
rific and luminous value. The properties of water
es range from 18 to 22 candle-power and from 580 to
Many plants supply a mixture of coal gas and water

f rich hydrocarbon gases produced by "cracking"
candle-power is from 40 to 60 and its calorific value
account of its richness oil gas is often diluted with
for commercial delivery.

pe of oil gas stored under a pressure of 150 pounds
ks for self-contained and portable systems of light-
nately 900 B.t.u. and 36 candle-power. An essential
m is an automatic reducing valve which supplies the
ire adapted to flame and mantle illuminants.

the reaction of water and calcium carbide, is a simple
out 1470 B.t.u.'s and 240 candle-power. For use in
systems acetylene is dissolved in acetone under a
nds per square inch. The usual container has a
volumes at this pressure.

mixture of air with gasoline vapor produced by
enerator commonly used comprises a blower operated
a carburretor and a mixing chamber. In the most
tor air is forced through sheets of cotton cloth which
ixture is produced. In the mixer the gas is diluted
ining from 2 to 5 gallons of gasoline to 1000 cubic
explosive limit. Self-contained lamps in which the
ated by heat from the lamp have a wide use in street
lue of this gas in flames is very low, but it is well
rners.

iefly of methane, has a calorific value of about 1000
value in open flames. It is excellently adapted to

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PERFORMANCE OF FLAME ILLUMINANTS. — Light from is due to minute incandescent carbon particles liberated from the gas The highest efficiency is obtained when the migration of these particle hence the pressure at the flame should not exceed two inches of wate flame should be set but little above the smoking point. The horizo distribution from flames is sensibly uniform. The spherical reducti ranges from 85 to 92.5 per cent, depending on the occlusion of light by ner. The batswing and fishtail burners used with ordinary gas should 90 per cent of the rated illuminating power of the gas when properly Acetylene is commonly burned in duplex burners with air holes givi pre-aeration. The usual one-foot acetylene burner gives 40 candle-po

INCANDESCENT MANTLES AND BURNERS. — The incand Welsbach mantle is the ashy residue of a woven structure of vegeta such as cotton, ramie or artificial silk, impregnated with oxides of ce thorium, with traces of other rare earths. The strength of mantle vari with the material and weave of the fibrous base. Its luminous prop pend on the purity and proportions of the oxides used. Mantles are quality chiefly by strength to resist shock, but the better grades ar superior in the maintenance of their candle-power.

The incandescent burner is made in two general types, upright and Each has a Bunsen tube with adjustable gas cock and air inlet. The a action and flame projection of the upright type is fairly self-regulat wide range of gas pressure and consumption. The inverted type ad narrow range of adjustment. The conditions required to obtain th efficiency from mantle burners are : (*a*) all gas and air ports must be adjusted to give the proper air-gas mixture and best projection pressu flame; (*b*) the flame should burn at the highest possible temperature mantle should be completely immersed in the hottest or outer zor flame.

Performance of Mantle Burners. — Candle-power and efficienc are based on lamps fitted with new mantles adjusted to the most efficie tions, this adjustment being, however, of such a character that any on into casual contact with gas lamps is quite competent to make it. Th performance of mantle burners in service is always somewhat below t values and depends to a marked degree on maintenance conditions. deterioration is due to (*a*) the fouling of the burner with dust, (*b*) the adjustment of air and gas ports, (*c*) the shrinkage of mantles and los active materials, and (*d*) the collection of dirt on glassware. Low-grad show very rapid deterioration, often amounting to 40 per cent in 5 R. F. Pierce (*Trans. Ill. Eng. Soc., Vol. VII, p. 686*) reports from relia under most unfavorable conditions, in an atmosphere charged with ir dust and so infested with insects that some of the burner tubes becam clogged the inherent deterioration in candle-power of well-adjusted lamps of the best grade to be as follows: Duration of test, 1000 hours; to mantle alone, 2.5 per cent; loss due to burner alone, 2.5 per cent; lo dirt on glassware, 10 per cent; total reduction in candle-power, 15 Tests of commercial installations receiving skilled maintenance show an performance from 15 to 25 per cent below the rated candle-power and e Without skilled maintenance the average performance is generally fr 50 per cent below rated candle-power and efficiency. (*Proc. Nat. El Assn., 1911, Vol. I, p. 809.*)

It is important to note that the principal sources of deterioration in candle power, as a general thing, are analogous to those operating in

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n from dust and varying conditions of energy supply and are substantially of equal weight with the two

and electric lamps under actual service conditions, amps was found to be within 10 per cent of labora- allations the performance was even somewhat above other hand, some of the electrical installations fell w laboratory rating, due principally to blackened e drop in the circuits.

ncy in comparing gas and electric installations, to ch tend to produce discrepancies in the performance too much emphasis on the discrepancies exhibited ctical purposes and under reasonable good service offer the best and most practical methods of com- uminants. Where good gas service conditions pre- ce of gas installations is not likely to be as low as w rated candle-power, the figures mentioned above where skilled maintenance is not avialable.

escent gas lamps varies with the pressure and the At a given pressure the lumen-hours per cubic foot nal to the calorific value of the gas. The pressure gas systems have little effect on lamp efficiency, as f gas consumption are about equally affected.

GAS ILLUMINANTS. — The curves of Figs. 1 tion of the gas illuminants in general use.

MANCE OF GAS ILLUMINANTS

Glassware	Gas conditions			Light production			
	C.P.	Pressure, in.	Cu. ft. per hour	L.H.C.P.	M.S.C.P.	Lumens	Lumen-hours per cu. ft.
chimney.....	21.5	2.5	5.12	90.5	96.3	1210	236
lome.....	21.5	2.5	5.12	130.2	85.7	1078	211
lobe.....	23.6	2.0	3.8	71.1	65.3	821	216
ster globe.....	23.3	2.0	18.8	263.6	259.5	3261	173
globe, opal ctor.....	23.3	2.0	18.8	332.2	279.4	3511	187
d glass ball...	21.9	2.5	3.31	68.8	54.7	688	208
flashed re- or.....	21.9	2.5	3.31	91.5	47.4	596	180
holophane re- or.....	21.7	2.5	3.31	71.4	46.6	586	177
eflector.....	18.13	2.00	3.65	65	46.1	579	159
ster globe.....	21.9	2.5	13.03	207.5	150.8	1895	146
globe.....	21.9	2.5	13.03	273.6	174.3	2187	168
globe and en- lled ref.....	23.0	2.5	17.07	516	266	3343	196

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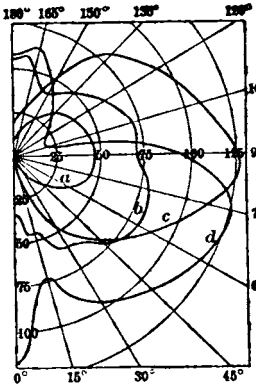


Fig. 1. Light Distribution of Upright, Single-mantle Gas Lamps

a. Junior type, mica chimney, 1.66 cu. ft. per hour
b. Standard type in opal globe, 3.8 cu. ft. per hour
c. Standard type in clear chimney, 4.66 cu. ft. per hour
d. Standard type with opal dome, 4.66 cu. ft. per hour

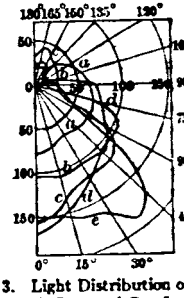


Fig. 3. Light Distribution o mantle Inverted Gas La

a. In roughed glass globe, per hour
b. With flat opal reflector, per hour
c. With opal dome reflector, per hour
d. With enamelled cone refl cu. ft. per hour
e. With holophane reflector 3.65 cu. ft. per hour
All tests with water gas of 20.5

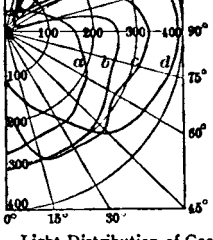


Fig. 2. Light Distribution of Gas Arcs

a. 4-mantle inverted, alabaster globe, 13.03 cu. ft. per hour
b. 4-mantle inverted, clear globe, 13.03 cu. ft. per hour
c. 4-mantle upright, alabaster globe, opal reflector, 18.8 cu. ft. per hour
d. 4-mantle upright, clear globe, opal reflector, 18.8 cu. ft. per hour

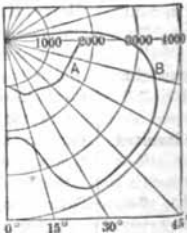


Fig. 4. Light Distribution of sure Inverted Gas Lam

A. 1-mantle, 31.6 cu. ft. per h
B. 3-mantle, 70.3 cu. ft. per h
inches-pressure

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ives performance data of low-pressure gas illuminants
s of test. Under ideal laboratory test conditions, the
e somewhat better.

nat in column 7 in this table, values of mean spherical
for various types of gas lamps equipped with reflectors
d to mislead certain readers to try to interpret these
ete units, because of the difficulty of arriving at accurate
he effectiveness of the reflectors and accessories. It is,
an spherical candle power values in reference to lamps
ors or other accessories, and care should therefore be
s table to take into account that the lamps are equipped

Systems. — The amount of air entrained in the mantle
pressures is insufficient to produce the highest flame
efficiency. Three methods of gas supply are designed
, viz., (*a*) to provide a gas pressure at the lamps of from
(*b*) to provide gas at ordinary pressure and compressed
em of piping and (*c*) to supply both gas and air under
roduced by the three systems are approximately on a
ration in Germany of inverted high-pressure lamps as
(*Lectures on Illuminating Engineering, Johns Hopkins*
p. 872) may be summarized as follows:
. Globe life, 2230 hours. Energy for gas compression,
400 cubic feet of gas. Consumption of 3-burner lamp,
Costs per lamp-hour of 3-burner inverted lamp: com-
ntenance and renewals, 0.58 cent; gas at 61 cents per
ts; total per lamp-hour, 4.87 cents; total per lamp-year
$178.97.
e high-pressure inverted single-mantle lamp is approxi-
r hemispherical candle-power for a gas consumption of
per hour. The 3-mantle inverted lamp gives approxi-
t 70 cubic feet per hour. These efficiencies can be sus-
t careful attention to maintenance conditions. Fig. 4
ibution curves of high-pressure lamps.

atic Ignition. — The automatic ignition of gas lamps
the following methods:
uming from 0.05 to 0.10 cubic foot per hour is fitted to
ain cock is opened a momentary jet of gas is supplied
g the ignition of the main burners. On some remote-
systems a momentary extra pressure is applied as the
uce this jet action at the local burners.
rk is produced in the gas issuing at each burner by means
he primary circuit contains a battery, ignition switch
r. The secondary coil is in series with the several spark
f the wire is grounded. Good insulation of the second-

e provided with a small spot of sponge platinum which
e by catalytic action due to the rapid absorption of gas.
es are apt to be short-lived.
nition cock is frequently employed with show-window
operated during definite time intervals on a flat rate

IGHTING (Pre-war figures). — The following table
cost of operation of various gas lamps. The assumed

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cost of gas is $1.00 per thousand cubic feet and the assumed average lig as 80 per cent of the nominal ratings with clear glassware. These cos taken in reference to service conditions, including the effects of dirt.

Type of lamp	Cost per 1000 lamp-hours			C 10 m
	Renewals and maintenance	Gas	Total	
1-Mantle upright.....	$0.60	$5.00	$5.60	
1-Mantle miniature.....	0.40	2.00	2.40	
1-Mantle inverted.....	0.50	3.30	3.80	
4-Mantle upright.....	1.65	18.80	20.45	
4-Mantle inverted.....	1.65	13.00	14.65	

Gas vs. Electricity. — For comparison with the above it may be r under initial laboratory performance conditions for given assumed l watt ratings the operating costs of 100-watt tungsten lamps with 5 cents and 10 cents per kw-hr. are respectively $0.75 and $1.40 pe lumen-hours. Corresponding costs for 250-watt lamps are $0.61 respectively. The advantages of electric lighting are chiefly co flexibility in the size and location of illuminants. The chief disadv electric lighting are danger of shock from abnormal voltages, the fi faulty wiring and the greater likelihood of service interruption. Th high-grade incandescent mantle lamps is a closer approach to daylight of the tungsten lamp, but is considered by many as less pleasing.

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– (*See also Gas; Internal Combustion Engines; Power*
ne name gas producer is usually applied to the appa-
urifying producer-gas (*see Gas*). The name, however,
e apparatus in which the heating of the fuel takes
l to designate the apparatus used in the manufac-
In this article, the name gas producer will be used
the apparatus used in making and purifying pro-
generator in which the heating of the fuel takes
oiler for producing the necessary steam, and various

e simplest form of generator is merely a cylindrical
vided with a grate, a roof and an outlet for the gas.
o five feet thick is maintained in it and air and steam
l. The oxygen of the air combines with some of the
orming carbon monoxide, the steam reacts with the
drogen and carbon monoxide, and the hydrocarbons
y the heat. In addition to adding combustible gases
ition, the steam diminishes the formation of clinker,
the escaping gases and makes a gas lower in nitrogen,
ating value, than would be produced if air alone were
removal of ashes, revolving grates are used, or else
and the bottom of the producer rests in a shallow pit
ich the ashes are removed from time to time. The
a hopper set in the roof of the producer, and opening
coal, but sometimes special forms of rotating hoppers
distribute the coal evenly over the bed. To avoid
the "caking" of some varieties of soft coal, stirring
ed in the upper part of the producer to break up the

porator is essentially a steam boiler, the water being
gases from the generator to circulate around the pipes
the water. The steam thus formed is fed into the
proportion of air.

. — In order to remove the dust, tar and other harm-
passed through various devices designed to absorb or
es. The filter consists of some porous material, such
awdust, in a suitable retainer. Liquid "scrubbers"
ging the gas into intimate contact with water, which
various impurities. This is accomplished by causing
water, by passing the gas through a chamber into
by passing the gas over surfaces continually kept moist
spray type of scrubber is usually a large cylindrical
latter aiding in absorbing the tar from the gas as it
scrubbers are also employed, which may be designed
the gas and water, or to drive out the impurities by
g scrubbers are particularly effective in removing tar,
s present in gas made from bituminous coal.

ERS. — The various forms of gas producers, of which
, differ chiefly in details of construction and in the
s parts of the apparatus. Two distinct processes of
in use—the up-draft process and the down-draft
purposes these processes are applied by different
ways resulting in the following four general types of

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(*a*) Up-draft suction producers
(*b*) Up-draft pressure producers
(*c*) Down-draft producers
(*d*) Double-zone producers.

In the suction and down-draft types, the pressure in the gas generat that of the atmosphere. This is also true in at least one of the zo double-zone producer. In these types, the "suction" or draft th producer may be produced by an exhauster or directly by the suction engines which they supply.

In the pressure producer the air and steam are forced through th under a light positive pressure (usually equivalent to from 2 inches to water in the generator space above the fuel-bed).

The double-zone producer is, as its name implies, a combination draft and down-draft principles. Two incandescent zones are maint the gas is withdrawn at the center or waistline of the producer.

UTILIZATION OF BY-PRODUCTS. MOND PROCESS. — is about the only by-product of producer gas which has enough c value to justify the additional expense required to save it. This accomplished by the Mond process, which is the one in most general excess of steam is injected with the air, lowering the temperature an preventing the destruction of the ammonia in the coal. (The pro hydrogen and carbon dioxide in the gas is also increased and the pro nitrogen decreased.) The gas, after passing through a mechanical s caused to pass through a tower where it is thoroughly washed w sulphuric acid. The ammonia in the gas combines with the sulp forming ammonium sulphate. This acid solution of ammonium sul culates through the tower over and over again until it reaches a given saturation; then a certain amount of it is by-passed out of the s fresh acid is added. In this system, the heat energy lost by the gas is also used to preheat the air which is used in generating the gas a considerable increase in the economy of the process. From a t containing not less than 1.3 per cent nitrogen, it is possible to pro 90 pounds of sulphate of ammonia and from 140,000 to 160,000 140 B.t.u. gas.

RATING AND PERFORMANCE. — A gas producer is usuall horse-power, the rating being the number of horse-power which can be by gas engines supplied from the producer when the latter is gasi at a maximum rate. Such a rating is, of course, indefinite, as developed by the engines depends upon their design and the perc load which they are carrying, and the rate of gasification depends quality of coal and the care taken in firing. The following dat results of a series of tests on bituminous coal and lignites mad U. S. Geological Survey at St. Louis on a 250-horse-power Taylor and a three-cylinder vertical Westinghouse 235-horse-power ga These tests are summarised in a paper by R. H. Fernald in the *J Soc. Eng., 1907, Vol. 12, p. 551.* The table on page 625 is derived curves there given.

All items in this table affected by load factor are given only for loa from 90 to 100 per cent of full load (235 brake horse-power). The wei per horse-power-hour does not include the coal required to produce injected into the fuel bed. The efficiency is based on calorimetric meas no deduction being made for the latent heat of condensation of the w in the products of combustion of the gas.

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250 H.-P. GAS PRODUCER

000	10,000	11,000	12,000	13,000	14,000	15,000
1.9	1.7	1.5	1.3	1.1	1.0	0.95
1.6	10.1	8.9	7.8	7.0	6.2	5.5
8	45	52	57	65	74	87
0.30	0.35	0.40	0.45	0.5b	0.55	0.60
6	69	70	72	75	80	85

ing are average efficiencies of conversion and scrub- in fuel available in cold, clean gas) for producer-

er cent..... 70
, per cent..... 76
s, per cent..... 73

ng the efficiencies may be taken on the following

Per cent of efficiency of full rating
100
97
92
80

on (*Power, Dec. 1, 1908*) gives the following rules nensions of the various parts of a producer plant: .125 square foot per horse-power capacity. This

$$d = \frac{\sqrt{P}}{2.5},$$

l bed in feet and P the horse-power capacity. o horse-power, the walls of the generator should be es, 12 inches thick. Hence, for sizes smaller than diameter of the generator in feet is $d_0 = d + 1.5$ 2.

proximately twice its internal diameter; for sizes eight is usually greater than twice the internal the height is usually slightly less than twice. three-fourths of the internal diameter of generator one and one-half times the height of generator. rs, of which there should be two, equal to internal

3 to 4 feet for plants ranging from 25 to 200 horse-

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COSTS (Pre-war figures). — The following approximate formu of producer-plant equipments have been derived from a large numb installations. They include the purchase price of generators, eva the necessary scrubbers and filters, but do not include erection, foundations; P is the horse-power rating of the producer.

Up to 250 horse-power..... $\$500 + 10 \times P$
250 to 1000 horse-power... $20P - \$2000$

The cost of such plants erected including producer equipment, and foundations averages from \$80 to \$110 per rated horse-power, buildings, for plants up to 250 horsepower. Plants from 1000 to power average about \$70 per horse-power, including buildings.

Gas holders..... $\$1000 + \$0.26 \times$

Detailed manufacturers' estimates of investment cost and cost of twenty-six producer plants are given in the paper by Mr. Fernald *Soc. Wes. Eng., 1907, Vol. 12, p.551.*

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G. — The following terms are commonly em-

A wheel with teeth cut in its periphery, designed milar wheel or with a screw or worm.

e and Pitch Diameter. — Referring to Fig. 1, *B* with their o gears, are h lines of the of the pitch eter.

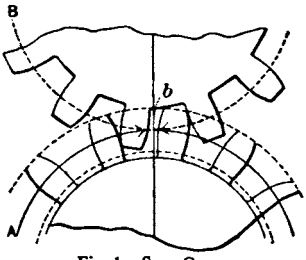


Fig. 1. Spur Gear

Fig. 1, the rence in the d the width the circum- s called the

ircular pitch in inches, e pitch circle, between the center lines of two suc-

$$\text{r pitch} = \frac{\pi \times (\text{diameter})}{\text{Number of teeth}}.$$

stance in inches, measured along the *chord* of the ter lines of two successive teeth; let N be the eter of pitch circle, then

$$\text{dal pitch} = D \sin\left(\frac{180^\circ}{N}\right).$$

quotient of the number of teeth by the diameter

eel of a gearing consisting of two gear wheels gear wheel on the shaft of a railway moto: is called is also used for the smaller of two gears mounted

driven by a chain.

Ratio. — The ratio of the number of teeth in to the number of teeth in the smaller wheel; this io," or the number of revolutions of the smaller volution of the larger wheel.

el in which the external surfaces of the teeth lie lanes of the teeth pass through the axis of the gear wheel.

heel in which the external surfaces of the teeth r may mesh with another gear having its axis in-

ears of the same pitch and diameter mounted will act as a single gear. If one gear is keyed on the two wheels are not in line, but the teeth of of the other, the two gears form a stepped gear. ed gear on a parallel shaft the number of teeth in

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contact will be twice as great as in an ordinary gear, which will inc strength of the gear and its smoothness of action.

Twisted Teeth. — If a great number of very thin gears were placed one slightly in advance of the other, they would still act as a step Continuing the subdivision until the thickness of each separate gear tesimal, the faces of the teeth instead of being in steps take the form or twisted surface, and we have a twisted gear. The twist may take a and if it is in one direction for half the width of the gear and in the direction for the other half, we have what is known as the herring double helical tooth. This form of tooth is much used in heavy m practice, where great strength and resistance to shocks are necessar are frequently made of steel castings. The angle of the tooth with a lin to the axis of the gear is usually 30 degrees.

Spiral or Helical Gears. — If a twisted gear has a uniform twist i what is commonly called a spiral gear (properly a helical gear). Th which the pitch surface intersects the face of the tooth is part of a he on the pitch surface.

Pitch Angle. — The pitch angle of a helical gear is the angle the center line of the tooth and a line perpendicular to the axis of the

Screw or Worm. — A spiral wheel may be made with only one hel wrapped around the cylinder several times, in which it becomes a worm. If it has two or three teeth so wrapped, it is a double- or triple screw or worm.

Worm-Gearing. — When the axes of two spiral gears are at rig and a wheel of one, two or three threads works with a larger wheel threads, it becomes a worm gear, or endless screw, the smaller wheel being called the worm, and the larger, or driven wheel, the worm whe this arrangement a high velocity ratio may be obtained with a sing wheels. For a one-threaded wheel the velocity ratio is equal to th of teeth in the worm wheel. The worm and wheel are commonly so co that the worm will drive the wheel, but the wheel will not drive the wo

Differential Gearing. — Various forms of differential gears are us object is to devise a motion such that the velocity ratio is equal to th the number of teeth in one gear wheel to the *difference* between the of teeth in this gear wheel and the number of teeth in the other wheel form of differential gearing one wheel meshes with a set of teeth on of a second wheel. The second wheel is so arranged that it cannot tu its own axis but its center is caused to move in a circle concentric with wheel.

But for the limitation that the difference between the wheels mu too small, the possible ratio of speed might be increased almost ind and one pair of differential gears made to do the service of a whole train If the problem is properly worked out with bevel gears this limitation completely set aside, and external and internal bevel gears, differing single tooth if need be, made to mesh perfectly with each other.

DESIGN OF GEARS. — In order that the teeth of wheels an may run together smoothly and with a constant relative velocity, it is that their working faces shall be formed of certain curves called c The essential property of these curves is that when two teeth are in co common normal to the tooth curves at their point of contact must pas the pitch point, or point of contact of the two pitch circles. Two su are in common use — the cycloid and the involute.

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d in detail in Kent's *Mechanical Engineers' Pocket-k for Machine Designers.*

ion.* — Gears are usually made of cast iron or tisfactory results the teeth should be machined. n pinions, and composite gears, consisting of alter- and steel or bronze, are also used where smooth ary. Of this latter form of gearing the cloth of being strong, not liable to damage from cold spheric changes, and vermin proof.

bonded with bakelite, known as "micarta," is r gears where quietness of running is desirable. *p. 368, Aug., 1916*) give the following as the physi- Tensile strength parallel to laminations, 10,000 ression strength perpendicular/parallel to lamina- per square inch; transverse strength, maximum arallel to laminations, 17,000 pounds per square per inch per degree centigrade, 0.00002 inch par- rpendicular to laminations; specific gravity, 1.4; pound; oil absorption practically zero; water n at 21° C.) 0.25 to 2 per cent by weight, depend- dge exposed.

ED BY GEARING. — The strength of gear- hat may be transmitted by them depend upon so factors that the formulas and rules given by variation. The pitches indicated in the accom- ed * as representing safely conservative practice ller teeth may afford sufficient strength in some be adhered to with as few exceptions as possible.

Diametrical pitch	Maximum horse-power transmitted	Diametrical pitch
12	10	4
10	15	3
10	20	3
10	25	3
8	50	2½
8	60	2½
6	75	2
6	100	2
5	125	1½
	150	1½

ING. — An extensive series of experiments on efly worm and spiral gearing, is described by *E.*, Vol. 7, p. 273. The average results are shown approximate average figures in the table on the

By D. B. Rushmore.

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The experiments showed the advantage of spur gearing over all o in both durability and efficiency. The variation from the mean resu exceeded 5 per cent in either direction, so long as no cutting occurre variation became much greater and very irregular as soon as cutti The loss of power varies with the speed, the pressure, the temperatur condition of the surfaces.

The excessive friction of worm and spiral gearing is largely due t thrust on the collars of the shaft. This may be considerably reduced bearings for the collars. When two worms with opposite spirals r spiral worm gears that also work with each other, and the pressure o is opposite that on the other, there is no thrust on the shaft. A low for a worm gear means more than the loss of power, since the powe lost reappears as heat and may cause the rapid destruction of the wor

PER CENT EFFICIENCY OF SPUR, SPIRAL AND WORM G

Gearing	Pitch angle, degrees	Velocity at pitch line per min.			
		3	10	40	1(
Spur pinion	..	90	93.5	97	98
Spiral pinion	45	81	87	93	95
Spiral pinion	30	75	81.5	89	93
Spiral pinion	20	67	75	84.5	90
Spiral pinion	15	61	70	80.5	87
Spiral pinion or worm	10	51	61.5	74	82
Spiral pinion or worm	7	43	53	72	76
Spiral pinion or worm	5	34	43	60	70

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TERNATING-CURRENT. — (*See also Alternat-d Magnetism, Principles of; Generators, Direct-Current; Rules.*) In all dynamo-electric machines of the usual polar) the electromotive force induced in any one con-ue and alternates in direction. If the terminals of any rought out to an external circuit by means of revolving an alternating current will flow in the circuit. In order uous current it is necessary to add a commutato. or rec-le and elementary form of electric generator is an alter-nd the direct-current generator is a special form adapted nutator to give a continuous or unidirectional current.

– Alternating-current generators may be classified erent distinguishing characteristics. The following se characteristics in the order of their prominence.

ors. — In the synchronous type the action of inducing sults from the relative motion of the armature con-nagnetic field produced by exciting coils in which a nt flows. The frequency of the alternating electro-ectly on the number of field poles and the angular part.

. — In the induction type the magnetic field is of the and is produced by polyphase alternating currents gs with the load current. The mechanical construc-nduction motor with a short-circuited polyphase wind-per. The frequency depends upon the characteristics n practice the frequency is determined or "set" by a er generator or motor, in the external circuit. This ssary to supply the exciting current of the induction eans of the frequency setter the power factor of the qual the inherent power factor of the generator.

Disadvantages of Induction Type. — A minority of be of the induction type with advantage as they will ts in case of a short circuit on the system. Their current is less. A certain number of the units must pe to "set" the frequency and supply the exciting machines. Consequently, if there is a large propor-s the synchronous machines operate at a poor power capacity effect in the load system, such as synchronous

Revolving-armature Types. — In the revolving-e type there are two, or some multiple of two, poles, coil for the direct-current excitation, and the flux in and purposes constant in value. The relative move-nductors causes the variation in flux interlinkages nsity.

re constructed with an armature revolving inside a s and voltages increased it was found that a more rial could be obtained by making the armature the at the insulation of the high-voltage member was ember was kept stationary.

enerators of large capacity (500 kilowatts and greater) volts and up) are made of the revolving-field type.

the inductor type the direct-current excitation is con-stationary) coil and the variation in magnetic flux is

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obtained by revolving a spider with bare projecting poles which a reluctance of the magnetic path. Thus the flux-threading any armature coil is always in the same direction, but varies in intensity o

Comparison of the Inductor Type with Revolving Field or R Armature Type. — There are no windings or insulation on the moving of the inductor type, which is therefore adapted to high speeds. Th variation in the reluctance of the main magnetic path and the consequ tion in magnetic densities in the field structure of the inductor causes eddy currents, hence the construction of this type has been aband machines of large power. It is still used for radio work however. S *Communication*.

Single Phase, Two Phase or Quarter Phase and Three P The single-phase generator is usually about 30 per cent heavier and mo than a polyphase generator of the same rating. By changing the armature connections a polyphase machine may frequently be recon be a three-, two- or single-phase machine.

As transmission by three-phase currents is more economical of cop by two-phase or single-phase currents, all power transmission lines a phase. Consequently unless there is some local condition requiring two phase, the three-phase generator is preferable.

Two-phase and three-phase generators of the same capacity and strain are of practically the same dimensions, weight and cost.

Trade Terms. — It has become almost universally the custom t an alternating-current generator as *ASB*, *AQB* and *ATB;* the *A* sta alternator, *S* for single phase, *Q* for quarter phase, *T* for three phase a revolving field.

Separately-excited and Self-excited Types. — For years it was a to develop a satisfactory and simple self-excited alternator and some v sucessful but not simple. The object was to obtain a constant voltag load by means of automatic self-excitation. However, with the perf the automatic voltage regulator the need for automatic self-regulatio and there is now very little demand for self-excited alternators.

METHODS OF RATING. — All a-c. generators are rated in amperes (kv-a.) and unless otherwise specifically stated are rated at t which they will give continuously with a rise in temperature not excee tain values depending upon the character of the insulating materials *Standardization Rules A.I.E.E.*

Machines, or those parts of machines, insulated with mica, asbestos heat resisting material are allowed a rise in temperature of 70° C. as by thermometer, or 75° if measured by resistance. This includes mo alternators, both armature and field, and the fields of many other alte

Machines, or those parts of machines insulated with varnished ca impregnated cotton or linen, are allowed a rise of 50° C. as measured mometer, or 55° if measured by resistance. This includes the arm most slow and moderate speed machines.

Most machines have their fields designed sufficiently liberally to ena to give their rated kv-a. at 80 per cent power factor with rated volt this is stated in the specifications. It should be noted that the heati *armature* depends upon the kv-a. and not upon the kilowatt load. T the power factor of the load connected to the alternator, the gre heating of the *field coils* for the same kv-a. output.

VOLTAGE. — Alternators are now built to generate voltages up t and 15,000 volts between lines, either single phase or polyphase. Al

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he insulation and the danger of damage from dis-
xpensive to install transformers with a lower voltage
s consider the limit of economical voltage of gener-
13,000 volts.

frequency depends upon the speed of rotation and
ne speed of rotation of the revolving part is given in
frequency is

$$\frac{\text{r.p.m.}}{60} \times \frac{\text{number of poles}}{2}.$$

it was found much more economical to run at high
uencies such as 133 and 125 cycles per second, were
ns increased in size and complexity, electrical diffi-
these high frequencies and the tendency has been to
ow we have 60, 50, 40 and 25 cycles per second as
25 and 60 are standard in this country. In Europe
60. Of late there has been an attempt to have 15
r railway work.
is preferable where there is a very long transmission
r inductive voltage drop, and where there is much
h as synchronous motors and rotary converters, as
better adapted to parallel operation at low fre-

ycles in U. S. A., and 50 in Europe) is preferable for
t is steadier. The higher frequency is also prefer-
ers are used, as these are cheaper and more efficient

VOLTAGES AND CURRENTS. — For moderate
n lines, the method of connection is decided by such
convenient number for the conductors per slot for
r higher voltages the Y connection is usually chosen
n on the machine insulation for a given voltage
666.

ingle-phase generator the voltage per phase is the
n lines and the current per phase is the same as the
uct of voltage and current giving the volt-ampere

Phase. — In a properly designed machine of this
lf the rating, thus the voltage and current per phase
vely the same as the voltage and current per phase
s equal to 1000 × (kv-a.) ÷ 2 × volts per phase.

nes of this type may be connected either Y or Δ.
the current per phase is the same as the current in
00 × (kv-a.) ÷ $\sqrt{3}$ × (volts between lines), while the
between lines) ÷ $\sqrt{3}$.
e the line current is equal to 1000 × (kv-a.) ÷ $\sqrt{3}$ ×
e current per phase is equal to (line current) ÷ $\sqrt{3}$,
is equal to the voltage between lines.

T POLE GENERATORS. — The procedure in
rrent generaotr for a given power output, voltage
n requirements regarding regulation, efficiency, etc.,
tly empirical. The data of four specific designs are

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given below in the section on *Examples of Design and Performance*. Th of procedure is to lay out a preliminary design from rough calculations, the performance of this design, modify the preliminary design where t lation indicates, recalculate the performances, etc., until a design is a which meets the given requirements.

Definitions. — The following terminology is used in the discussi design of generators:

Pole Arc. — The arc subtended by one pole face, measured periphery of the armature; in the following discussion it will be exp inches.

Pole Pitch. — The arc measured along the periphery of the from the center of one field pole (N-pole, say) to the center of the pole (S-pole); in the following discussion it will be expressed in inches.

Ampere Conductors per Inch of Armature Periphery. — T uct of the number of conductors per inch measured along the periphe armature by the effective amperes flowing in each conductor.

Slot Pitch. — The distance in inches measured along the periphery between the centers of two adjacent slots. The slot pitch to the pole pitch divided by the number of slots per pole.

Coil Pitch. — The number of slots spanned by a coil; that is, has one side in slot number 1, and the other side in slot number 7, the the coil is $7 - 1 = 6$. A coil which spans a distance exactly equal to pitch is said to have a "full pitch," but if it spans a lesser distance to have a "fractional pitch." For example, if there are six slots per a coil has one side in slot number 1, and the other side in slot numbe said to have a fractional pitch of $\frac{5}{6}$ or $\frac{4}{6}$.

Leakage Factor. — The ratio of the flux per pole which enters t ture core to the total flux (including the leakage flux) which would be p by the field winding.

Preliminary Calculation of Main Dimensions. — *Let*

P_0 = output in kilovolt amperes (kv-a),
ρ = ratio; pole arc divided by pole pitch,
B = average magnetic flux density per square inch in air gap,
σ = ampere-conductors per inch of periphery,
V = peripheral velocity in feet per minute at gap,
D = diameter of armature in inches,
L = length of armature along shaft in inches,
N = revolutions per minute,
p = number of poles,
f = frequency in cycles per second,
$A = D + p$.

Then the following relation holds for either a single-phase or a p machine, other than turbo-alternators:

$$P_0 = \frac{\rho\sigma BVDLk_2k_3}{144 \times 10^9},$$

Five of the six design constants in the right-hand member of this equa subject to choice; the equation then fixes the sixth constant. The c the values of the various constants should be based upon modern prac idea of which is given below in the following paragraphs. For values constants k_2 and k_3 see the section below on *Predetermination of Perform*

For turbo-generators see section below on *Design of Turbo-alternators*.

Ratio of Pole Arc to Pole Pitch (ρ) is governed by two anta phenomena; for the sake of small magnetic leakage and good form f

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sired; for the sake of low reluctance to the main
l a high value is desired. The usual values are

ity (B) is limited by
quired to produce it,
by the heating result-
lues B are given in the

Cycles	Lines per sq. in.
25	44,000 to 58,000
60	32,000 to 48,000
125	30,000 to 40,000

per Inch of Periph-
eating resulting from
entilation is good, in-
are very deep, as in
, the values of σ may
for continuous rating
of 40° C. are:

an ts	500 to 2000 volts	2000 to 7000 volts	Above 7000
350	200	...	...
600	400	300	250
000	700	500	400

ns of ventilation, σ may be much greater than the
nple, in turbo-alternators with forced ventilation.
V) is altogether a matter of mechanical design and
000 feet per minute to 10,000. Usual values are

h of Armature. — The diameter of armature (D)
revolutions per minute (N) by the formula

$$D = \frac{12\,V}{\pi N}.$$

, the diameter D is fixed when V is chosen. This
chosen values of ρ, B, σ and V then fixes the value

is not given, reasonable values for D and L may
n accordance with normal and economical condi-
ual to the pole pitch.
neter divided by num-
ation (1) reduces to

$$\frac{AD}{10^9}.$$

nd A are chosen. The
be adjusted to the fre-
of poles (*see next para-*
diameter per pole are
able.

Cycles	A = diameter per pole, in.
25	5 to 12
60	2.5 to 5
125	1.75

(p) and Revolutions per Minute (N). — The

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number of field poles is related to revolutions per minute N and the f by the formula

$$f = \frac{Np}{120}, \quad \text{or} \quad p = \frac{120f}{N}.$$

Hence when the frequency and speed are both given, the numb is fixed. When N is not given, but L is assumed approximately eq as above, the number of poles is found, when D has been determi the relation

$$p = \frac{D}{A}.$$

A value of A must of course be chosen such that p is an even num speed N is then obtained from the relation

$$N = \frac{120f}{p}.$$

Armature Windings. — While there are many forms of armature which may be used, there are practically only two forms that are i use in this country. These are the "Chain Winding" and the "Lap W

Chain Winding (Fig. 1). — This winding is characterized by number of coils equal to half the number of slots; that is, there is only of a coil in each slot. The coils may be either form wound and insulated, in which case slots with open faces are required; or they may be wound by hand in place, in which case partly or entirely closed slots may be used.

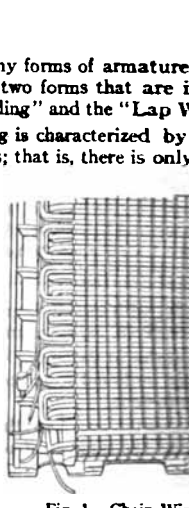


Fig. 1. Chain Win

There are at least two kinds of coils in each machine. These are characterized by the shape of their end connections, as these end connections lie some in one plane and some in another. If there is more than one slot per pole per phase, there must be four different shapes of coils, having two different pitches; the coils of any one phase per pole are placed concentrically. The chain winding is most generally used in high-voltage machines, 2000 volts or higher.

Lap Winding (Fig. 2). — This winding contains a much larger number of coils, all of the same form and size may be two, four, six, etc., sides of coils in each slot, the coils being placed side by side two coils deep. This winding is similar to the multiple-drum winding of a direct-current armature. With two coil sides per slot the slots must be open, but with more than two coil sides per slot the slots may be partly closed. This type of winding is satisfactory for low voltages and very convenient if there are a large number of slots per pole.

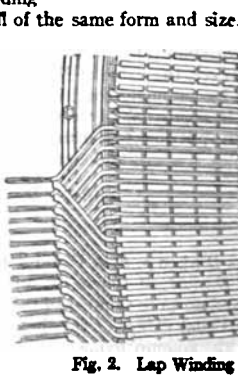


Fig. 2. Lap Winding

The coils are connected in groups of 2, 3, etc., per pole per phase, depending upon the slots per pole per phase. Successive groups or poles of the same phase are connected in series or multiple by "pole connections."

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ch coil may contain from one to many turns in

Phase (S). — Let

er inch of periphery,

e at gap,

r phase at rated load,

ase.

ted winding, such as is used in two- or three-phase

f each phase in series,

$$S = \frac{\pi \sigma D}{2QI}.$$

d in 2, 3, or more parallel paths, the factor 2 in

anged to 4, 6, etc., respectively. For single-phase

below.

Pitch of Slots (s). — The number of slots per pole

se generator may be any multiple of 2, and in a

ltiple of 3. The pitch of the slots for any assumed

$$= \frac{\pi D}{p \times (\text{slots per pole})},$$

e armature at the gap and p the number of poles.

tors per Slot is $\sigma s / I$, where σ is the number of

f periphery, s the slot pitch, and I the effective

— The size of each conductor is a compromise

e a reasonable current density in the conductor,

y fill a reasonable slot (*see discussion of magnetic*

density in the copper conductor should be from

ch in small machines to 2000 in medium and

a high-voltage machines.

ed in the slots so that the slots are usually about

re wide. The size of the slots should be such as

n over and above the space occupied by the con-

ering as they may have. The space required for

ht slots is as follows:

Coil sides per slot	Insulation, inches	
	Vertical	Horizontal
2	0.350	0.150
2	0.430	0.180
2	0.50	0.30
1	0.75	0.375
1	0.835	0.50
1	1.125	0.75

y vertical depth of slot may be found in a machine

h 2 coil sides per slot by multiplying the over-all

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diameter of cotton-covered wire, or depth of bar, by the number of co in a vertical row and adding 0.43 to the product.

Slot Factor. — The ratio of cross section of copper in a slot to cross section of slot is known as the slot factor. Normal values of the slot factor for a 1000-kilowatt machine are given in the accompanying table. For smaller machines the slot factor is slightly less and for larger machines slightly greater.

Voltage	Slo
500	
1,000	
2,000	
4,000	
6,000	
10,000	

Preliminary Dimensions of Magnetic Circuit. — The diameter of the armature and the axial length of the pole face for the preliminary design are fixed by the above calculations There remain to be determined the air gap, the dimensions of the armature teeth, the length and radial depth of the iron, the dimensions of the field poles, and the dimensions of the fi Preliminary values for these quantities may be arrived at as indicat

Air Gap. — The minimum clearance between armature core and field poles in modern generators is given in the accompanying table. The average length of the air gap, due to the chamfer on the poles, is about 25 per cent greater.

Armature Diameter, in.	M air
40	
80	
120	
160	
200	
240	

Armature Teeth. — The dimensions of the armature teeth depend upon the number and dimensions of the slots, which in turn must be such as to contain the necessary conductors. Another important limitation to the width of the teeth, however, is the value of the magnetic flux density therein. Let s = pitch of slots, a = pole arc, g = average radial depth of air gap. Then the effective numbe under each pole is $(a + 2g) \div s$. The effective width of the tooth is its a section one-third the distance from its minimum width towards its width. The effective axial length of the teeth is approximately equ of the axial length of the pole face L determined above. From t the effective cross section of the teeth perpendicular to the flux determined, and this divided into the total flux per pole ϕ gives th flux density in the teeth. The value of ϕ from the preliminary ca above is $\pi\rho LDB \div p$, where ρ = ratio of pole arc to pole pitch, D = di armature at gap, B = average magnetic flux density in gap, and p = poles. The average flux density in the teeth in modern alternatin generators ranges from 90,000 to 110,000 lines per square inch.

Armature Core. — The axial length of the armature core slightly greater than the axial length of the pole face. A fair all twice the radial depth of the air gap. The core is usually built up steel punchings, 14 mils thick, the punchings having received pre thin coat of varnish. Ventilating ducts from ⅜ to ½ inch in width (along the shaft) are usually provided, these ducts dividing the core tions from 2.5 to 3 inches thick (measured along the shaft). The axial length of the armature iron is therefore the total length of the core less the space occupied by the air ducts and insulation between p This latter is about 10 per cent of the net length after deducting occupied by the air ducts.

One-half the total flux per pole passes through each section of the

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ne armature core of modern alternating-current
to 70,000 lines per square inch. Let B_a = the
sen, l = effective axial length of armature iron,
necessary radial depth of the armature core is

ial length of the pole face f is about 0.5 in. less
e. The pole arc a has already been determined.
et core (c in Fig. 3, see below) and the width of
have yet to be determined. The width of the
to 75 per cent of the pole arc (see Fig. 3), and
nachines from 50 to 150 per cent of the width.
e such that the core will accommodate the field
which is determined as follows:
s required per pole to force the flux through the
re ϕ = flux per pole; g = average radial depth of
ial length of pole face. The ampere turns re-
netic circuit is about 40 per cent of this for most
cent of this for most 60-cycle machines. Hence
equired to produce the flux ϕ is approximately
nes, and $0.38\,\phi g + af$ for 60-cycle machines. The
on each field spool at full load, however, will be
f the armature reaction, by an amount depending
ns per pole and the power factor. For prelim-
winding space, however, it is sufficient to increase
e calculated by about 50 per cent, giving as the
mpere turns per pole $F = 0.66\,\phi g/aL$ for 25 cycles
cles.
t density of 1000 amperes per square inch in the
n of the copper in the winding is then $F \div 1000$.
winding including the cotton insulation and inter-
er than the cross section of the copper when wire
er when strip is employed. The field pole may
date this winding, which is usually wound on a
nsulating collar at each end, and 0.25 inch for the
ecting material.
of the core, the flux density in the core should
uld not exceed 100,000 lines per square inch in
ϕ = useful flux per pole, ν = leakage factor, f =
h of core, then the flux density is $B_c = \nu\phi \div bf$.
erators ranges from 1.1 to 1.5.
ameter of the armature and the radial length of
es fixes the internal diameter of the field yoke
e of revolving-field type). The radial depth of
cast iron or cast steel, is determined by the flux
eful flux per pole, ν = leakage factor, e = axial
ux density in the yoke, then the radial depth is
hines B_y ranges from 25,000 to 30,000 lines per
, and from 70,000 to 80,000 lines per square inch

necessary to attempt an accurate calculation of
n of the armature and magnetic circuit has been
required regulation. The method of calculating
g the number of field ampere turns is given in the

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After the excitation in ampere turns per pole required for various power factors desired (according to the specifications or the service re the generator) has been determined, that condition of operation whicl the greatest number of ampere-turns F is selected. A field winding v give this excitation and a margin for safety, with the exciter voltage is then designed. Using this value of F and a current density of 1000 per square inch, the cross section of the field winding is $1.4\,F + 1000$ w of insulated wire, or $1.15\,F + 1000$ when made of insulated strip. The the coil will be $c - 0.75$ (see Fig. 3), allowing $\frac{5}{8}$ inch at each end for and insulation. Therefore the depth of winding will be for wire $\delta = 1.4$ $(c - 0.75)$ + thickness of spool on which the wire is wound, or $\delta = 1.15$ $(c - 0.75)$ + thickness of spool. The spool is usually 0.25 inch thick.

The radiating surface of the coil is then

$$A = 2\,c\,(f + b + 4\,\delta).$$

Resistance and Temperature Rise of Field Winding. — in temperature per watt radiated per square inch of surface of a fiel pends on the peripheral speed of the revolving field or revolving armature. The accompanying table gives the temperature rise in degrees centigrade per watt radiated per square inch. For other rates of radiation the temperature rise is proportional. Let w = watts radiated per square inch for the assumed temperature rise (usually 45° C.), A = area of radiating surface, then the allowable loss per pole is wA; and the field current is then $I_f = wA + v$, where v = volts per pole. The volts per pole should be taken as 80 per cent of the exciter voltage divided by the number of poles (all field spools in series), allowing 20 per cent for emergencies (low speed, etc.). The number of field turns per pole is then $t = F + I_f + 0.5$, the half turn being a convenience in connecting up. The proper resistance (r) of the field w then $wA + I_f^2$, and the necessary cross section (q) of the conductor i inches is

	Peripheral speed, ft. per min.	Tem °C. per
Revolving field	1,000	
	2,500	
	5,000	
	10,000	
Revolving armature	1,000	
	2,500	
	5,000	
	10,000	

$$q = \frac{0.0186\,t\,(f + b + 2\,\delta)}{12{,}000\,r}.$$

(The resistance of 1000 feet of copper 1 square inch in cross section at 0.0093 ohm and $2\,(f + b + 2\,\delta)$ is the mean length of turn.) From t section the nearest size of wire may be chosen and r, w and volts per culated by reversing the above procedure.

The cross section of the winding should now be recalculated, and the adjustments made to make it fit the winding space available on the fi

Bearings, Shafts, Bedplates, etc. — Alternating-current generat be belt-driven or direct-connected and the latter type may have eithe zontal or vertical shaft.

Belt-driven generators are only used in the smaller sizes up to 500 k The smallest sizes usually have two bearings and an overhanging pull larger sizes frequently have three bearings and the weight of the pulley of the belt are taken by two of the bearings.

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Generators with horizontal shafts for direct connection to water wh

gs and a coupling and are complete in themselves,
fts and bearings.
shafts for direct connection to steam engines are
es, shafts or bearings. The generator frame is
y a suitable sole plate. The engine bearing serves
ngs. The revolving field is carried by an exten-
e shaft and bearings are usually furnished by the
ving member of the generator is pressed on the
e generator is built.
s used with water-wheel-driven generators, and in
olving part of the generator may be balanced by
r jet.
revolving-field type the magnetic yoke is made
lywhee.. Such machines are known as flywheel

ing the foundations for the generator, the manu-
vance a template showing the shape and size of
acing of bolt holes.

OF PERFORMANCE OF SALIENT-
From the above calculations a preliminary draw-
may be laid out. The next step is to calculate
rmine what will be the regulation, the efficiency
e various parts.
rter-phase or a three-phase machine are very
in the paragraphs immediately following. The
ase machine are described below. Examples of
performance are also given below.
The first step is the calculation of the magnetiza-
ng the relation between the voltage per phase at
the field ampere turns. To do this the useful flux
given value of the no-load voltage is first calcu-
ere turns per pole required to produce this flux
number of points to give a magnetization curve
voltage should be calculated.
lux cut by the armature conductors.) — Let
e terminal voltage per phase with zero armature

er second,
eries per phase,
g on the shape of the pole shoe, which may be
hoe constant,"
g on the distribution of the armature winding,
ed the "winding-distribution constant,"
g on the pitch of the armature coils, which may
ch constant."
ntering the armature is

$$\phi = \frac{E \times 10^8}{4.44\, k_1 k_2 k_3 f S}.$$

(k_1). — This constant is proportional to the form
n around the periphery of the armature. In all
s are so shaped that this distribution is practically
= 1. This is usually done by making the air gap
t the center of the pole.

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One method of doing this is to make the outline of the pole face a
circle of such a radius (less than the radius of the armature in rev
machines) that the gap at the tips is twice the gap at the center.

For very accurate predeterminations the distribution of the flux
calculated. (*See S. P. Thompson, Dynamo Electric Machinery, Vol.
C. A. Adams, Trans. A.I.E.E., Vol. 33.*)

Winding Distribution Constant (k_2). — This constant all
fact that if there is more than one slot per pole per phase, the co
the various slots of one phase under a pole do not generate e.m.f.'s
the same phase. Since the slots pass under the pole consecutively
of the conductors reach a maximum consecutively. These e.m.f.'s
fore be combined vectorially and not merely added together. k_2
in single-phase, two-phase and three-phase machines.

The following table gives the values of k_2 for uniformly distribute
with equally spaced slots.

Slots per pole	Value of k_2		
	1 phase	2 phase	3 phase
1	1.000	.....	.....
2	0.707	1.000	.....
3	0.666	.....	1.000
4	0.65	0.925	.....
6	0.64	0.912	0.966
8	0.64	0.905	.....
9	0.64	.....	.....
12	0.64	0.90	0.960
18	0.64	0.90	0.960
24	0.635	0.90	0.958
∞	0.632	0.90	0.958

These constants apply to a winding uniformly distributed around
ture periphery. This is always the condition in a two- or three-pha
A single-phase machine usually has its working winding irregularly
so the above constants are only of theoretical interest. (*See special
single-phase machines below.*)

Pitch Constant (k_3). — It is sometimes desirable to use coi
fractional pitch, particularly in machines of large pole pitch, in or
copper and I^2R loss, and also in any machine to give a particularly
shape. When this is done each turn connects in series two conductors generating e.m.f.'s which are not in phase and their resultant is therefore not as great as their arithmetic sum. The constant k_3 is the ratio of this resultant or vector sum to the arithmetic sum of the two e.m.f.'s. The relation between k_3 and winding pitch expressed as a percentage of the pole pitch is given in the accompanying table.

Per cent pitch	
100	
83	
80	
75	
67	
50	

Leakage Factor (ν). — The leakage factor, i.e., the ratio of the total flux produced by the field to the flux which enters the armature.

ating the permeance of the path of the armature
he various leakage paths. The sum of the per-
age paths, divided by the permeance of the main

rage radial depth of the air gap is approximately
he gap is therefore $1.25\,g/af$. The reluctance to
art of the magnetic circuit is about 20 per cent
machines, and 40 per cent in 25-cycle machines.
of the permeance of the path of the main flux is

ycles, and $P_0 = \dfrac{af}{1.75\,g}$ for 25 cycles.

entering each side of a pole has a path l_1 inches
ross section. The permeance of this path to the
of poles is $2\,cf/l_1$. There are two of these paths
ion, from opposite sides of each pole. The total
le is therefore $4\,cf/l_1$. If a uniform m.m.f. acted
lux would be proportional to this permeance, but
at the yoke to the full m.m.f. per pole at the pole
one-half the m.m.f. per pole. The leakage flux
proportional to the m.m.f. per pole and to one-
the "effective permeance" of this path is

$$P_1 = \frac{2\,cf}{l_1}.$$

es to the flux which leaks out from the end sur-
es, giving as the effective permeance of this path

$$P_2 = \frac{2\,bc}{l_1 + b/2} = \frac{2\,bc}{l_2}.$$

pole tips is due to the total m.m.f. per pole, and
therefore

$$P_3 = \frac{4\,c_2 f}{l_3}.$$

of the poles at the chamfer is also due to the total
this path is

$$P_4 = \frac{4\,c_3 f}{l_4}.$$

$$1 + \frac{P_1 + P_2 + P_3 + P_4}{P_0}. \qquad (3)$$

he
o-
ow
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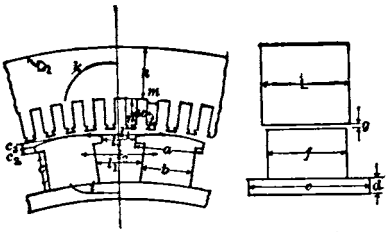


Fig. 3. Dimensions of Magnetic Circuit

Fig. 3. All dimensions are in inches.

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Prepare a table like the following:

Part	Flux	Cross section, A	Flux density = flux/A	Ampere turns per inch, m *	Length of path, λ
Field yoke....	$0.5\ v\phi$	de	.....	.....	i
Field pole.....	$v\phi$	$0.95\ bf$	.....	.....	c
Air gap.....	ϕ	af	.....	.....	See below
Arm. teeth....	ϕ	See below	.....	.....	n
Arm. core.....	$0.5\ \phi$	kl	.....	.....	k

* The value of m is found from the B–H curves in the article on *Magneti* when the flux density has been calculated.

Field Yoke. — The field yoke carries only half as much flux piece, as the flux divides at this point. The material is usually cast i steel. Find the magnetic density as indicated and refer to the proper tion curve to find the ampere-turns magnetizing force per inch for t (see Fig. 4). The length of path is one-half the distance from th one pole to the center of the adjacent pole and is shown by i in Fig the total ampere turns as indicated.

Field Pole or Magnet Core. — This carries all the flux. T is usually sheet steel of high permeability, but sometimes solid steel The factor 0.95 is used for laminated steel poles; for solid poles this course unity. The length of this path is usually taken as c, the le space for the field spool. This is not strictly accurate, but the den pole shoe (c_2) is so low that the excitation required for this part is n

Air Gap. — All the flux in the pole piece does not cross the ga leaks across the interpolar space. The value of the flux in the gap is same as the useful flux in the armature. For the area of gap sectio tection (af) of the pole shoe is taken. The length of the path in the taken as the mean of the gap length. As the maximum length (a tips) is usually made twice the minimum, and the outline of the p made the arc of a circle, the average length is usually 1.25 times the The ampere turns per inch are $0.313 \times$ (density per square inch).

The total ampere turns calculated as above indicated is sometimes by a constant (0.9 to 1.1), to allow for the spreading of the flux into t

Armature Teeth. — The flux is confined at any one time t portion of the teeth per pole known as "teeth under one pole." Sin spreads somewhat on leaving the pole piece it is logical to assume th up a peripheral length equal to the pole arc plus twice the length of t If, therefore, this length is divided by the pitch of teeth at the periph armature, the quotient is the average number of teeth carrying fl given instant. This figure may quite properly contain a fractional teeth. The teeth being wedge shaped or sectors of a circle, that cr (not the mean cross section) which will give the average excitation must since saturation increases more rapidly than the cross section decrease approximate value is found at a point one-third the distance from the width towards the maximum width.

The effective cross section of the teeth is then equal to this width by the product of the effective length of the core by the number of

ive length of core is the net length of iron in the
ce occupied by air ducts and insulation between
s usually 10 per cent of the measurable length of
) = 0.9 × (total length of armature core less space

he flux divides again in the armature core, one-half
ection of the armature core. The core is made of
he cross section of core is equal to the radial depth
tiplied by the effective length of iron in the core.
e greater than one-half the pitch of poles at this
Fig. 3.
er pole as thus calculated, corresponding to the
per phase give one point on the magnetization
fficient number of points should be calculated in
one to extend the saturation curve up to about
ge per phase.

The length of wire in the armature winding is
th of one turn and the number of turns. Let L =
in inches; γ = per cent pitch of coils; D = diam-
number of poles; S = number of turns in series
of conductor* (wire or strip); m = number of
10 for low-voltage machines, and 12 for high-volt-
the curves in the ends of the coils). Then the

$$l = 2L + \frac{k\gamma D}{p},$$

s

$$R = \frac{0.0093\,lS}{12{,}000\,am},$$

at 60° C. of 1000 feet of conductor having a cross
C. is the approximate temperature of the armature

hase to a direct current. The alternating-current
nts and hysteresis, is about 15 per cent greater;
below.
phase machine this resistance is the same as the
s. In a Y-connected three-phase machine the
s twice the resistance per phase. In a Δ-connected
sistance between terminals is two-thirds of the

tance. — The load current in flowing through the
a local magnetic flux which interlinks with the
ing inductance. This inductance causes a loss of
ffect, or lag of current behind the e.m.f.
rcuit, expressed in henries, is

$$L = 1.016\pi S^2 P \times 10^{-8},$$

n series,
path in inches.

cross section of the copper in the cable is approximately
on of the cable, exclusive of insulation. The length of
cable is about 7 per cent greater than the length of the

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The corresponding reactance is $2\pi fL$, where f is the frequency in second.

There are several paths for this so-called armature leakage flux surrounding one or more slots, namely, the path around each slo around a group of slots of one phase, the path around the end The effect of the flux of one phase on the conductors of another (m tance) must also be considered.

The slots lying under a pole have a path of greater permeance lying opposite the interpolar space or between poles, as the form completely surrounded by iron.

With the exception of the path around the end connections, the of each path is readily calculated by the same process as used above ing the leakage factor. The path around the end connections is and the permeance so small compared with that in the core proper, that it is convenient and sufficiently accurate to add a percentage for this flux. This is done by allowing for every inch of the projecting length of the end connections one-tenth as much flux or inductance as for an inch of the embedded portion of the conductors.

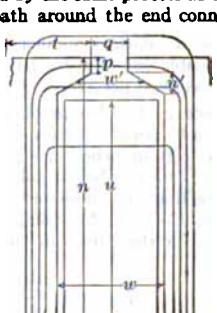


FIG. 4. Leakage Flux

In calculating the permeance of the various paths only the length of the path in air is considered, as the reluctance of the path in iron is so small compared to the path in air as to be negligible.

Let l = effective length of armature core; l' = length of end conn end); P_1 = the total permeance of all the leakage paths for a slot u piece; P_2 = the total permeance of all the leakage paths for a slot tween two poles, and the other quantities as in Fig. 4. Then

$$P_1 = \left(\frac{u}{3w} + \frac{n'}{w'} + \frac{p}{q} + \frac{t}{2g}\right)\left(l + 0.1\,l'\right)$$

$$P_2 = \left(\frac{u}{3w} + \frac{n'}{w'} + \frac{p}{q} + \frac{t}{t+q}\right)\left(l + 0.1\,l'\right)$$

In addition to the above symbols, let f = frequency in cycles per se the slots per pole per phase; s' = slots in series per phase; c = eff ductors per slot = 2 × (turns per phase)/slots per phase; k_2 = "pitch (*see above*). Then the effective reactance in ohms per phase corres the permeance P_1 is

$$x_1 = 20.1 f p' c^2 s' k_2 P_1 \times 10^{-8},$$

and corresponding to the permeance P_2 is

$$x_2 = 20.1 f p' c^2 s' k_2 P_2 \times 10^{-8}.$$

For reactance of turbo-generators see p. 658.

Reactance Drop.— For preliminary or approximate calcula better and more conservative to use the value found for the induct slots "under the poles," as this gives a greater reactance and voltag as the poles usually cover about two-thirds of the armature periph

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e armature reactance drop per phase is taken as
current per phase.
ions both values must be used, and the power
onent of the current considered separately. Let
nd I the armature current per phase. Then the

$$\sqrt{(x_1 \cos\theta)^2 + (x_2 \sin\theta)^2},$$

to taking for the effective armature reactance

$$\sqrt{(x_1 \cos\theta)^2 + (x_2 \sin\theta)^2}.$$

hen current flows through the armature the arma-
t of a magnetomotive force which reacts on the
ts or diminishes the useful flux. If the current
h the generated e.m.f. it causes a "cross magnetiz-
s passing midway between any pair of poles.
t in the armature changes, the direction of the
armature m.m.f. shifts, and a component is intro-
field magnetizing force (for lagging current) or
g force (for leading current). In a polyphase
e due to the armature m.m.f. for a given armature
ude and has a fixed direction with respect to the
ding on the phase of the current.
r projections nor interpolar spaces, the direction
force would be such that the angle between this
erpendicular to the field magnetizing force would
etween the induced voltage and current.
rnator having interpolar spaces the reluctance of
ure m.m.f. is intentionally much greater than that
e result of this is that the effect of armature reac-
uniformity of the field iron, however, changes the
magnetizing forces and renders accurate calcula-
ever, the approximation resulting from the assump-
of field iron is sufficiently accurate. The error
n is on the safe side, since the armature reaction
han its actual value.

Ampere Turns per Pole. — Let S = number of
effective value of armature current per phase; p =
ch constant of the winding (*see above under Mag-*
armature ampere turns per pole effective in pro-

for two-phase machine,

$\frac{I}{}$, for three-phase machine.

reaction for a given effective value of the current
he armature reaction in single-phase generators is
se machines below.
pere turns of different machines at full rated load
low pole pitch, and is less for high frequencies than
rmissible armature-reaction ampere turns depend,
gulation.

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A reasonable value for armature reaction would be between 150 ampere turns per pole for a 25 cycle machine and between 1000 and 60 cycle machine.

Synchronous Reactance. — The effect of the armature leakag and armature reaction upon the terminal voltage of a generator at excitation are of like character, since the voltage induced in the armat each of these causes is in quadrature with the current. The "s reactance" of a generator is the equivalent reactance which would same effect as the armature leakage reactance and armature reactio

The synchronous reactance may be predetermined by finding th ampere-turns (from magnetization curve) corresponding to a volta the drop due to leakage reactance and adding to these ampere turns ture reaction ampere turns. The voltage from the magnetization c sponding to this sum divided by the armature current per phase synchronous reactance per phase. In the calculation of regulat "magnetomotive force method" (see below), however, it is more co express the synchronous reactance in terms of the excitation ampe overcome it.

Regulation. — The regulation of a generator machine is defined of the difference in terminal voltage at no load and at full load to t voltage, the field excitation being kept constant at its full-load value. as a percentage the regulation is $100(V_0 - V) \div V$ where V is t terminal voltage and V_0 the no-load terminal voltage at full-load field

Two different methods have been employed for the calculation of one known as the "magnetomotive-force" method, and the other a tromotive-force" method. Both are approximations, the first giv lower than the actual value, and the second a value higher than value. More accurate methods are given in the *Standardisation R A.I.E.E.*, which see.

Magnetomotive-force Method. — One way in which this been applied is the following: Let V = terminal voltage per phase a R = alternating-current resistance per phase in ohms (= 1.15 ti current resistance); I = full load amperes per phase; $\cos\theta$ = powe the load; X = leakage reactance per phase in ohms. Calculate

$$V' = \sqrt{(V\cos\theta + RI)^2 + (V\sin\theta + XI)^2} \quad \text{and} \quad \theta' = \tan^{-1}\left[\frac{V\sin}{V\cos}\right.$$

taking θ' positive for I lagging behind V'. From magnetization cur excitation ampere turns corresponding to V' and let n = armature reac turns per pole for current I (see p. 635). The total field ampere-tu

$$F = \sqrt{m^2 + n^2 + 2mn\sin\theta'}.$$

Let V_0 = voltage per phase from the magnetization curve correspon excitation F; then the regulation is

$$100\,\frac{V_0 - V}{V}.$$

The difference between V' and V and between θ' and θ is usually and in preliminary calculations m may be taken as the excitation ar corresponding to V, and θ' may be taken equal to θ.

Electromotive-force Method. — Let V = terminal voltage at full load; R = alternating-current resistance per phase in ohm ceding paragraph); XI = volts per phase from magnetization curve

equired to send full-load current through armature
ent; I = full-load amperes per phase; $\cos\theta$ = power
per phase E at no load, corresponding to the full-
r sum of V, RI and XI, or

$$\sqrt{(V\cos\theta + RI)^2 + (V\sin\theta + XI)^2}.$$

oo $(E - V)/V$, and the full-load field ampere turns F
esponding to E on the magnetization curve.

synchronous alternating-current generator or motor

and windage.
l copper loss.

loss.

approximately constant for various loads, but the
of the load current.

ge depend in magnitude upon the details of the
struction, the amount of induced ventilation and
ve a method of predetermining this quantity which
and makes. Each manufacturer has an empirical
ines. This loss ranges from 2.5 per cent in 100 kv-a.
10,000 kv-a. machines. These values are for com-
n bearings (two in number). Some machines are
ring, the other bearing being a part of the prime
n which case the friction chargeable to the genera-
with devices to produce ventilation, such as fan
ving part, have greater friction losses.

ore loss is made up of hysteresis and eddy-current
incipally in the armature core and teeth, but if
ere may be a considerable loss in the frame of the

culate the magnitude of these losses in the armature
ty and flux density are definite in this part, but
e not only to the fundamental frequency and main
ue to the passage of pole tips past the teeth and the
. The total core loss is the sum of the hysteresis
e *Magnetic Properties of Iron and Other Metals* for
y-current losses and formulas for their calculation.
The calculation of the field current and of the resist-
ding is given above in the section on *Field Winding*.
r excitation will be the product of this resistance,
d the number of poles.
ely excited, which is usually the case, the losses in
nvention of the Am. Inst. of E. E., not chargeable

oss. — The calculation of the direct-current resist-
ure winding is given above in the section on *Arma-*
armature copper loss is equal to the number of
ent resistance times the square of the current per

a current flows in the armature conductors a local

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flux is set up which will cause eddy currents in these conductors, if th well subdivided, and in the surrounding iron; as well as a hysteresis surrounding iron. The loss due to this load flux is called the "load l

The load loss is a function of the leakage flux and the subdivision ductors. A large number of turns of fine wire will involve a very If the conductors must be large, they may be made of stranded cab to shape. It is almost impossible to calculate this loss, and very measure it. A rough method is to assume the resistance per phase in 15 per cent, as this loss. like the true copper loss, is proportional to the the armature current. The total amount of the loss is less than 1 p the input in well-constructed machines.

Efficiency. — Let P = total output in kilowatts; R_a = resistance of armature; I_a = armature amperes per phase; R_f = resistance p field winding; I_f = field current; q = number of phases; p = numbe C = total core loss in kilowatts; and F = friction and windage loss in Then the per-cent efficiency is

$$\frac{100\,P}{P+C+F+(1.15\,R_a q I^2_a + p R_f I^2_f)\times 10^{-3}}.$$

This assumes the load loss equivalent to increasing the armature (as calculated or measured by direct current) by 15 per cent. If th is determined from the short-circuit core loss the formula for efficien

$$\frac{100\,P}{P+C+F+L+(R_a q I^2_a + p R_f I^2_f)\times 10^{-3}},$$

where L is the load loss in kilowatts.

The efficiency is a maximum for that load at which the constant equal to the variable losses.

Customary values for the efficiency at full load and each of the los load for various sizes of generators are given in the following tabl values are merely indications and vary with the frequency, voltage, sp factor, etc. A 60-cycle low-voltage machine will be likely to have a ciency than a machine of the same rating for 25 cycles or high voltage

EFFICIENCY AND LOSSES, USUAL VALUES

Rating, kv-a.	Efficiency, per cent	Friction, per cent	Excitation, per cent	Core, per cent	Ar
100	91	2.5	2.5	2.4	
500	94	1.4	1.5	2.2	
1,000	95	0.9	0.9	2.1	
2,000	96	0.6	0.7	1.8	
3,000	96.5	0.6	0.6	1.7	
5,000	97	0.55	0.4	1.6	
10,000	97.2	0.5	0.35	1.5	

* Copper and load loss.

Heating. — The rise in temperature of the field coils is ascertai incidental step in the calculation of the field winding as explained

The rise in temperature of the armature is best determined by given by Arnold (*see Wechselstromteknik, Vol. IV, p. 141*). In thi tion the losses in the projecting portions of the end windings are assu

ated by the end windings while the core loss and copper loss in that portion the winding embedded in the slots are radiated by the surface of the armature core. Let L = length of armature iron in inches; λ = mean length of nature turn in inches (*see Armature Resistance, below*); R_a = armature resistce per phase in ohms; I_a = armature amperes per phase; D_1 = outside diter of armature punchings in inches; D = inside diameter of armature chings; s = number of ventilating ducts; q = number of phases; t = rise in perature in degrees centigrade per watt radiated per square inch of surface. he the watts to be radiated are

$$P = \text{core loss} + \frac{2LqR_aI^2_a}{\lambda},$$

d the radiating surface, including only one-half the area in the air ducts, as e sides of the air ducts are not as effective as the rest of the surface, is

$$A = \pi L(D_1 + D) + \frac{\pi}{4}(D_1^2 - D^2)(2 + s).$$

e rise in temperature by resistance in degrees centigrade is then

$$T = \frac{Pt}{A}.$$

e value of t for a well-ventilated stationary armature ranges from 30 to 40, pending upon the thickness of coil insulation, and the peripheral speed of e field. For a stationary field and revolving armature the value of t given ve for the rise in a revolving field may be used.

Checking Calculations. — Substitution in the following formula gives an ellent check on the above calculations:

$$\frac{DL_f}{Q} = \frac{KA \times 10^8}{fB_g na},$$

here D = diameter of rotor at gap in inches; L_f = length of pole face parallel shaft; Q = total kv-a. of generator; f = frequency in cycle per second; = armature-reaction ampere turns; a = pole arc in inches; A = diameter pole in inches; B_g = flux density, lines per sq. in. in air gap; and K = 22.5 single-phase and 15.9 for two-phase or three-phase generators.

SINGLE-PHASE GENERATOR. — Single-phase generators do not make effective use of the material as do polyphase generators, for the reason that e armature winding can occupy effectively only about one-half of the peripheral surface of the armature; if it occupies more than this there will be voltes generated in the windings which are so out of phase with each other that e resultant voltage is only from 63 to 70 per cent of the sum of all the voltages nerated.

Therefore, if a polyphase generator is used as a single-phase machine with the ame magnetic densities and the same copper densities, the output will be much ss on account of the lesser voltage available. It is, therefore, customary to verload the magnetic elements of the machine somewhat to raise the voltage nd thus reduce the overload on the copper which would be necessary to get he desired output. However, if both the iron and copper densities are increased until the machine gives as much output single phase as it is intended to ive polyphase, there will be an increased heating. Thus, for the same heating, btained by a readjustment of the iron and copper losses, a machine of a given irst cost will give about 75 per cent as much output single phase as may be btained polyphase.

In addition to the disadvantage of a single-phase generator that it cannot

make use of all the periphery of the armature, it also labors under t vantage that its armature reaction is pulsating instead of constant, introduces an additional loss in the form of eddy currents.

By using two phases in series of a three-phase machine, or one phase phase machine, a fairly good single-phase machine is obtained. By the winding slightly differently the same number and arrangement of (or coil sides) can be connected up to give a simpler winding requiring ings of coils, that is, a winding "in one plane."

The formula for the calculation of the e.m.f. of a single-phase ge $E = 4.44\, k_2 k_3 f S \phi\, 10^{-8}$, where the symbols, with the exception of k_2, same significance as in the formula for polyphase machines, p. 629. The value of k_2 depends upon the portion of the armature periphery (including the teeth between slots) occupied by the main winding. Let A = this fraction of the armature surface, then the corresponding values of k_2 are given in the accompanying table. The value of A corresponding to a uniformly distributed winding is unity.

A	
1	
¾	
⅔	
½	
⅓	

The average value of the armature-reaction ampere turns per pole of a single-phase machine is SI/p, where S = the number of turns, I = the armature current per phase, and p = the number of poles, but this pulsates between 0 and twice the above value. The evil effects of sating may be reduced by employing a short-circuited winding havi at 90 degrees to the main field winding. A squirrel cage or "am winding in the pole faces is frequently employed for this purpose.

Due to this pulsating action the load losses are greater and this taken into account in calculating the efficiency and regulation by c the effective armature resistance as 1.15 to 1.5 times the direct-curr ance.

The leakage reactance of a single-phase machine pulsates betwee equal to that obtained by the formula above in the paragraph on *Leakage Reactance*, and a value two-thirds as great. Satisfactory r obtained by multiplying the value obtained from the formula by 0. effective single-phase value. In this case the whole winding is con one phase.

DESIGN OF TURBO-GENERATORS. — In turbine-driven the steam turbine is usually built by the same company that build erator, and the two machines are practically one unit. The steam t developed to such an extent that for a given capacity in power it weigh a reciprocating engine, occupies much less space, costs less and is more cal of steam and fuel. Good economy in steam turbines, however, i only with high angular velocities. This has made it difficult to appl bine to useful purposes. The electric generator has shown itself to b suitable device to absorb the power of the turbine and make it availa divided form and at convenient speeds for general application. H required many years of experience to develop an electric generator wh operate successfully at the high angular velocities suitable for direct to the steam turbine. The principal difficulty was the design of a co which would withstand the enormous stresses in the revolving mem resulted from the centrifugal force. Thus the design of the machine is largely a question of the type and construction of the rotor, wh field.

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peeds. — Most turbo-generators have much more
ss on the armature than do slow-speed machines,
f copper is not far different in the two classes. The
ess magnetic iron on account of its high speed. It
of 5000 kv-a. capacity to operate at 3600 r.p.m. and
t 1800 r.p.m. To do this involves the use of per-
00 to 27,000 feet per minute. At these high speeds
r kilowatt is much reduced. Increasing the speed
of material to about one-quarter. This low weight
higher cost of construction necessary to withstand
orces. Most of the machines, even the large sizes,
most six poles. This involves the use of a pole pitch
0-cycle machines, and 60 to 90 in 25-cycle machines.
concentrated in such small bulk, a great deal of energy
e dissipated in a small space. Thus special means of
ed, such as numerous air ducts, fan blades on the
and a supply of clean, cool air.

— The design of a turbo-generator differs from
e described above, because the revolving field of the
groups of coils placed in slots and distributed con-
centers or cores, which resemble large teeth. The
bout one-third of the pole pitch and has no slots;
field winding gives a peaked shape to the flux wave
le to approach a sine form as near as practicable as

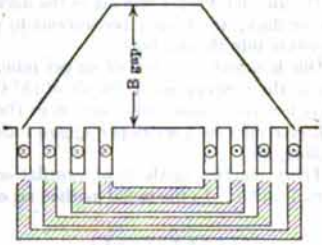


Fig. 6. Field Distribution

rs a developed cross-section of one pole. Thus the
pole pitch, but the average flux density is approxi-
num.

ery large in order to provide a path for the large
equired. On account of the high peripheral speeds
pole is high.

the revolving member is from 1000 to 1500 pounds
al near the periphery. A method for determining
very part is given in *Electric Machine Design*, by
namo-electric Machinery, by Hobart and Ellis.

stantial and rigid construction, so that the critical
the normal speed of operation. There are several
ominent among which are:

rned to shape with radial slots containing a distrib-
aft is in one piece with the field core; see Fig. 5.
onsisting of steel discs about three inches thick held

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between the two end-plates by through-bolts; the radial or parallel sl milled in the assembled structure.

c. Steel laminations with radial slots, assembled on a forged steel sh

d. Laminated pole pieces attached to a spider by keys. (These are being built although there are a large number in service.)

In these revolving fields the length is about the same as the diamet large machines the length is greater than the diameter. The air ga one to two inches. A uniform air gap is necessary to prevent noise an

Construction of Stator. — Since the pole pitch is large, a large n slots per pole is used (12 to 24) and this gives a low armature self in and high short-circuit current. Due to the long pole pitch the end co are long and subjected to considerable mechanical forces, as a resu leakage flux. They must, therefore, be held securely in place by non supports. For armature reaction in ampere-turns per pole values of f to 20,000 are common, and the field winding is usually of a capacity times the armature ampere-turns. The regulation is poor (20 to 30 This defect is readily overcome by the use of automatic voltage regul *Regulators*). The current density in the copper (2000 amperes per squ is lower than in slow speed machines, while the constant "ampere co per inch periphery" has high values, viz., 600 to 1500.

Provision for Ventilation. — The ventilation of these machines is similar to that of air-blast transformers. Thus there must be provi sufficient air to carry off the heat generated with a reasonable rise in ten of the machine and the air; (*b*) Ample duct capacity to prevent too hig of the air; (*c*) Proper spacing of the ducts so that there is no part very an air duct; (*d*) Proper precautions to prevent the air from carrying moisture into the machine.

One hundred cubic feet of air per minute at 20° C. will carry off 1 k rise in the temperature of the air of 18° C. Velocities of the air of fro 6000 feet per minute are common in the machine proper. The surfa will give off 4 or 5 watts per square inch with a rise of 35 to 45° C. a cooling air.

There are two methods of ventilation, the "radial" and the "ax Figs. 7 and 8. In the radial method air enters the air gap at both ends

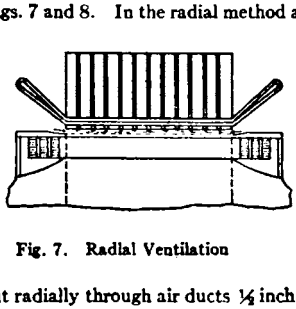


Fig. 7. Radial Ventilation

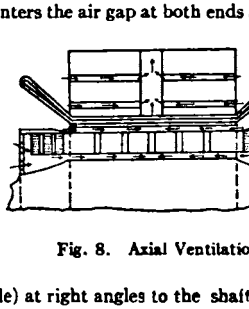


Fig. 8. Axial Ventilatio

out radially through air ducts ⅛ inch wide) at right angles to the shaf air ducts are placed in the stator every two or three inches. In the axia the stator core contains many holes parallel to the shaft through whic passes, usually entering at both ends and passing out through large ra at the middle of the core. Generally both methods are employed in one and whichever method predominates determines the classification. T the outside diameter of the machine, the more appropriate is the axial because of the depth of core. The machine is totally enclosed in either

e air is taken in at a definite entrance and expelled at a definite exit, usually
n from outside the power-house and expelled outside also. An excellent
ission of ventilation is given by Lamme in the *Trans. A.I.E.E., Jan., 1913.*
also Knowlton, *G. E. Review, May, 1916;* Newbury, *Trans. A.I.E.E., Nov.,*
Lamme and Newbury, *Trans. A.I.E.E., Nov., 1916.*

Suitable Speed and Number of Poles. — For 25-cycle machines, 2 poles
1500 r.p.m. are used for all sizes including 35,000 kv-a. For 60 cycles,
oles and 3600 r.p.m. are used up to 6000 kv-a. 4 poles and 1800 up to 30,000
a. and 6 poles for larger sizes. Table I gives representative values of
ensional constants.

TABLE I.—GENERAL DIMENSIONS AND DESIGN CONSTANTS OF TURBO-GENERATORS

	1	2	3	4	5	6	7
Frequency	25	25	25	60	60	60	60
Poles	2	2	2	2	2	4	6
Kv-a.	2,000	5,000	20,000	2,000	5,000	20,000	30,000
R.P.M.	1,500	1,500	1,500	3,600	3,600	1,800	1,200
Diam., rotor, in.	38	38	61	23	25	50	75
Length rotor, in.	35	56	58	46	60	75	94
Stator slots	48	48	72	30	36	72	108
Depth of slots, in.	4.5	5	7	3	4	6	8
Peripheral velocity, ft. per min.	15,000	15,000	24,000	22,000	24,000	24,000	24,000
Amp.-cond. per in.	600	900	1,300	600	900	1,300	1,500
Arm. reaction amp.-turns	11,000	16,000	37,000	6,600	11,000	16,000	15,000
Flux per pole, megalines	58	100	175	40	60	83	112
Avg. gap density, kilolines per sq. in.	28	30	32	24	26	28	30
Air gap length, in.	1.	1.25	2.5	0.75	1.	1.5	1.5
Rotor slots	36	36	48	24	24	48	72
Depth of slots, in.	5.	5.5	7.	3.5	4.5	6.	8
Weight of generator, lb.	50,000	100,000	300,000	34,000	62,000	250,000	430,000

Preliminary Calculation of Main Dimensions. — Equation (1), page 634, applies, but customary values of some of the constants are quite different for reasons stated above.

ρ is usually unity with distributed windings.

B, the average density in air gap varies from 25,000 lines per square inch in 60-cycle machines to 32,000 in 25-cycle machines. Maximum density is 1.57 times the average.

V, the peripheral velocity, varies from 15,000 feet per minute in small, low frequency machines to 27,000 in large machines, figured at the surface of the revolving field.

σ, the ampere conductors of the armature per inch periphery of the field, must be figured on the same diameter as V in order for the equation to check. σ has values as in Table I.

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D = outer diameter of field, in inches.
L = total length of field parallel to shaft, in inches.
k_2 and k_1 the same as on page 634.

Connection of armature winding may be single-phase, two-phas phase Y, or three-phase delta. For all three-phase machines for m 6600 volts, the Y-connection is usually employed, for the reasons given 642.

Number of Turns in Series per Phase (S) is found as on page preliminary value.

Armature Reaction Ampere Turns (n) per pole is found as per fo page 647, and is an important criterion of design in turbo-generators very close to the values given in Table I.

Number of Slots and Conductors per Slot are determined by t the turns in series by the relation

$$2QS = cs,$$

where Q is the number of phases, S the turn in series, c the conductor and s the total number of slots. With values of $2QS$ set, values of 1, 2, 4 and any other even number are tried until the combination w most nearly satisfy the equation is found. s must be divisible by the of poles and the number of phases, in order to make a conventional Usual values for s are given in Table I.

Size of Armature Conductor. — For preliminary purposes, a curren of 2000 amp. per square inch may be assumed, which divided into th per phase gives the cross-section of one "effective" conductor in squa By "effective conductor" is meant the conductor which carries t current per phase. On account of the large currents in large mach frequently advisable to divide the winding into multiple paths, two multiple for instance, then each conductor carries half the phase cur is called half an effective conductor. To reduce eddy currents and bending, the conductors are usually made up of from 4 to 30 strands angular wire laid parallel and insulated from each other. This makes i to build up a conductor of convenient shape, but necessarily reduces factor.

Size of Armature Slots is determined, first, by the space necessary ductors and insulation, and, second, by the depth which is best suite diameter of armature. The slot factor is low for machines of this size reasons: (1) high voltage is customary, (2) a considerable part of th left vacant to serve as a passage for ventilating air, (3) the winding deep in the slot to give sufficient reactance to limit the instantaneo circuit current. A typical slot would be 6 inches deep by 1 inch wide winding and wedge occupying only 5 inches of the depth. Custom factors are given in Table II, usual depths in Table I and space all insulation and air in Table II. The dimensions given for insulation in the insulation on both sides of the coil, that is, an allowance of 0.30 in 0.15 inch on each side. The area of the slot is equal to the cross-secti copper divided by the slot factor and the width of slot is equal to t section divided by a suitable depth as judged from values in Table I.

The Armature Winding is usually a double layer barrel with as m as slots and one, two or three turns per coil. The coils usually hav two-thirds that of a pole in order to shorten the end connections, sav and space, and reduce the copper loss. It is of the lap winding type Fig. 2. There may be as many circuits in multiple in each phase

FACTOR AND SLOT INSULATION

Slot Factor	Insulation, inches	
	Depth	Width
0.35	1.25	0.17
0.35	1.50	0.25
0.33	1.50	0.32
0.30	2.00	0.46
0.27	2.00	0.55

the amount of current per circuit. Each turn is hat it lies near the top of the slot on one side and side.

robable armature resistance is figured at this point he armature does not exceed that which may be s figured as on page 645, except that the straight s 1 or 2 inches beyond the core, adding 7 to 8 turn. It is customary to figure the resistance of n temperature the resistance of 1000 feet of copper 07 ohm. The total I^2R loss should be from 0.2 per erate size machines; less in large machines. See

n Armature is found as given on page 641, and has Table I. This is because the output per pole is so nt runs quite uniformly from 1.1 to 1.15 and is low h and distributed field winding.

adjusted so that the magnetic densities are about stator and rotor teeth and in the air gap the density naximum density (in the center of a field pole) is e density (see *Induction Motors, Polyphase*). For a may be assumed.

MAXIMUM MAGNETIC DENSITIES

	25 cycles	60 cycles
.....	90,000	80,000
.....	100,000	85,000
.....	50,000	45,000
.....	100,000	100,000
.....	90,000	90,000

ruction. — The rotor teeth in the final analysis d to determine if there is sufficient material at the fugal force due to the masses of the tooth and the the preliminary lay-out a number approximating

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those given in Table I is selected, say 36 for a 2-pole machine, and t spaced as if there were 54 slots, but two groups of 9 each are omitted at rically placed positions, thus forming the pole centers. This will give per pole, in which will be placed 9 coils per pole, each of a different p all concentric with the pole center.

For each diameter there is a certain number and depth of slots wh the best proportion between amount of copper and strength of tooth may be judged from Table I. The width of a slot is made approxim to 0.66 of the pitch on the circle at the bottom of the slots.

The Length of Air Gap is much influenced by its function in tion. For the electrical characteristic of the machine it is found des have the length such that the ampere-turns excitation expended in at no load and normal voltage are about equal to the armature re rated load.

No Load Magnetization Curve. — This is calculated as for i motors (q.v.) on account of the distributed field winding and the pe of flux. The average densities are figured on a basis of full pitch pole all stator teeth per pole carrying flux. The maximum density in ga teeth and rotor teeth is obtained by multiplying the average density for a sine wave. With saturation in the teeth (over 110,000) or with wide pole centers, this constant becomes 1.5 or 1.4 respectively.

On account of the long air gap (long compared to slot openings widths) the effect of slots in contracting the flux in the gap is not ma that the density in the air gap may be taken the same as at the surfa rotor. Investigation shows that the increase in density in the air to the slots is only from 2 to 4 per cent and this is balanced by figu density at the surface of rotor instead of at the mean gap diamet section of rotor teeth is figured at a point one-third the distance f bottom of the slots and the total section includes the one large cent and several smaller teeth.

The average length of the path of the magnetic flux in the two core siderably less than one-half the pole pitch on account of the distribu It is usually about 100 to 120 magnetic degrees.

The materials used are generally silicon steel for the stator and for for the rotor. The tendency of the flux to pass through the slots inste teeth is not so great in these machines as in other types because, in t the flux can spread out with saturation, and in the stator, because sities are not very high. A magnetization curve between no load volts terminals and ampere-turns per pole is usually plotted up to a voltage cent of rated voltage.

Armature Leakage Reactance. — The formula used for slow-spe nators will not apply because of the large number of slots per pole and connections and the formula used for induction motors is not suited b the long air gap.

Arnold (*Vol. IV, p. 8*) gives a formula and proof which has been found very well to present day turbo-generators. Referring to Fig. 4, all di in inches, let P_s be the effective leakage flux per ampere-conductor in then

$$P_s = 3.2L\left(\frac{u}{3w} + \frac{u'}{w'} + \frac{p}{q}\right),$$

where L = total length of core in inches.

Let P_t be the leakage flux per ampere-conductor from tooth tip to t set up by the belt of s_1 slots per pole per phase, then

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$$P_t = L\left(2.36 \log_{10} \frac{\pi s}{2q} + A\right),$$

ere s = pitch of teeth at face and "A" has values as follows:

q =	1	2	3	4	5	6	7	8	9	12	15
A =	0	.3	.6	1	1.7	2.1	2.7	3.2	3.8	4.8	5.5

Let P_c be the leakage flux per ampere-conductor around the end connections, ing up by and interlinking the whole belt of s_1 coils, then

$$P_c = l_c\left(1.18\, s_1 \log_{10} \frac{2\, l_c}{U_c}\right),$$

here l_c = length of end connection at one end = $\left(\frac{1.8\,\gamma D}{2p}\right)$ as in the calculation mean length of turn.

U_c = perimeter of a belt of coils = $u + 2s_1 w$ in a double layer winding (see g. 4).

Then the total reactance in ohms per phase is

$$x = 2\pi f p s_1 c^2 k_2 k_3 (P_2 + P_t + P_c) 10^{-8},$$

here f = frequency;

p = number of poles;

c = effective conductors per slot = $\frac{2S}{ps_1}$.

The reactance drop in volts is "x" times the current per phase, and this drop ded by the rated voltage is the per cent reactance, or per cent reactance drop, ch is usually from 8 to 16 per cent.

Excitation at Rated Kv-a. — This is figured as on p. 648, Magneto-tive Force Method, giving conservative values, or as recommended in the dardization Rules of the A. I. E. E. The excitation required in ampere ns per pole is found for full kv-a. output at 100 per cent and 80 per cent wer factor.

Design of Field Coils. — These are usually designed to give the excitation quired at 80 per cent power factor with about 80 per cent of rated exciter ltage, that is at 200 volts d-c. impressed across the field circuit terminals.

The suitable cross-section (sq. in.) of field conductor is found by the relation

$$a = \frac{0.0115 \times (m l t) \times F \times p}{E_x \times 12{,}000},$$

here $(m\,l\,t)$ = mean length of field turn (ins.) figured as for the armature turn cept as to pitch diameter (at center of slots) and as to pitch of end connections, ually 67 per cent, and

F = required ampere-turns *per pole*;

p = number of poles;

E_x = Assumed voltage across field;

0.0115 = resistance per square inch per 1000 feet of copper at 125° C., the temperature commonly assumed for field copper.

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This section, a, is definite for the conditions assumed and is indepe
the number of turns. The number of turns depends upon the allow
or heating. The more turns (more copper) the less the loss.

The working field current I_f is found (a) by assuming 1500 amp. pe
inch in this section of conductor for the excitation for 100 per cent pow
or (b) by assuming a definite loss for excitation and dividing this los
assumed voltage on the field. The number of field turns per pole
$t = F + I_f$ and these turns are distributed equally in the available
should be noted that each turn lies in two slots. The field slot factor h
from 0.4 to 0.6, the lower value applying where much space must be
to ventilating air. Field coils made up with mica and asbestos insulat
ate successfully with a specific loss of 0.90 watt per square inch of coil
giving a rise of about 50° C.

Efficiency and Losses. — The losses are friction, excitation, core-lo
ture I^2R and load loss. The last two are usually combined and re
as the "armature copper loss." The principal friction is that due to
and is a function of the ventilation. The excitation loss is treated abo
core-loss is best calculated on the basis of the loss per cubic inch at
maximum densities as discussed in the article on *Magnetic Properti*
material used is usually 14 mils thick, having a hysteresis coefficient η
and eddy current coefficient $\epsilon = 0.00007$. In turbo-alternators the
by test usually comes out very close to the calculated value, thereby
from some other machines in which a factor greater than unity must
for practical results.

The armature copper loss is greater than the true ohmic loss by fr
50 per cent on account of the load losses.

TABLE IV. — USUAL EFFICIENCIES AND LOSSES

Kv-a	Per cent efficiency	Per cent friction	Per cent excitation	Per cent core-loss	Pe ar
2,000	96	1.50	0.70	1.20	
5,000	97	1.20	0.45	1.00	
10,000	97.5	1.00	0.35	0.90	
20,000	98	0.80	0.25	0.77	
30,000	98.2	0.70	0.20	0.75	

Heating of Armature and Field may be estimated by means of
given under the section above on *Ventilation;* 100 cubic feet of air pe
is provided for each kilowatt of loss. The rise in the armature coils
100° C. per watt per square inch of coil surface and in the field coils abou
per watt per square inch.

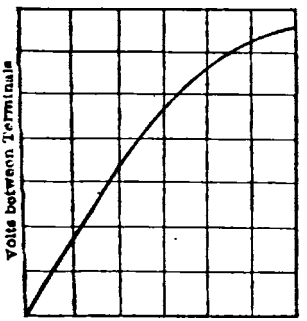
Synchronous Impedance is very high on these machines and th
short-circuit current correspondingly small. It is frequently the case t
excitation for rated voltage and no load, the short-circuit current is
the rated load current. Thus voltage regulation by external means
lutely necessary, the inherent regulation being from 20 per cent to 30
at unity power factor and rated load.

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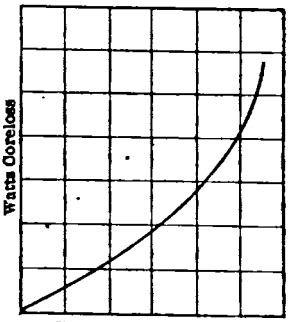
TESTS OF ALTERNATING-CURRENT GENERATORS. — (*See also Standardization Rules of the A.I.E.E.*) The principal tests are

Magnetization or saturation test;
Core-loss and friction tests;
Synchronous-impedance test;
Load-loss test;
Resistance measurements;
Heat runs;
Insulation tests.

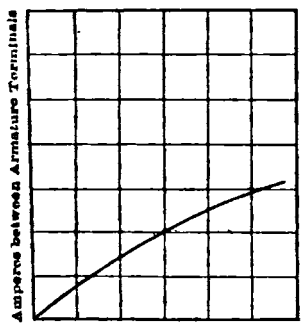
Examples of test results are given below; typical test curves are given in Fig. 9.



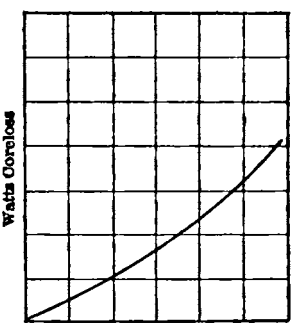
MAGNETIZATION CURVE



CORE LOSS CURVE



SYNCHRONOUS IMPEDANCE



SHORT-CIRCUIT CORE LOSS

Fig. 9. Typical Test Curves

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Magnetization Curve. — The magnetization curve, popularly n
" no-load saturation curve," shows the relation between the no-load vo
the current in the field. Fig. 10 shows the connections for making
On account of the existence of the hysteresis loop (*see article on Magn
erties of Iron*), it is necessary, in running this test, to increase the
rent gradually from point to point and never reduce the value at
until the highest excitation has been obtained. The curve differs
from the magnetization curve of a closed sample of iron because the
circuit of the alternator contains a considerable air gap, the magn
curve of which is a straight line. Therefore, if the saturation cu
machine contains a portion which is very straight, the indications
the air gap is of considerable magnitude. If the machine is op
very high magnetic densities, this is indicated by the fact that the
responding to rated voltage is found at a point on the curve where it
horizontal.

Some machines obtain good regulation by operating at high satur
this is a cheaper method than by using a low value of armature rea
leakage reactance.

The magnetization curve is usually plotted in terms of the volts between terminals. In comparing the observed and calculated magnetization curve it should be noted that the calculations are expressed in terms of the volts per phase.

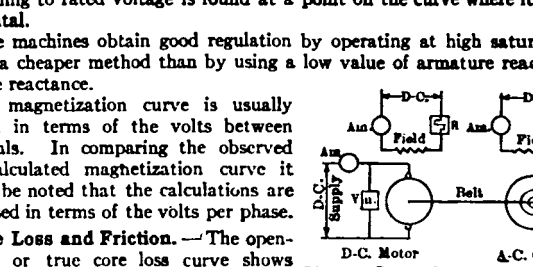


Fig. 10. Connections for Mag
Curve, Core Loss and Friction

Core Loss and Friction. — The open-circuit, or true core loss curve shows the core loss in watts for each value of the no-load terminal voltage. It is made by driving the generator at rated speed by means of a small m
efficiency of which is known, and varying the generator excitation
shows the connections for this test. The voltage and mechanical
(= input to motor multiplied by its efficiency) required for each value
tion are noted. The power P_0 for zero excitation is the friction lo
machine. The core loss for any excitation is $P - P_0$. The no-load s
curve can be made at the same time as the core-loss test.

Synchronous Impedance. — The synchronous-impedance curve s
relation between various values of field current, or excitation ampere t
the current that flows in the armature on short circuit. It is made
circuiting the armature through ammeters and operating at full frequency with various values of field current. Fig. 11 shows the connections for this test. Of course only fractional values of normal excitation are used, or the current in the armature would be so great as to cause damage.

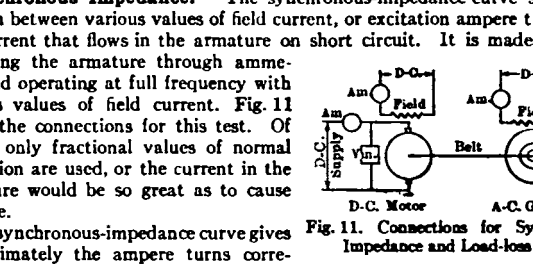


Fig. 11. Connections for Sy
Impedance and Load-loss

The synchronous-impedance curve gives approximately the ampere turns corresponding to armature reaction and the leakage reactance drop in t
ture combined, i.e., the ampere turns corresponding to the synchron
ance. The approximation arises from the effect of the armature
and the low saturation or magnetization of the magnetic circuit under
circuit conditions.

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Stray Load-losses. — These include iron losses, and eddy-current losses in r copper, due to fluxes varying with load and also to saturation.
The following is quoted from the *Standardization Rules of the A. I. E. E.:* Stray d-losses shall be determined by operating the machine on short circuit and rated-load current. This, after deductiug the windage and friction and R loss, gives the stray load-loss for polyphase generators and motors. These es in single-phase machines are large; but the Institute is not yet prepared specify a method for measuring them.

Resistance Measurements must be made when all parts of the machine are some known temperature. They are also made after the heat run, when the achine is hot, to check the temperature as measured by thermometers (*see ticle on Resistance and Conductance*).

Field Resistance is measured by the simple voltmeter-ammeter method *rticle on Resistance and Conductance*).

Armature Resistance. — The armature resistance between terminals is also measured by the simple voltmeter-ammeter method, by connecting two of the terminals to a sorce of direct current (the other terminal being free), the rotor (field or armature of course being at rest). In the case of a single-phase or two-phase machine the resistance as thus measured is the resistance per phase. In the case of a three-phase machine, let R_t = the resistance as thus measured and R_p = the resistance per phase. Then for a Y-connected armature $R_p = R_t \div 2$, and for a Δ-connected armature $R_p = 3R_t \div 2$. If the connection is not known, the calculation of the resistance drop and copper loss may be figured correctly assuming it either Y or Δ connected, provided the resistance per phase and current per phase are both calculated on the same assumption regarding the connection. In the case of a two-phase machine the resistance between terminals A and B and between B and C (B being the common terminal) should each be measured, and the average taken. In the case of a three-phase machine the resistance between A and B, B and C, and A and C should be measured and the average taken.

Calculation of Regulation and Efficiency from Tests. — From the results of the preceding observations, the regulation and efficiency of the machine at various loads may be calculated by the methods given above, in the discussion of *Predetermination of Performance*, using the test data instead of the calculated quantities. The synchronous-reactance ampere turns may be taken as equal to the synchronous-impedance ampere turns, since the resistance drop in the armature on short circuit and reduced excitation is seldom over 10 per cent of the synchronous-reactance drop, and as the two are in general rature the synchronous-impedance drop differs from the synchronous reactance drop by less than one per cent. In using the magnetization curve and the synchronous-impedance curve one must keep in mind whether they are plotted in terms of voltage and current per phase or in terms of volts between lines and line current.

Full-load Saturation Curve. — This curve shows the relation between the terminal voltage and field current with full-load current in the armature. It may be plotted from tests or calculated from the magnetization curve and the synchronous impedance in the same manner as the regulation is calculated.

Armature Leakage Reactance. — There are three methods by which the leakage reactance may be determined:

(1) **Synchronous-impedance Method.** — This gives only approximate results but is very generally used as a synchronous-impedance test is made on every generator. Let n be the field ampere turns per pole required to force full-load current through the short-circuited armature. Let a be the calculated

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armature-reaction ampere turns per pole (see above), with rated
Then $n - a$ is the excitation necessary to induce the leakage reactanc
(IX) in the armature. From the open-circuit saturation curve find th
corresponding to $(n - a)$ ampere turns. Reducing to volts per
necessary, and dividing by the current per phase, the result is the
reactance X per phase in ohms.

(2) **Full-load Characteristic Method.** — This method is also
mate. Let the excitation in ampere turns per pole required to give rate
at full non-inductive load be q. Let the ampere turns to give rate
without load be m. Then $n = \sqrt{q^2 - m^2}$ is taken as the synchronous-i
ampere turns, and the leakage reactance is calculated as described in
ceding paragraph.

(3) **Inductance-measurement Method.** — This method giv
values, but is not very often employed. From an external source o
frequency, full-load current is sent through the armature of the mach
tested, with the fields excited to the normal value but not rotati
voltage drop across the armature terminals is measured for several
positions of the coils with respect to the poles, ranging through an arc
one-half the pole pitch. Let Z = the voltage per phase divided by the
R = the resistance per phase corrected for load loss (i.e., the effective r
as determined from the short-circuit core-loss curve), then the leakage r
per phase is $X = \sqrt{Z^2 - R^2}$. This reactance will vary with the po
the coils and the maximum and minimum may be found by making
culation for the different positions of the coils with respect to the fields.

Heat runs are made at rated load and various other specified loa
parts in which the rise in temperature is of interest are:

Armature core surface;
Armature core ventilating ducts;
Armature conductors;
Collector rings;
Both pole tips;
Field winding;
Bearings;
Frame;
Room.

The temperature of the field and armature winding should be measu
by thermometers and by the resistance method. In taking the tempe
a hot surface by thermometer a small pad of waste should be placed
bulb after the thermometer is put in place. The pad should not be t
or it will prevent the normal radiation from the surface.

With large machines it is inconvenient and expensive to test under
conditions. For determining the heating without actually developing
power of the machine there are several methods available.

Reversed-field Method. — The field circuit may be tapped
full-load field current sent through a portion of the field coils in a
opposed to that for normal operation. For example, in a 24-pole mac
current in 8 of the field coils may be directed in such a manner that
reversed with respect to the remaining 16. The armature winding will
generate a voltage due to the 8 poles that are not neutralized and the
approximately one-third rated value. If the armature is short circuit
rent will flow due to this reduced voltage, and this current can be mad
proximate closely the full-load value by making a proper division of t
If the machine is operated under these conditions the friction, excitat

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s and armature copper loss will be very nearly equal to their value under rmal operating conditions, yet to drive the machine only an amount of power proximately equal to the sum of the losses is required.

Synchronous-motor Loading. — If two machines are available they y be connected up as a generator and synchronous motor and the field excita- n of the motor adjusted so that a current of full-load value, but having a ge reactive component, will flow in the armature, the power factor being arly zero. The power required to drive the generator at full-load excitation t full-load current will then be small.

Direct-current Loading. — Full-load losses may be simulated on a e-phase generator by connecting the three phases in delta and leaving the open at one point, to which a direct-current ammeter and a source of direct rrent may be connected in series. The delta is first closed through an alter- ating-current ammeter and the triple-frequency current in the delta (*see lternating Currents*) is measured. The direct-current ammeter and source direct current are then connected in series with the delta and the direct rrent increased until the sum of the squares of the local current of triple equency and the direct current is equal to the square of the rated current per hase.

Open-circuit Short-circuit Method. — Another ingenious method, ad- cated by Hobart, consists in alternating open-circuit and short-circuit tests, ch under exaggerated conditions, so that at the end of each hour the total att hours lost in each part are equal to the watt hours that would be lost in rmal operation. For example, let the core and field copper loss be 4 kilowatts, d armature copper loss 1 kilowatt. If, now, the machine is operated for minutes with armature short circuited and the excitation adjusted to give kilowatts copper loss, and for 40 minutes on open circuit with excitation djusted to give 6 kilowatts core and field copper loss, then the loss per hour the armature copper is 1 kw.- hr., and in the field winding and core 4 kw.- hr., the same as under normal conditions. For an exact division of the time between he open-circuit and short-circuit conditions, the core and field copper loss uring the short-circuit run must be taken into consideration. After several hours of this relaying the machine will have reached a temperature correspond- ing to full-load operation.

Insulation Tests. — The insulation of a machine is usually tested by apply- ing a given voltage between the conductors and the part of the machine from which they are insulated. An insulation resistance test is also made.

Voltage Tests. — During manufacture the coils are tested separately, and after the machine is assembled a voltage test between the completed windings and frame is made. After the heat run, while the machine is still warm, a third test of the insulation between windings and frame is made.

For this third test an alternating voltage is applied between armature and frame, according to the ***Standardization Rules of the A.I.E.E.*** (q.v.)

The voltage should be increased gradually and the final value should be applied for one minute. In this test the machine acts as a condenser and therefore care should be taken that the frequency is not so high or the inductance of the supply circuit so great as to set up resonance. It is advisable to have considerable resistance in the supply circuit.

To prevent an uneven distribution of voltage, all the terminals of the winding should be connected together by fine wires and one terminal of the high-potential circuit connected to the common connection. The high potential should be measured by a spark gap connected in shunt to the machine.

Insulation Resistance. — The insulation resistance is measured by connect- ing one terminal of a 500-volt direct-current supply to the windings of the ma-

chine through a voltmeter with a 500 scale, and connecting the othe terminal to the frame. If the resistance of the voltmeter is R_v ohm voltmeter deflection x, the insulation resistance is $R = \frac{R_v}{x}(500 - x)$.

EXAMPLES OF DESIGN AND PERFORMANCE. — In the pp. 667 and 668 will be found the essential data both of the mechanica trical features of four representative alternators. The list of items wil useful as a guide in collecting data on various machines. Perform are deduced from tests.

OPERATION. — In the operation of an alternating-current gen following factors should be considered:

Phase Connections and Grounding. — When a third harmonic in the e.m.f. wave of a three-phase generator, the triple frequency e.m three phases (or windings) are additive when the three phases are co Δ, that is, the Δ forms a short circuit to the third harmonic e.m.f.'s, a triple frequency current may therefore be set up in the windings irres the load on the machine. On this account, large three-phase gene usually Y-connected, since with this connection the third harmon between any two terminals of the machine neutralize each other. when two or more Y-connected machines are operated in parallel neutrals grounded, a triple frequency cross-current of considerable may be set up between the machines, unless the wave form of the e.m various generators are exactly the same, which is practically never the prevent such cross-currents with Y-connected machines with grounde it is the usual practice to ground the neutral of but one generator Provision must of course be made to shift this ground connection fro chine to any other, so that a ground connection can always be maint spective of which machine or group of machines may be running.

The advantages and disadvantages of grounding the neutral are di the article on *Grounding of Electric Circuits*.

Division of Load between Alternators in Parallel. — The divisi between two or more alternators operating in parallel cannot be c altering their field excitation, as is the case with direct-current g Changes in the load taken by any alternator of a group can be effecte admitting more or less steam to the driving engine or turbine (or v water-wheel). In order that the various alternators shall share the load properly, it is therefore necessary that the governors on the sev movers give the same speed-load characteristics.

Although the field excitation has no effect on the distribution of the lo the alternators, it does affect the power factor of the load delivere machine. The excitation of each alternator should be so adjusted t livers its load at the same power factor as the others.

Starting a Single Generator. — Before a generator is started up it must be inspected and cleaned and filled with oil if necessary. The r then brought up to the proper speed and the bearings again inspected the oil-rings are running properly. The exciters or excitation circuit i in readiness and the rheostat in the alternator field circuit adjusted for resistance. Before exciting the field the armature insulation must be t dry. If it is not the armature is short-circuited through an ammete for several hours at a partial excitation to give about rated current in circuited armature. When the insulation is thoroughly dry the short removed and the excitation adjusted to give rated voltage at the terminals with correct speed. To shut down the machine the loa

ATA ON TYPICAL A-C. GENERATORS

ns in Inches, Weights in Pounds

	1 ATB	2 ATB	3 ATB	4 ATB
...	4	8	54	48
...	6250	2500	2500	5000
...	1800	375	133	150
...	4000	6600	2300	4000
...	60	25	60	60
...	Y	Y	Y	Y
...	40	92	170	192
...	64	120	180	204
...	52	34	20	30
...				
...	24	7	8	11
...	0.5	½	½	½
...	72	144	648	432
...	3.06×0.75	2⅝×0.9	2⅛×0.4	2⅛×⅝
...	0.16×0.08	0.75×0.17	0.75×3/16	0.6×0.15
...	39	1	2	4
...	78	4	2	4
...	55	⅞	⅞	1
...	0.81	0.5	0.375	0.313
...	0.81	0.625	0.47	0.415
...	30	23	6	8
...	52	33.5	19.5	29
...	8.66	15	4	5.5
...	4.25	8	7	9
...	90	96.5	33.5	49.5
...	(.625×.19)	2¼×0.06	1.5×0.16	1⅛×0.14
...	....	36	24	40
...	....	4	4	5
...	69,000	140,000	170,000	300,000

TA ON TYPICAL A-C. GENERATORS

all in terms of rated or full-load values

		1 ATB	2 ATB	3 ATB	4 ATB
.....	kv-a.	6250	2500	2500	5000
.....	kw.	6250	2000	2500	5000
.....	volts	2310	3320	1350	2300
.....	amperes	902	219	628	723
.....	maxwells	48.4	43.3×10^6	5.6×10^6	12.6×10^6
.....	ohms	0.006	0.072	0.018	0.14
.....	ohms	0.327	0.43	0.37	0.84
ad...	amp. turns	14,600	12,770	7230	7720
ad..	amp. turns	18,000	13,470	7830	8280

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ELECTRICAL DATA ON TYPICAL A-C. GENERATORS—C

Percentages are all in terms of rated or full-load values

		1 ATB	2 ATB	3 ATB
Friction loss	kw.	48	29	14
Core loss at rated volts	kw.	75	40	43
Syn. imp., volts between term.	volts	...	3070	1000
Syn. imp., total amp. turns	amp. turns	11,430	5300	2800
Short-circuit core loss, full-load current	kw.	29	3.4	5.3
Leakage reactance drop	per cent	17	23	7.8
Regulation at full load	per cent	18	16.7	5.8
at power factor of	per cent	100	80	100
Friction loss	per cent	0.54	1.4	0.54
Core loss	per cent	1.38	1.9	1.66
Field copper loss	per cent	0.44	0.65	0.77
Armature copper loss	per cent	0.29	0.52	0.90
Load loss	per cent	0.15	....	0.20
Efficiency at full load	per cent	97	95.5	96.0
Rise in temp. by thermometer:				
Armature	°C.	40	35	45
Field	°C.	46	35	45

removed by opening the circuit breaker; then the field rheostat is maximum resistance as is also the rheostat in the exciter field if t individual exciter. Then the field circuit is opened.

Paralleling of Generators. — Before connecting a generator to b which one or more other generators are connected, the following must be satisfied:

1. The frequency of the generator must be the same as that of the
2. The frequency of the generator, and therefore its speed, must be for an appreciable interval of time.
3. The voltage of the generator must be the same as the voltage bars.
4. The generator and bus-bar voltage must be in phase.

If the two machines have not the same frequency or if the freque constant, a condition will occur intermittently in which the two ve 180° apart or the two machines are in series on a short circuit, and a current will flow. If the voltages are not equal, a large "wattless" current may flow, and if the two voltages are not in phase, a large rent will flow which will cause a mechanical shock. To indicate w conditions are fulfilled any one of several "synchronizing" device employed, as described in the article on *Synchronizers and Synchrosco*

Synchronizing with Lamps. — The simplest method of syn small machines is to use incandescent lamps as shown in Fig. 12. In the connections are such that the lamps remain dark when the above are satisfied, while in Fig. 12B they will remain bright under these c If the frequencies are wrong the lamps will flicker (the slower the nearer the two frequencies). If the voltages are wrong the lamps in

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ily. Transformers should be used with the lamps in hines.



Fig. 12. Connections of Lamps for Synchronizing.

hem. This current will tend to drag ahead the machine e to the inertia of the rotating parts the machine which "overreach" and become leading, and under certain e see-saw action will be set up. When this takes said to "hunt." The value of this current is pro--circuit current of the machines and to the angular in electrical degrees. In a machine having a large a very small variation in angular displacement of the a considerable (20-fold) phase displacement in electrical

is necessary to have:

ving reasonably constant tangential effort and angular ne maximum variation in angular displacement between bars should not exceed 2.5 electrical degrees.

ion the machines shou d have constants such that they itive as pendulums to the strokes or impulses of the

is not too sensitive to slight and sudden variations in ernor.

drop (usually not over 10 per cent) in the connections This refers particularly to groups of machines in power

"Amortisseur" windings on the fields of the ma- ced in these windings cause them to act as electrical

n alternator when suddenly short circuited will deliver many times as great as will flow after conditions have is due to the fact that it takes a finite period of time ture reaction to weaken the magnetic field. During damage may be done to circuit breakers, etc. This is turbo-alternators, as these, due to their construction, sient short-circuit current.

Reactance. — It is therefore frequently the case that are connected in circuit with these machines to prevent ring in case of sudden short circuit. See *Reactance Coils*.

erators on Short Circuit. — Induction generators are e they lose their excitation almost immediately on short e becoming popular in large central stations.

Thermometers. — In large generators thermocouples or (*see Pyrometers*) are sometimes embedded in the es- f the winding, and connected to a suitable indicating imes the maximum temperature of the machine. See *les of the A.I.E.E.*

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SPECIFICATION FOR A-C. GENERATOR. — The followi
randa are intended to assist in writing specifications. See also article
fications.

Principal Characteristics and Conditions of Service. — Service
generator is to be used, such as a-c. lighting, single-phase railwa
operating railway or lighting synchronous converters, etc. Voltage an
of phases. Rated output in kilowatts or kilovolt amperes at stat
factor. Frequency and speed.

Style and Description; Details of Construction. — Type of
revolving field, induction type, etc. Details of speed, governing
mover, and how generator is connected to prime mover, e.g., direct
driven by steam turbine, reciprocating engine, water wheel, water tu
engine, oil engine, etc., with vertical or horizontal shaft. Whether
sated. Whether exciter is to be supplied; if so, its characteristics.
rheostat is to be supplied, its characteristics, including the effect
generator voltage of each step and of all steps; whether to be cont
hand or automatically. Restriction of excitation current and voltag
quirements respecting carrying capacity of slip rings. Accessibility of
Whether embedded thermometer coils shall be furnished. Windings
clamped securely to prevent any vibration of overhanging parts. M
protection of armature conductors if exposed. If belt driven, speci
details; whether bed plate is desired.

Work to be Done by Other Contractors.—Whether Contract
furnish and install the following. Main wiring, field wiring, field rheo
dial plate and chains. Point of division between engine and gener
tracts.

Performance and Tests. — (*See Standardization Rules of the*
Temperature rises upon which ratings are to be based. Details of
capacity. Efficiency at 25, 50, 75, 100, and 125 per cent load. Hi
tial tests of insulation. Requirements regarding effects of moist
insulation. Requirements for parallel operation, i.e., whether the m
to operate in parallel with similar machines or different ones. It is
specify that the terminal voltage shall vary according to a sine law. R
with 100 per cent power factor and normal speed; the load may
from zero to 150 per cent of rated load without causing more than
variation of voltage, the exciter field being kept constant.

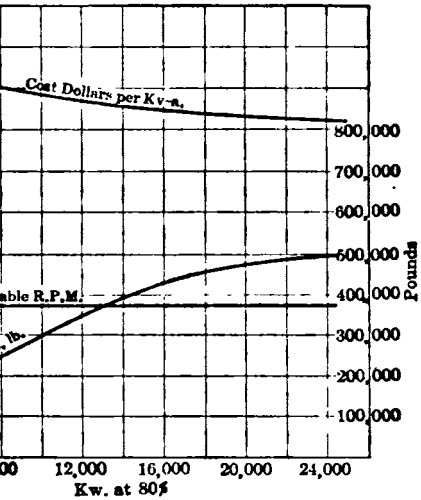
DIMENSIONS, WEIGHT AND COST (1922 prices). — While g
vary widely in their specific weights and costs, that is weight per kv
and cost per kv-a. rating, they may be divided into classes in which thes
teristics are fairly definite.

The conditions primarily affecting the specific weight are: method
speed, frequency, voltage and size. In addition there are the peripbe
and mechanical construction which cannot be easily classified. The m
rating is fundamental. For purposes of comparison the rating may
as the output in kv-a. which each machine will give continuously wi
in temperature not exceeding 50° C. On this basis the specific weight
as the speed, frequency or capacity increases, and increases with in
voltage. The cost per pound decreases as the frequency decreases
the capacity increases. The cost per pound increases as the voltage
ipheral speed increase.

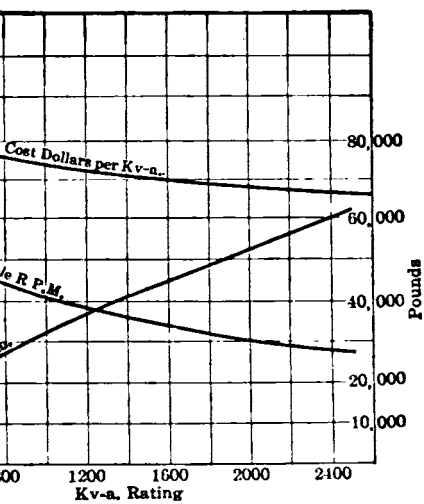
Alternating-current generators may be divided into three classes a
to their speeds and purposes:

High speed, as turbine-driven generators.

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nd Suitable Speed for 60-cycle Turbo-generator Sets, Including Turbine.



d Suitable Speed of Water-wheel driven 60-cycle A-C Generator.

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Medium speed, as belt-driven and water-wheel-driven.
Slow speed, as engine-driven generators.

Approximate weights, costs per kv-a. and suitable speeds are i
Fig. 13 for turbo-generators and in Fig. 14 for water-wheel-driven 60-c
volt, polyphase machines. The weight and cost of 25-cycle gen
from 10 to 20 per cent greater than for 60-cycle generators. T
machines for less than 2300 volts is practically the same as for 2300-
ment. Two-phase generators weigh and cost practically the sam
phase. Single-phase generators weigh and cost from 25 to 30 per
These data are of course suitable only for preliminary estimates;
particularly, are subject to large variations due to changes in comm
ditions from year to year. For final estimates exact dimensions and
should be obtained from the manufacturers.

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Torda, *Alternating-Current Machine Design;* Berg, E. J., *Electri*
Gray, A., *Electrical Machine Design;* Lawrence, R. R., *Principles of*
Current Machinery.

The following are a few references to recent articles in the techn
Design; *Br. Inst. of E. E.*, Dec. 1915, Jan. 1916, Feb. 1916; *A.I.E.E.*
A.I.E.E., Nov. 1916, July, 1918, Nov. 1919. **Wave Form;** *A.I*
1913, May, 1914, Sept. 1918; *Br. I.E.E.*, Feb. 1915. **Testing;** *A.I*
1913; *Br. I.E.E.*, Apr. 1919; *G. E. Rev.*, June, 1916. **Regulatio**
Rend., Oct. 1914; *A.I.E.E.*, July, 1918; *El. Journ.*, Apr. 1918;
Apr. 1914. **Parallel Operation;** *A.S.M.E.*, Oct. 1917; *G. E. Rev.*,
Selection; *G. E. Rev.*, June, 1916. **Troubles;** *G. E. Rev.*, Aug.
1916; *A.I.E.E.* Sept. 1915, Apr. 1916, May, 1918.

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CT-CURRENT. — (*See also Alternating Current, Principles of; Generators, Alternating-Current; Rules.*)

-current, or, as it is sometimes called, continuous- general use before the alternating-current type the distance to which energy is to be trans- s no doubt that the direct-current system is to ergy is to be transmitted over long distances the h its transformer has unequivocal advantages. ons is that a compromise is adopted. The major- provide alternating currents and many of the ovided by rotary converters. Thus the direct- ng of less relative importance while the direct- important position.

ndamental principle involved in the construction dynamo-electric machine is the production of an more conductors by the relative motion of these l. Such a machine may, as a rule, be used either

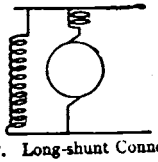
nt machine, either generator or motor, is one in is derived from a circuit of many turns and high t" or multiple with the armature circuit. The ine is poor regulation; that is, the voltage of a he load increases. This is so marked that some circuited, their terminal voltage dropping to zero,

es machine, generator or motor, is one in which ws through the field winding. Series generators constant current to an external circuit irrespect- f that circuit.

ne. — This type of machine is sometimes used in ing current is readily obtained from separately regulator is used.

ne. — This type of machine has on each field pole g a few turns of thick wire which carry the load ries winding. This winding causes the excitation and tends to keep the terminal voltage constant e field windings are proportioned to cause the than the voltage at no load the machine is said "flat compounded" machine has the same volt- ; an "under compounded" machine has a lower load.

t Connections. — A compound-wound machine as in Fig. 1 or long shunt as in Fig. 2. The nvenience of station wiring.



ctions Fig. 2. Long-shunt Connections

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Commutating Pole or Interpole Machines. — These ma
small auxiliary poles alternately placed with respect to the ma
excited by a few turns in series with the load. The effect of thes
improve the operation of the machine in the matter of commutation

Bi-polar Machines. — Small continuous-current machines are u
bi-polar or two-pole type with a more or less inclosed frame of cylin

Multi-polar Machines. — Large direct-current machines are c
polar type, that is, have a large number of radial pole pieces.

Belt-driven and Direct-connected Types. — Direct-curren
may be of either the "belt-driven" or the "direct-connected" ty
mined by the method of connecting to the driving unit. Belt-drive
are characterized by a higher angular velocity than direct-connecte

RATINGS. — It has been common practice (up to 1914) to rate d
machines on the basis of the output in kilowatts which they will g
ously with a maximum rise in temperature by thermometer of 50°
surrounding air at 25° C. See however the recent recommenda
A.I.E.E. in the article on *Standardisation Rules*.

VOLTAGE. — The standard voltages for which continuous-curr
are built are:

80 volts for use on shipboard.
110–125 volts for lighting purposes and incidental small power
motors, cooking utensils.
220 volts for three-wire systems with lighting and power combine
500–600 volts for power alone and particularly for railway service
1200–2400 volts for special railway service and heavy traction.
2000–6000 volts for series-arc-light circuits fed by series machines

ELECTROMOTIVE FORCE INDUCED IN ARMATUR

Z = total number of armature conductors
p = number of field poles.
m = number of parallel conducting paths between the positiv
tive brush sets; that is $\frac{Z}{m}$ is the number of armatur
in series between positive and negative brush sets.
under Armature Windings.)
ϕ = total useful magnetic flux per pole.
N = revolutions of armature per minute.
f = frequency in cycles per second.

If a coil of wire be revolved about an axis in a magnetic fie
in Fig. 3, each length of conductor, or side of the coil, will pass en
the armature in $\frac{60}{N}$ seconds. The time taken for a con-
ductor to pass through the magnetic field under each
pole, or from a to b, is $\frac{60}{Np}$. Hence the average value
of the electromotive force induced in each armature
conductor as it passes under each pole is $\frac{Np\phi}{60 \times 10^8}$ volts,
since a cutting of 10^8 lines per second gives one
volt. Since in an actual machine the conductors are uniformly
around the surface of the armature, this is also the average volt
ductor in each of the conductors between a and b at any ins



Fig. 3. I
Gen

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ries between the positive and negative brush sets,

l electromotive force between the brushes, when a
w) is provided, is

$$E = \frac{p\phi ZN}{60 \times 10^8 m} \text{ volts.}$$

each conductor alternates (i.e., passes through a
nd negative values) with a frequency of $f = \frac{pN}{120}$
e formula for the average e.m.f. between brushes is

$$E = \frac{2f\phi Z}{10^8 m} \text{ volts.}$$

eries between the positive and negative brushes is
e expressed as

$E = 4f\phi S \times 10^{-8}$ volts.

uous electromotive force can be obtained from the
for reversing the connection from each conductor
same time that the direction of e.m.f. induced in
his is accomplished by the commutator. Taps
nections of the armature windings are connected
nutator, so that as the segments come alternately
rushes the current delivered to the circuit is always

GS. — Though there are a large variety of types of
tical man and even the designing engineer seldom
he multiple-drum or lap winding and (2) the two-
winding. The other types may be used in a few
ines but a designer may work for many years with-
using them.

Winding. — This type of winding is very common
otary converters, induction motors and is somewhat
enerators. Its chief advantage is that it affords a
ber of coils and slots, and is very simple to lay
lisadvantage is that it is not easily adapted to
aracteristic is that there are always as many cir-

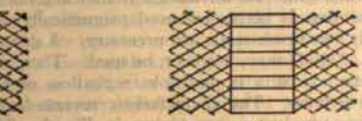


Fig. 5. Wave Winding

ny studs of brushes as there are poles. The dis-
rance is the direction of bending of the end con-
ig. 4. The characteristic form of the coils is shown

Winding. — The customary simplex multiple-
dition expressed by the formula

$$C = pz = 5,$$

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where

C = total number of coil-sides or bars,

p = number of poles,

z = average pitch* = $\frac{\text{front pitch} + \text{back pitch}}{2}$,

s = total number of slots,

b = number of coil-sides or bars per slot.

The total number of sides (C) is double the number of coils, has two sides. C must be a multiple of the number of slots (s number of poles (p).

The average pitch (z) must be an even number so that the fro pitches may be different and odd ($z - 1$) and ($z + 1$), respectively always two layers of coil-sides, top and bottom. One side of each c top layer in one slot and in the bottom layer in another slot. The and back pitches of a coil are always odd because they are made fro in the top layer (odd numbers) to one in the lower layer (even nu Fig. 6. Here the pitch is $14 - 1 = 13$.

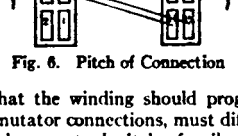


Fig. 6. Pitch of Connection



Fig. 7. Lap Win

In order that the winding should progress continuously the fr pitch of commutator connections, must differ by one coil (or two coi the back pitch, or actual pitch of coils. The actual spread of a (Fig. 7) is the same front and back and is equal to the "back pit

The total number of coils $Q = C/2$ is equal to the number of segments and must be a multiple of the number of slots. In gen common multiple of the number of poles and the number of slots drum winding is possible. It is sometimes desirable that the nu should not be a multiple of the number of poles. In order to gr in poly-coils z should be a multiple of the coil-sides per slot.

Series-drum or Wave Windings, Simplex. — This type of wi in direct-current armatures where the ordinary multiple drum woul too low a voltage or require too many turns of fine wire in each coil. Its advantage is that it gives an armature that is better balanced magnetically and that only two brush studs are necessary. A greater number of studs may, however, be used. There are always two circuits in multiple, regardless of the number of poles. The characteristic reverse bends of its face conductors are shown in Fig. 5. The characteristic form of the coils is represented in Fig. 8.



Fig. 8. Wa

Conditions for Wave Winding. — The conditions to b laying out a series-drum winding are expressed in the formula

$$C = pz \pm 2 = sb,$$

* Let the coil-sides be numbered consecutively from slot to slot, a travel through the conductors in the order in which they are connected starting at conductor No. 1, say, passes through the point or commutat to conductor No. 8 and thus through the back connection to No. 3, t pitch is $8 - 1 = 7$ and the back pitch is $8 - 3 = 5$, and the average pitch

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f coil-sides or bars,
),
f end connections,
f slots,
sides or bars per slot.

l-sides (C) is double the number of coils and must also
per of slots. In the formula $+2$ is preferable to -2,
shorter end connections.
ay be odd or even. If it is odd the front and back
s. If it is even the front and back pitches must be
a wire winding the back pitch must be one greater
l-sides per slot b in order to fit the coils into the slots

ots (s) is very much restricted and is intimately con-
poles unless the expedient of using a dead coil is used

r slot b must be even and cannot be 4 or 8 in a four-
be 6 or 12 in a six-pole machine, unless a dead coil

s. — By leaving one of the coils dead or out of circuit,
nd conductors is available. Four coil-sides per slot
es for six poles may then be employed. In general
divisible by the number of poles. The formula is then

$$C = pz - 2 = sb - 2.$$

ot connected in at all and the number of commutator
umber of active coils or one less than the total coils.
e coils is $C/2$.

nts for 4- and 6-pole machines with no dead coil are:
, then z may be 25, 31, 37, etc., and usual values ful-
= 17, 21, 25, etc. For $b = 10$, then z may be 47, 57,
23, 27, 31, etc.
then z may be 17, 21, 25, etc., and s may be 26, 32,

lings. — It sometimes becomes desirable to provide a
han two circuits in multiple but not as many as the
a case a multiplex wave winding would be selected.
ch the circuit passes completely around the armature
this we use two entirely separate electric circuits we
trant winding, denoted by the symbol O O. If, on the
oses on itself after passing twice around the armature
y reëntrant winding, denoted by the symbol ⊚.
re sometimes used when it is desired to have a num-
different from the number of poles. Thus we may
with four circuits in multiple which with a given
d give a greater voltage than a multiple-drum wind-
n a series drum. This would be a duplex winding.

ultiplex Winding. — The conditions are imposed by

$$c = ps \pm 2m = sb,$$

he same meaning as before and m is the number of.

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multiple windings and z m the number of circuits in multiple. If m prime to each other we have a singly reëntrant winding. The greates factor of m and s gives the number of times the winding reënters o words the number of independent windings.

The multiplicity and complexity may be carried to a very extr (*See under Armature Windings in any standard textbook.*) These windings are hardly ever used in the United States and England occasionally in Germany and France.

ARMATURE REACTION (OR ARMATURE INTERFERE

The armature reaction of a d-c. machine has a very important influe commutation and regulation of both generators and motors. It is of the magnetomotive force of the current in the armature conduct magnetic field set up by the field coils.

Separate Fluxes by Field and Armature Currents. — When cur in the field coils and no current flows in the armature, a flux is set up a path directly across the armature from pole to pole as in Fig. 9. On hand when current flows in the armature and there is no current in flux is set up in the armature across the axis of the poles, as in Fig.



Fig. 9. Field Flux

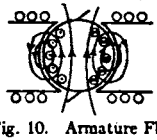


Fig. 10. Armature Flux



Fig. 11. Dis

Resultant Flux. — As a result of this action the flux is shifted arou one tip of each pole has its density increased and one tip has the d creased as in Fig. 11. If the brushes are at the geometrical neutral t longer on an axis at right angles to the flux; that is, they are no lon neutral point with respect to the resultant flux. With the brush position the coil underneath a brush is cutting flux and generating which is short-circuited by the brush and causes sparking. The brus therefore, be moved a small angle in the direction of rotation in a ge the opposite direction in a motor) until they are on the neutral axis. of the brushes aggravates the conditions, but nevertheless, unless the strength is too great, a position can be found in which a brush short coil that is in the real neutral position and is inactive.

Relations Shown Vectorially. — In Fig. 12 F_1 and A_1 are the m.m field and armature with the brushes on the geometrical or apparent ne

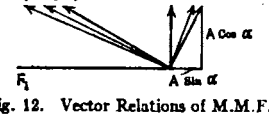


Fig. 12. Vector Relations of M.M.F.'s

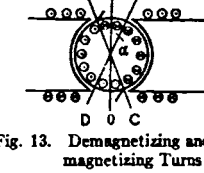


Fig. 13. Demagnetizing an magnetizing Turns

R_1 is the resultant of these. The brushes which are in line with A_1 right angles to R_1. If the brushes are moved to an axis at right angl at A_2, then the resultant becomes R_2 and the desired conditions have

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brushes still further to A_3 giving the resultant R_3 d A_3 at right angles to each other. The stronger the to the field flux the greater will be the angle through e moved.

moved through an angle α to the position A_2 there is nature m.m.f., $A \sin \alpha$, directly opposed to the field nt, $A \cos \alpha$, is at right angles to the field m.m.f. This eference to Fig. 13.

and Cross-magnetizing Action. — Let the move- to A_2 be represented in Fig. 13 by the movement from le α. Then the conductors in the angle 2α, between d D, carry currents whose m.m.f. directly opposes the eld coils; these are known as back or demagnetizing ler of the armature conductors, in A–C and B–D, a m.m.f. at right angles to the field and cause a dis- re known as cross-magnetizing conductors.

while all the conductors in the sections A–B and C–D onstitute back ampere-turns, these are opposed to the hen we come to our quantitative treatment in which we make use of the turns of 2α as the back ampere-

n Armature Reaction.* — The demagnetizing effect be almost entirely overcome by placing the brushes To prevent sparking under these conditions inter- use of interpoles does not in itself prevent armature le sparkless commutation when the brushes are set luce armature demagnetization to a minimum.

CTANCE. — Eacn coil of the armature carries a ction as it travels from a positive brush to a negative direction as the coil travels from a negative to a posi- rection of the current in each coil reverses during bars to which the coil is connected pass under the urrent in any circuit it is necessary to take out the rm of magnetic flux linked with the circuit, and put esented by a flux in the opposite direction. In doing e circuit a voltage which is proportional to the time and which opposes any change in the value of the he e.m.f. of self-inductance of the coil.

; Commutation. — To minimize the voltage of self- to keep the number of ampere-turns in each coil as e the reversal to take place as slowly as possible. It voltage of self-inductance by introducing an opposing ished in practical machines by giving the brushes a nterpoles.

Brushes. — The brushes are moved in the direction (opposite direction in a motor) away from the true rgoing reversal is moving in a flux coming from an density that it induces by rotation in that particular and neutralizes the voltage of self-inductance.

es on Commutation. — Interpoles or commutating he main poles over the neutral space. These poles

* See *Motors, Direct-current.*

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are excited by the load current until they give a flux of the proper dire value to induce the desired neutralizing voltage. (*See also above unc ture Reaction.*)

Increasing Resistance in Path of Short-circuit Current commutation. This changes the time constant of this circuit, that i the stored energy of the magnetism is dissipated in I^2R loss in this instead of in sparking at the brush. The usual method of accompli is to use carbon brushes which have a higher resistance of contact t brushes. Another method is to introduce a high resistance in the c between the winding and the commutator segment.

DESIGN. — The steps in the systematic procedure in the design machine of given voltage and power rating are given below. Simplex are assumed.

1. Statement of problem.
2. Suitable speed.
3. Number of poles.
4. Diameter and length of armature.
5. Length of air gap.
6. Number and size of slots.
7. Total flux, preliminary.
8. Number of turns on armature, preliminary.
9. Armature reaction, ampere-turns.
10. Number of conductors per slot.
11. Form of armature winding.
12. Size of armature conductors.
13. Exact size of slots.
14. Armature resistance and heating.
15. Design of commutator and brushes.
16. Reactance voltage.
17. Exact value of flux.
18. Cross-section of magnetic path; usual flux densities.
19. Excitation; calculation of magnetic circuit.
20. Stability factor.
21. Armature reaction or interference.
22. Field winding, series, shunt.
23. Interpoles or commutating poles.

The performance of the machine should then be calculated from liminary design to determine whether the design meets the imposed and such modifications as are necessary should then be made. Th calculating the performance are the calculations of:

24. Core-loss.
25. Friction.
26. Excitation loss.
27. Armature circuit loss.
28. Efficiency.
29. Regulation.
30. Heating.

Symbols. — The following notation is employed uniformly t this article; other symbols, and the same symbols with primes or subs defined in the paragraphs in which they are used.

(AR) = armature reaction ampere-turns per pole.
B = flux density in air gap, lines per sq. inch.
b = number of coil sides per slot.

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re-turns per pole.
uctors per slot.
of armature, in inches.
re voltage.
e of short-circuited coil.

of voltage induced in armature.

rent, in amperes.
ire, in inches.
lel paths between brushes.
minute.
kilowatts in case of generator; input in case of motor.

al magnetic path of short-circuited coil.
one armature conductor, in square inches.
ace of armature between brushes, in ohms.

f turns in series between brushes.

slots.
ity of armature in feet per minute.
ity of commutator in feet per minute.
coil-sides.

ge pitch of end connections.

nt.

le pitch is the arc from pole center to center of adja-
nt pole, measured at air gap; pole arc is the arc
vered by the pole face.
tors per inch of armature periphery.
per pole.

lem. — The rating in kilowatts or horse-power and
n. The current and speed may or may not be given.
l is found as follows:

$$I = \frac{1000\,P}{E}.$$

$$I = \frac{746 \times (\text{Horse-power})}{E \times (\text{Efficiency})}.$$

assume may be taken from the table of usual values

). — Machines are classified in commercial practice
peed and low speed. The proper speed for a machine
ss is given in the curves in the section below on *Cost*,

(p) depends upon the size, speed and character of the
er, much variation depending upon specific conditions.
are indicated in the first table on page 682.

gth of Armature are related by the following for-

$$D^2L = \frac{610\,P \times 10^8}{\sigma p\,BN}.$$

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Kw. rating	Number of poles		
	High speed	Moderate speed	Low speed
0– 10	2	4	4
10– 50	4	4	4
50–100	4	4–6	6
100–300	6	6	8
300–500	6	8	10
500 and greater	..	..	12 and more

Usual Values of the Constants in the formula at bottom c are:

Magnetic Density in Air Gap (B) has values from 40,000 lines per s in small machines, 55,000 in medium and 70, 000 in large machines. the density in the air gap is taken the same as the density at the pol

Ampere-Conductors per Inch of Periphery, or the Specific Loading product of the total conductors around the armature times the curre divided by the periphery of the armature. The usual values for σ a accompanying table.

Ratio of Pole Arc to Pole Pitch (ρ) varies from 0.6 to 0.85 with an average value of 0.7.

Kw. rating	σ-amp.-co inch of p
	For continuous rating
0–150	250–400
150–400	400–600
400 and greater	600–900

Determination of D and L. — Having found D^2L the two factors may be separated by two methods. Assuming a square pole face (a desirable proportion for economy of armature and field copper), then

$$L = \frac{\pi \rho D}{p},$$

and substituting in D^2L we can solve for D.

Another method of determining separate values for D and L is by a tion of the peripheral speed. The peripheral speed is fairly unifo machines, having values of from 3000 to 5000 feet per minute. average value near 4000. The diameter of armature is given by the

$$D = \frac{(\text{Peripheral speed}) \times 12}{\pi N}.$$

5. Length of Air Gap in inches for a given diameter has a v approximately by the table in the next paragraph. This gives a for preliminary work but it may be found advisable to change it l design.

6. Number and Size of Armature Slots. — A rough approx practice gives the number of slots as four times the diameter in inc eral practice is shown in the following table.

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Air gap, in.	No. of slots	Depth of slots, in.
0.08	25- 40	0.6
0.10	30- 60	0.75
0.12	40- 80	1.00
0.125	60-100	1.25
0.15	80-150	1.50
0.19	100-200	1.75
0.25	150-300	2.50
0.35	200-400	3.25

Armature (ϕ) is fixed by the assumed gap density B eter D of the armature:

$$\phi = \frac{\pi \rho L D B}{p}.$$

in Series (S) between brushes is

$$S = \frac{E \times 10^8}{4 f \phi}.$$

Ampere-Turns per Pole are

$$(AR) = \frac{IS}{p}.$$

mpere-turns per pole (AR) should not exceed certain check as explained in the accompanying table.

Kw. rating	Armature reactive ampere turns per pole (AR)
0-100	1500-3500
100-300	3500-6000
300-500	6000-8000

higher than advisable it he value of the flux by

ctors per Slot (c). — If ots on the armature, the tors per slot (c) must are sometimes antag- olution is a compromise. ling:

$$c = \frac{2 p S}{s}.$$

g:

$$c = \frac{2 \pi \sigma D}{Is} \quad \text{and} \quad c = \frac{4 S}{s}.$$

per and give a number of conductors which can be slot having a depth of from 3 to 4 times its width. r a multiple winding we then choose a series winding. **Winding** (for general discussion of forms of wind-

inding. — If the number of conductors per slot (c) a multiple-drum winding, we choose an arrangement coil sides per slot and assume the conductors per slot

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at a value the nearest multiple of the coil sides per slot, thus gro conductors into coils.

Series-drum Winding. — If a series-drum winding is indica For a four-pole machine choose a number of conductors per slot (by 6 and a number of slots (s) in the series 29, 33, 37, etc., endeavorin that value of $\frac{sc}{4}$ that comes nearest to our preliminary value of S, t of turns in series between brushes. Or for a four-pole machine choose of conductors divisible by 10 and a number of slots in the series 27, 3 gives a value of $\frac{sc}{4}$ the nearest the preliminary value of S.

For a six-pole machine choose a value of c divisible by 4 and a slots (s) in the series 26, 32, 38, that gives a value of $\frac{sc}{4}$ nearest the de of S.

The preceding values of s give the best winding arrangement but other combinations giving unequal front and back pitches and longer co

Revised Value of Turns in Series (S). — Having chosen values for s and c to fit the form of winding desired we must revise our p assumption for the turns in series, S, to accord with the actual windi for a multiple drum $S = \frac{sc}{2p}$, and for a series drum $S = \frac{sc}{4}$.

12. Size of Armature Conductors. — The current in each conduct to the line current I divided by the number of poles in a multiple-dru and to $I/2$ in a series-drum winding of the simple type. The cross each conductor is equal to the current per conductor divided by the amperes per square inch, which varies from 3000 in small machines and 2000 in intermediate size machines to 1500 in large machines.

Kw. rating	Slot f
	For 125 volts
0– 10	0.28
10– 50	0.35
50– 100	0.40
100– 400	0 50
400–1000	0.60

13. Exact Size of Slots, Slot Factor. — The total number of slots is definitely set by the style of winding. The maximum allowable depth depends upon the diameter of the armature. The width of each slot should be from 0.4 to 0.6 of the pitch of the slots, which is the quotient of the periphery of the armature divided by the number of slots. The ratio of the total cross-section of copper in a slot to the cross-section of the slot is known as the slot factor and has more or less consistent values.

Type of slot	No. of bars or coil-sides per slot	Allowance for coil and slot insulation, in.	
		Width	Depth.
Open	2	0.09	0.30
Open	4	0.14	0.35
Open	6	0.15	0.35
Partly closed	4	0.15	0.40

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of the slots are found by adding to the width and
ed conductors, suitably arranged, an allowance for
on. The allowances in the preceding table are for

nce and Heating. — The mean length of turn is
is roughly estimated as

$$l = 2L + \frac{10D}{p}.$$

at 60° C. of the armature from brush to brush is

$$R_a = \frac{0.0093\,Sl}{12{,}000\,qm}.$$

rmature is R_aI.
ber is R_aI^2.
of the copper in ° C. is given approximately for pre-

$$T_c = \frac{100\,R_aI^2}{(a+b)ls},$$

dth of coils in slot, in inches.
pth of coils in slot, in inches.

utator and Brushes. — The diameter of the com-
he diameter of the armature. The peripheral speed
er minute and should not exceed 4000 unless a special
number of segments should be such that the average
than 15.

$$\text{bar} = \frac{(\text{Rated voltage}) \times (\text{Poles})}{\text{Number of segments}}.$$

uction the pitch of segments should not be less than
about 30 mils is occupied by insulation.

shes. — The width of the brushes is limited by the
ments which it is permissible to cover and the width
mber of segments covered is limited by the reactance
. In general, the width of the brushes is from 2 to
ts. The area of the brush surface is such as to allow
r square inch of brush contact surface at full load.
equally over a number of studs equal to one-half the
ultiple-wound armature and may be all on one stud
a series-wound armature.

ommutator. — The total length of brushes per stud
ommutator is

$$\frac{(\text{Total surface of positive brushes})}{(\text{dth of brushes}) \times (\text{No. of studs})}.$$

mutator is greater than this by about 0.5 inch to
n brushes and at the ends. It is also customary to
e end of the commutator for insulation to prevent
general have a gross superficial area of from 0.67 to
of total current.

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Resistance of Brushes and Brush Contact is a variabl
Some designers allow 2 volts total drop in positive and negative br
all conditions of load.

Another method is to use the values for the resistance per square i
brush and brush contact as given in the accompanying table.

Kind of brush	Resistance of each brush, ohm			
	20 amp. per sq. in.	40 amp. per sq. in.	60 amp. per sq. in.	80 amp. per sq. in.
Hard	0.051	0.03	0.023	0.018
Medium	0.037	0.021	0.015	0.012
Soft	0.024	0.014	0.011	0.009

Friction of Brushes on Commutator. — The value of this

$$\text{Friction in watts} = \frac{(\text{No. of brushes}) \times (\text{Pressure per brush}) \times}{45}$$

where

V_c = peripheral speed of commutator, feet per minute.
k = coefficient of friction = 0.2 to 0.3.

The usual value of pressure on the brushes is from 1.5 to 2 pound
inch of contact surface.

Rise in Temperature of Commutator is

$$T = t \times \frac{(\text{Brush } I^2R) + (\text{Brush friction})}{\text{Surface of commutator}}$$

where t has the value indicated in the accompanying table; t is t
ture rise in °C. for a total commutator loss of 1 watt per sq. in.

Peripheral speed of commutator, ft. per min.	Value of t.
2000	15
3000	12
4000	10

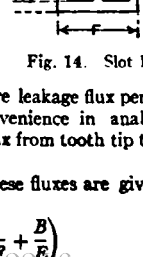


Fig. 14. Slot Diagram

16. Reactance Voltage. — The armature leakage flux per amper
may be resolved into three parts for convenience in analysis.
fluxes are: P_s flux inside the slot itself, P_t flux from tooth tip to tooth
flux about the end connections.

Referring to the dimensions in Fig. 14 these fluxes are given by
sions:

$$P_s = 3.2\, l \left(\frac{A}{3F} + \frac{B}{E} \right)$$

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$$P_t = 2.35\, l \log_{10}\left(\frac{\pi m}{2q}\right)$$

$$P_c = 1.17\, l_c \left(\log_{10}\frac{2\,l_c}{U_c}\right),$$

e length of iron core,
lar distance between pole tips,
of slot opening at face,
of end connection at one end,
ter of one coil of end connections,
inches.

n series between adjacent commutator segments,
per coil in a multiple winding,
mes turns per coil in a series winding,
sh thickness)
gment pitch),
a full pitch winding and approaches unity as the pitch
eases,

$l\,(2P_s + 2P_t + P_c)10^{-8}$ henries.

tion,

$$f_c = \frac{12\,V_c}{120\ (\text{brush thickness})}.$$

ipheral speed of commutator, feet per minute

peres per circuit in armature $= \dfrac{(I \text{ line})}{\text{no. of mult. cir.}}$.

tbe current in the short-circuited coil varies according
tive, or r.m.s., value of the reactance voltage is

$$e_x = 2\pi f_c L I_c \text{ volts.}$$

Flux Leakage Coefficient (*v*). — The exact number
d under *Form of Armature*
ove. The useful flux in the

$$\frac{R_a I) \times 10^8}{4fS}.$$

or magnet core and the field
his, due to the leakage be-
io of the flux in the field to
is known as the leakage co-
easily determined for each
y the method given in the
Alternating-Current; or if
strength of field is always
med without great error.

Rating in kw.	Leakage coefficient
2.5	1.2 –1.5
5	1.18–1.4
10	1.16–1.35
25	1.15–1.30
50	1.14–1.28
100	1.12–1.20
500	1.08–1.15

of Magnetic Path. — Usual Flux Densities. —
ies for determining the proportions of the magnetic circuit
panying table.

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Part	Material	Lines per sq. in.
Field yoke	Steel	70,000–100,000
Field yoke	Cast iron	35,000– 70,000
Pole core	Steel	70,000–100,000
Air gap	Air	40,000– 70,000
Armature teeth	Steel laminations	90,000–125,000
Armature core	Steel laminations	60,000– 90,000

The proper cross-section of each part is found by dividing the flux in by an assumed density. (*See also following paragraph.*) In most dimension, as the length along the shaft, is known and the other is th

19. Excitation. — Calculation of Magnetic Circuit. — It is ac calculate the densities and excitation for a value of flux corresponding t at the speed at full load, as this is the most important condition. It practice to assume a loss of voltage of 5 per cent at full load instead of predetermining the value.

Values of Flux in Different Parts of Magnetic Circuit. — mature teeth and air gap the total flux is equal to the calculated value ful flux. In the armature core the flux divides and we have one-half flux in each branch. The field flux or flux in pole cores is greater useful flux and is equal to the useful flux multiplied by the leakage (ν). (*See section 17.*) In the yoke the flux divides and each branc one-half as much as the pole core.

Ampere-Turns. — The number of ampere-turns required for is best calculated by the assistance of a tabulation like the following the symbols refer to the dimensions shown in Fig. 15.

1	2	3	4	5	6
Part	**Flux**	**Cross-Section**	**Flux density**	**Amp.-turns per in.**	**Length of path**
Field yoke....	$\frac{\nu\phi}{2}$	de	.....	.....	i
Pole core.....	$\nu\phi$	0.785 f^2 or fb	.....	.....	c
Air gap.....	ϕ	aL_p	.....	0.313 B	g
Arm. teeth....	ϕ	$Tl_t\, l_i$	.....	.....	s
Arm. core.....	$\frac{\phi}{2}$	hl_i	.....	.....	k

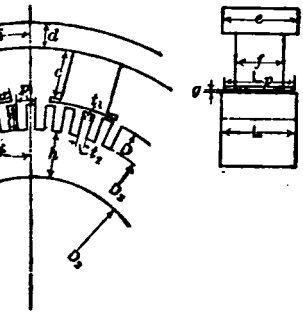
Net ampere-turns for flux: .....

The dimensions in column 3 can be taken directly from a sketch Fig. 15. If the pole is circular its area is 0.785 f^2 and if it is square

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of pole shoe L_p is usually about 0.5 inch less than core.

n of the armature teeth is found as follows: At any of the teeth are carrying flux. These are known as



5. Dimensions of Magnetic Circuit

T, and are slightly greater than those actually under e tendency of the flux to spread,

$$T = \frac{a + 2g}{p_1},$$

face.

ent cross-section of the teeth is not that which gives at which gives the mean excitation required and is

$$\frac{(t_1 + 2t_2)}{3} l_t = t_0 l_t.$$

l to give the effective length of iron, excluding that lation between laminations.

$0.9 \times (L -$ space of air ducts).

ection of armature teeth $= T t_0 l_t$.

umn 2) divided by the cross-section (column 3).

ampere-turns per inch which are to be taken from espective materials as given in the article on *Magnetic* magnetizing force for a one-inch gap is always

ths of the respective paths as shown on Fig. 15.

ampere-turns required for each part of the path and the values in column 5 by the respective lengths in values in column 7 is the excitation in ampere-turns e field to establish the necessary flux in the machine. n the armature this would give a voltage about 5 per d voltage of the machine. See section 21 below for e reaction.

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20. Stability Factor. — It is necessary at this point in the design the relations to see if the machine is liable to be unstable or require an shift of the brushes. If interpoles are to be used this is not importa interpoles are not to be used certain conditions must be fulfilled. The of these conditions is the "stability factor" which is the quotient of ampere-turns required for gap and teeth divided by the armature turns beneath the pole.

The ampere-turns beneath the pole are equal to

$$\frac{\text{(Armature reaction ampere-turns)} \times \text{(Pole arc)}}{\text{Pole pitch}}.$$

The conditions to be filled are that at maximum current in the arm armature ampere-turns beneath the pole shall not exceed the field amp required for gap and teeth. This is covered by the custom of making th factor at full load have a value of from 1.3 to 1.5 in generators and 1 motors.

21. Armature Reaction or Interference. — The current in the conductors sets up a magnetomotive force which reacts on the magne force of the field coils and prevents them from setting up as much flux there is no current in the armature. It is, therefore, necessary to have strength at any load greater than at no load by an amount sufficient come or neutralize the armature reaction, or to provide special auxili for the purpose. There are four methods of estimating the effect of interference and overcoming it.

(*a*) It is common practice in the manufacture of d-c. machines to field coil of such ample capacity that it is sure to be more than suf overcome armature interference and set up the flux desired. This fie adjusted in practice by putting an adjustable resistance in series with field and a suitable resistance in multiple with the series field. For thi It is usual to provide a total number of field ampere-turns per pole (F) the net ampere-turns per pole at full load required for flux, as calculat item No. 19, plus a number of field ampere-turns equal to 40 per ce armature reaction ampere-turns as calculated under item No. 9.

(*b*) The effect of armature reaction is divided into back ampere-t cross ampere-turns. The excitation ampere-turns per pole to over back ampere-turns (caused by shifting the brushes) is

$$A' = \frac{\text{(Armature reaction)} \times \text{(Brush shift in segments)} \times 2p}{\text{Total commutator segments}}$$

The excitation to overcome the effect of the cross ampere-turns upon many variables but in machines designed in accordance with practice it bears a fairly uniform relation to the cross ampere-t pending upon the value of the ampere-turns in gap and teeth, as foll

Cross ampere-turns = (armature reaction ampere-turns) − back turns).

Field ampere-turns to compensate for cross ampere-turns is then (cross ampere-turns).

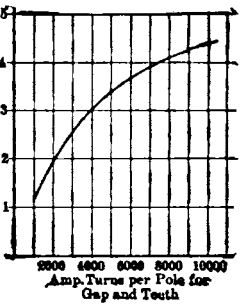
Where K has values as shown in Fig. 16 (*given by Cramp, see Bibli*

Thus the total field ampere-turns at full load is then equal to

$$F = \text{(Net ampere-turns for flux, section 19)} + A' + B'.$$

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orking with the saturation curve of the machine to ect of the cross ampere-turns on the saturation in



Constant for Cross Ampere-turns

This method is too elaborate and complicated to be more value for educational than for practical pur- ery fully in the books by S. P. Thompson and E. *below*).

used as described in section 23.

arious Loads. — At no load the excitation required essary to produce a flux corresponding to the rated y load corresponding to a current I the excitation in al to the sum of: (1) that required to produce a flux where R is the total resistance of the armature between ance and the resistance of the series field; (2) that back ampere-turns caused by I, and (3) that required mpere-turns due to I. The process of calculation 0 and 21 for full-load conditions is, therefore, repeated

If the machine has a series field this should be laid ld coils are sometimes placed outside of, and concentric

For a compound-wound machine the ampere-turns d are equal to the difference between the full-load -load ampere-turns. As it is usual to shunt about through a shunt resistance the number of series turns

$$t_1 = \frac{\text{Ampere-turns required}}{0.75 \times \text{Load current}}.$$

h turn in square inches is taken equal to the full-load

wound in copper strap like a ribbon, the width being of field spool if it is wound under the shunt winding, the two coils are placed side by side. The thickness nt of the cross-section divided by the width.

with an extra odd half turn to facilitate connection, g is

ness + 0.016 for insulation) $(t_1 + 1)$.

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Allowance for a layer of insulation inside and outside adds about o. to the depth of winding.

The mean length of turn l_f' is (see Fig. 15):

For square pole $l_f' =$ (periphery of pole) + 4 (depth of winding).

For round pole $l_f' = \pi\,(f +$ depth of winding).

The resistance per spool is

$$r_1 = \frac{0.0093\, l_f' f'}{12{,}000\, q_1},$$

where q_1 is the cross-section of a turn.

The total drop in voltage in the series field is $0.75\, r_1 I$ which should be 0.5 per cent and 1 per cent of the rated voltage.

Shunt Field. — The shunt field is required to give a certain nu ampere-turns, usually equal to the no-load ampere-turns. Let this nu ampere-turns per pole be F. At 1000 amperes per square inch the cros of copper in a coil would be $F/1000$. The total cross-section of the coil, i insulation, is determined by means of the space factor f'. Then the cros

of the coil $= \frac{F}{1000 f'}$, where f' has a value of 0.5 if No. 18 B. & S. wire 0.55 for No. 12, 0.60 for No. 6, and from 0.6 to 0.8 where copper r used. Where very small wires are used f' becomes as small as 0.25 (*cle on Electromagnet Windings*).

The depth of winding will be

$$b_2 = \frac{F}{1000 f' c_2},$$

where c_2 = length of coil (*see Fig. 17*).

The superficial area will be (see Fig. 17) $A_2 = 2\,(f + b + 4\, b_2) c_2$.

The rise in temperature in ° C. of the coil will be from 60° to 80° per square inch of A_2; thus for 40° rise on the spool the watts (w_2) per spoo be from $0.5\, A_2$ to $0.6\, A_2$ depending upon the ventilating effect of the armature.

Voltage per spool under normal conditions, allowing 25 per cent to spare for rheostat, will be

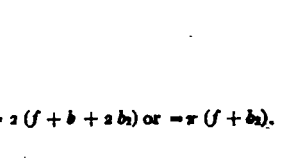


Fig. 17. Dimensions of Field C

$$e_2 = \frac{0.75\, E}{p}.$$

Current in shunt field $= i = \frac{w_2}{e_2}$.

Turns per spool $= t_2 = \frac{F}{i}$.

Mean length of turn, in in. $= l_f = 2\,(f + b + 2\, b_2)$ or $= \pi\,(f + b_2)$.

Resistance per spool $= r_2 = \frac{e_2}{i}$.

Cross-section of conductor in sq. in. $=$

$$q_2 = \frac{0.0093\, l_f t_2}{12{,}000\, r_2}.$$

The size of wire having a cross-section as nearly equal to q_2 as po chosen and arranged in layers. Single cotton-covered wire is used. The

by dividing c_1 by the outside diameter of the single

be made for the thickness of the spool and of the

rangement are settled it is advisable to recalculate
he resistance, and the heating to be sure that the
nterfered with the preliminary assumptions of watts

nutating Poles are used where either the armature
voltage is very great. If the armature reaction at
per cent of the field ampere-turns at no load, then
ered. If the reactance voltage is greater than 2.5
onsidered.
oles may be roughly made in accordance with the
e companies by making its width equal to the width
and proportioning the winding to have 1.4 times as
armature reaction ampere-turns (AR). The axial
ntly less than that of the armature, the gap density
tbe iron or steel of the pole should not be saturated
current is flowing through its windings.
ng inductance is connected across the terminals of
adjusted for sparkless commutation. When the
mpound-wound generator it is possible to decrease
ls to such a value as will produce the proper flux for
the interpoles take care of the armature reaction.
ent as many ampere-turns as the armature will b

nterpoles. — A more exact method starts with the
age, e, and an assumed density in the air gap of
gth of the interpole is then

$$L_1 = \frac{10^8 \times e}{kB_1 v_a},$$

city of armature in inches per second,
ors in series in short-circuited coil = 2 t (*see formula*
ltage, section 16).

face is made equal to or a little greater than twice
The flux per pole in gap is $\phi_1 = B_1 L_1 a_1$.
higher for interpoles than for the main poles and is
o 1.8.
ept low in the pole core so that there will be margin

mpere-turns to force this flux through the gap and
nd increased densities in the field and armature core
lue be A''.
ampere-turns per pole be B''.
ns on the interpoles should be $A'' + B''$.
pole is $(A'' + B'')$ divided by the full-load current
nding itself is laid out in the manner employed in

N OF PERFORMANCE FROM DESIGN. —
etermining what will be the performance of a given

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24. Core-loss. — The core-loss consists of hysteresis and eddy cu in the armature teeth and core. It is best calculated by taking from in the article on *Magnetic Properties of Iron* the hysteresis loss per at one cycle per second for the proper density and the eddy loss per at one cycle per second for the proper density and thickness of sh values are substituted in the following formulæ.

Total loss in core $= V_c C_h f + V_c C_e f^2$,
Total loss in teeth $= V_t C_h f + V_t C_e f^2$,

where

V_c and V_t = volume in cubic inches of core and teeth respectively,
C_h = constant from hysteresis loss curve for proper density,
C_e = constant from eddy loss curve for proper density, and thickn
f = frequency.

A rough value for V_c and V_t can be conveniently obtained from in the table for the calculation of the excitation, section 19. Then

$V_t = p \times$ (area path) $\times$ (length of path),
$V_c = 2p \times$ (area path) $\times$ (length of path).

The calculation of the core-loss is one of the most unreliable and uns steps in the design, as the value calculated by theoretical principle multiplied by a factor having a value between 1.5 and 3 to obtain t the core-loss that will be found in the finished machine, on account o tions of flux caused by the teeth. This factor is obtained in commerc from tests on machines similar to the one being designed.

25. Friction and Windage can be calculated by formula for any line of similar machines but no method applicable in general can Machines are designed so that the value of the friction loss very close mates those given in the table in section 28. The true friction vari as the speed, and the windage as the square of the speed. In shunt the speed does not change much with the load so this loss may be ass stant in this class of machines (*see Motors, Direct-current*).

Stray Power Loss. — This term is sometimes used to includ core-loss and friction and windage.

26. Excitation Loss or RI^2 in Shunt Field. — Since in a s machine the loss in the field rheostat is charged against the machin loss is equal to the terminal voltage multiplied by the current in the s The loss is usually constant and only subject to the arbitrary variati hand regulation.

27. RI^2 Loss in Armature Circuit, including the brushes, series connections, varies as the square of the armature current, and, therefor mately as the square of the load, and also irregularly to a small ext the variation of brush contact resistance with the value of the curr temperature of the copper must also be considered. (*See Resis Conductance.*)

28. Efficiency. — The efficiency is the ratio of the output to the output and all losses. It is predetermined by estimating the value o for the particular condition of load under consideration, as descril preceding paragraphs.

If P = the output in watts and the symbols A, B, C and D re spectively the values in *watts* of the various losses described in s 25, 26 and 27 for the load P, then

$$\text{Per cent efficiency} = \frac{100 \times P}{P + A + B + C + D}.$$

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num for that load at which the variable loss D is equal losses $A + B + C$. Hence the desirability of making n a machine which is to be operated most of the time

s and Losses. — An idea of a reasonable value for the s of various sizes and the distribution of the losses is ble. It must be remembered that the efficiency of a e may vary throughout a wide range depending upon

Friction (total), per cent	Excitation, per cent	Core-loss, per cent	Arm. RI^2, per cent
6	6	4	4
5	4.2	3.2	3.6
4	3.6	3.0	3.4
3	3.0	2.8	3.2
2.6	2.2	2.2	3.0
2.3	2.0	1.7	2.6
2.2	1.8	1.6	2.4
2	1.6	1.4	2.0

very important in a d-c. generator as compounding ing any desired voltage at full load. Most generators field which will give 15 per cent overcompounding at nding effect is desired a certain portion of the load eries field, which adjustment is made by trial.

of a shunt generator may be predetermined as follows: e the total excitation in ampere-turns per pole to erminals at full load. C is made up of the m.m.f. to nd the m.m.f. to overcome armature reaction. Let ld for an excitation C as shown by the no-load satura-

$$\text{cent regulation} = 100\,\frac{E_0 - E}{E}.$$

se in temperature of the field coils was found in section ure of the armature conductors was roughly checked essary to determine more accurately the probable rise mature conductors as the heat due to the core-loss ture of the armature windings. The following method account all the variables in this complex problem and onstants gives very reliable results.

icated in Fig. 18.

ature core itself is taken as the sum rface, the two annular surfaces at he annular surfaces in the air ducts. n the ducts is used since this surface external surfaces. It is assumed by this surface consists of the core- he armature $R_a I^2$ which occurs in tors embedded in the slots.

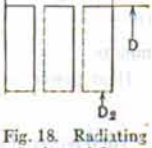


Fig. 18. Radiating Surface of Core

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A part of the heat due to $R_a I^2$ in the conductors flows from the copp the slot insulation to the iron, if the temperature of the copper is h that of the iron. Sometimes, however, at light loads for instance, th ture of the iron is greater than that of the copper and the flow of heat This condition is taken care of in the following method.

The remainder of the heat due to $R_a I^2$ is dissipated through the in the end connections to the surrounding air which is in motion due t pheral speed of the armature.

Power in watts dissipated by surface of armature core is

$$P_1 = \text{core-loss} + R_a I^2 \left(\frac{2L}{l}\right),$$

I = full-load current; R_a = resistance of armature winding; L = t of core; l = mean length of armature turns.

Effective radiating surface of armature core in square inches is

$$A_i = \pi DL + \frac{\pi}{4}(D^2 - D_2^2)(2 + d).$$

D = outside diameter of armature (Fig. 15); D_2 = inside diameter of d = number of air ducts.

Rise in temperature in ° C. of armature core above air is

$$T_i = \frac{P_1}{A_i} t.$$

t = 30 for narrow, or high-speed armature; = 40 for long or armature.

Permeance of heat path from copper to iron through slot is

$$M = \frac{U_s L s}{k_1 d_1},$$

where

U_s = perimeter of slot insulation; s = total number of slots; k_1 = d_1 = thickness of insulation in slot; L = length of core.

Heat power in watts transferred from copper to iron or vice versa is

$$Q_1 = M(T_c - T_i),$$

where

T_c = rise in temperature of copper above air

Permeance of heat path from copper to air at end connections is

$$N = \frac{U_c l_c Z}{k_2 d_2 + k_3},$$

where

U_c = perimeter of end connection; l_c = length of end connection; number of bars or coil sides; k_2 = 400 to 500; d_2 = thickness of insulati connection; $k_3 = \frac{170}{1 + 0.00025\,V}$; V = periphery speed of armature minute.

Heat power in watts transferred from copper to air by end connecti

$$Q_2 = NT_c.$$

Total power of $R_a I^2$ in armature winding is

$$P_2 = Q_1 + Q_2 = M(T_c - T_i) + NT_c.$$

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the temperature rise, in °C., of copper of con- air is

$$T_c = \frac{P_2 + MT_i}{M + N}.$$

stants and Choice of Values:

ire per watt per square inch at the surface of the op in thermal potential from iron to air. It is af- ed and by the length of the armature.

potential per watt per square inch for slot insulation ch. For any other thickness d_1, the drop is $k_1 d_1$.

potential per watt per square inch for insulation on ickness is one inch, $k_2 d_2$ for any thickness d_2.

potential per watt per square inch between the sur- the surrounding air. For stationary conditions velocity increases k_3 decreases.

bound together in the slot but separate on leaving for using s and Z in the different equations.

CT-CURRENT MACHINES. — Direct-current ur characteristics: efficiency, regulation, commu- necessary to subject a machine to actual full-load heating and commutation and it is desirable to do so but the efficiency is determined more accurately by which does not involve loading the machine.

c. machines are: (*see also Standardization Rules.*) ents, cold and hot. (2). Saturation curve. (3). (4.) Load run for commutation and regulation. ounding test. (7). Insulation test.

ments — The first measurements are made when temperature as the room, that is, after it has been epending upon its size. This is in order that the nce and temperature may be accurately known. -field, series-field and armature winding proper are

Winding. — In measuring the resistance of the able to measure between two diametrically opposite of a multiple-wound armature. The effective re- lculated from this by the formula

$$R_a = \frac{4R'}{p^2},$$

ured as above, and p = number of poles.

Winding. — In measuring two-circuit series-drum easure between two commutator segments separated eriphery of the commutator divided by the number effective resistance of the armature.

stance. — The resistance of the brushes and brush ita such as given in section 15 in the above section ade with the actual circuit is not very satisfactory. he practice to measure the resistance of the entire o brush by the drop in potential method for several ure being at rest. This is not accurate, however, ntacts depends upon the speed.

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2. **Saturation Curve.** — The saturation curve is not of immedia in determining the quality of a machine but is more particularly of the designing engineer. It is made by driving the armature at speed and supplying current to the shunt fields from a separate sourc tial. As the current in the shunt field increases the potential generated by the armature varies and this is measured by a voltmeter.

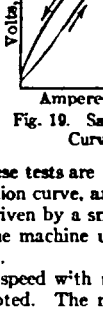


Fig. 19. Sa Curv

On account of the existence of the hysteresis loop (*see Magnetic Properties of Iron*) it is necessary to increase the field current gradually and never to reduce the value at any step until the maximum value has been reached. The curve is plotted with volts as ordinates, and field current or ampere turns as abscissæ and shows the typical knee curve of all saturation curves. Different curves are obtained with increasing and decreasing excitation as shown in Fig. 19.

3. **Core-Loss and Friction, or Stray Power.** — These tests are the same arrangement as used in determining the saturation curve, a made at the same time. The machine to be tested is driven by a sm having a capacity about 10 per cent of the rating of the machine u All the losses and constants of this motor must be known.

First the machine under test is driven at the desired speed with in the fields and the power taken by the driving motor noted. The output of the driving motor is calculated and this gives the friction large machine.

Then the large machine is excited and the power to drive it is de This power represents the core-loss plus the friction loss. Dedu friction loss already determined, the values of the core-loss for vari of excitation are found. See also *Magnetic Properties of Iron*.

The combined core-loss and friction loss constitute the stray powe

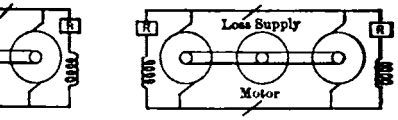
4. **Load Runs.** — The machine is run and the excitation adjust the proper voltage at no load. The load is then added and the termin noted. If E_0 = voltage at no load and E = voltage at full load, the is $\frac{E_0 - E}{E}$.

If the machine has not commutating poles it is necessary to ma liminary test in order to set the brushes at that position which give compromise in sparking at no load and full load. Commutation is observing the action of the brushes at full load and 150 per cent l conclusions are a matter of judgment and experience, although sparking have been arbitrarily agreed upon and are represented in series of pictures.

5. **Heat Runs** are made by operating the machine at full load fo of time until the temperatures of the various parts that can be not operation have become constant. The greater the capacity of the m longer will be the time necessary.

Dead-load and Pumping-back Methods. — Heat runs may either by the "Dead Load" method in which a resistance load, such a rheostat, is connected to the terminals and full rated load power is r drive the machine; or by the Hopkinson or "Pumping-back" method two machines having similar characteristics are run together, one a generator to supply electrical power to the motor which in turn drive by means of a belt or similar mechanical connection. For this tes supply" is required which may consist of a source of either electrical

ount of power required is from 10 to 20 per cent nachines. The connections are shown in Fig. 20, Fig. 21 for mechanical loss supply.



st, Electrical Fig. 21. Hopkinson Load Test, Mechanical Supply of Losses

ings. — During the heat run there are taken at hermometers which show the temperature of the nd surrounding air. After the heat run the thermus parts of the machine, the bulbs being protected ls of cotton, and the following temperatures are

	Field coils;
g ducts;	Bearings;
winding;	Frame;
	Room.

ical circuits should be measured and the average culated from the formula,

$$= \frac{R_1}{R_0}(239 + t_0) - 239,$$

t and cold resistances respectively, and t_1 and t_0 res respectively, 98 per cent conductivity copper n *Copper*.

– In order to adjust the current in the series field enerator will give specified voltages at no load and operated at no load and the current in the shunt lesired no-load voltage. The load is then put on hat at full load the terminal voltage is too great. ther resistance metal are then connected in multiple shunting current from the series field the voltage s desired. This shunt resistance is then made up cted in circuit. Before making the no-load adjustcite the shunt field for a moment in order to over o section on *Parallel Operation* below.

fter the heat runs it is customary to apply a highon of the machine. This consists of applying an each electrical circuit and the frame of the machine of the potential depends upon the capacity and under test and is definitely specified in the Stand-. E. (*q. v.*).

N AND PERFORMANCE. — In the tables on the essential data including mechanical, electrical of four examples of direct-current machines In

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these data are included all the factors necessary to determine the eff
lation, commutation and heating of the machines. Dimensions a
and weights in pounds. Performance data are deduced from tests.

SERIES ARC-LIGHT GENERATORS. — These machines
to give a constant value of current in the external circuit irrespe
resistance or counter e.m.f. in that circuit. This is accomplished
the voltage impressed on the external circuit to decrease whenev
tendency of the current to increase. The load usually consists
(20 to 50) of arc lamps connected in series, each taking about 40
lamp requires the same value of current and the total voltage is pr
the number of lamps in use. If a lamp is no longer needed it is sh
by a switch and the current in the remainder of the lamps remai
because the generator automatically reduces the voltage supplied.
lation of the current is obtained by two or more of the following m
high armature reaction which tends to weaken the field whenever
increases; (2) movable brushes to vary the number of turns in se
brushes; (3) a series field arranged so that turns may be shunted, sh
or cut out; and (4) a high degree of saturation in the magnetic circui
so that the flux changes very slightly for considerable change of m.

The pole face density is usually quite high and the path of the flu
is of high reluctance, whereas the path of the armature flux is of low
thus there is much field distortion. The machines are usually wou
to 4000 volts. The distorting effect of armature reaction is usually
to take care of sudden and small variations of the load, and large
variations of the load are taken care of either by moving the brushe
position giving either a lower or higher voltage, or by commutating
some of the turns of the series field.

Brush Arc Machine. — This was the first arc-light machine to
out. It consists of a ring armature having a winding of the open-
There are a number of spool-wound coils on the armature, diametric
coils being connected in series to an independent pair of commutat
The brushes make a series connection of the various groups of co
of highest e.m.f. being connected in series, those of medium e.m.f.
and those of low e.m.f. being left out of circuit. The numerous fi
on both sides of the ring armature. The two poles facing each oth
same polarity so that the flux flows along the ring of the armatu
pole to the next pole on the same side of the ring. Regulation is
shunting field turns and shifting the brushes for good commutation
oil pump is used as a regulator to move the handle of the field regu
move the brushes.

Thomson-Houston Arc Dynamo. — This machine contains
shaped armature with a three-part open-circuit winding. The th
being spaced at 120° on a ring armature and connected in "Y," t
going to the segments of a three-part commutator. The commut
spaces between segments and a jet of air to blow out any arcs betw
and segments. There are four brushes on the commutator, connec
At some part of each revolution two coils are in multiple, at other p
one. A relay moves the brushes so that as the load increases the
negative brushes move farther apart thus giving more voltage. A
of a pair moves forward the other moves backward thus keeping the
cal with respect to the neutral axis. The field structure is of a holl
construction.

Wood Arc-light Machine. — This generator has a closed-circ
ring armature with a commutator having a large number of segme

CAL DATA ON D-C. MACHINES

ons in Inches, Weights in Pounds

	1 Motor	2 Generator	3 Generator	4 Generator
....	2	6	6	8
....	2.25	35	500	250
....	1200	1050	900	150
....	115	125	275	250
....	23.4	280	1830	1000
....	7.13	20.25	31.5	45
....	1.63	13.5	19.5	32
....	4.69	3.38	14.	21.5
....	....	1×0.38	5–0.375	7×0.5
....	34	109	108	128
....	0.95×0.22	1×0.28	1.12×0.36	1.32×0.52
....	28	2	2	6
....	d=0.054	0.16×0.32	0.26×0.4	0.5×0.125
....	4	2	6	8
....	Drum	S.D.	M. D.	M.D.
....	1	1	100%	1
....	0.06	0.156	0.188	0.312
....	6.83	7.38	11.5	13.25
....	4.25	3.13	13.5	21
....	4.25	3.13	13.5	21
....	3.94	4.83	8.5	8.13
....	3.44	5.25	10	10
....	6	8	15	21
....	2.75	2.5	8	5
....	2210	481	900	372
s...	d=0.018	d=0.083	B.&S.No.10	0.144×0.156
....	28	9.5	1.5	4.5
s...	0.14×0.13	5.06×0.05	2.5×0.75	9.25×0.075
....	5	13.5	20.75	30
....	3.13	6.25	13.5	14.5
ents	34	109	108	384
....	2×2	6×3	6×10	8×8
....	0.75×1	0.75×1.38	1.25×1.25	0.75×1.25
....	0.87	.....	2	.....
....	0.87×3	.....	2×13	.....
....	0.09×0.09	.....	2.5×0.75	.....

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ELECTRICAL AND MAGNETIC DATA ON TYPICAL D-C. M

Percentages are all in Terms of Rated or Full-load Values

Type		1 Motor	2 Generator	3 Generator
Rating	kw.	2.25	35	500
Rated voltage	volts	115	125	275
Rated current	amperes	23.4	280	1830
Flux per pole	maxwells	1.12×10^6	1.19×10^6	8.8
Leakage coefficient	.....	1.2	1.13	1.18
Excitation amp. turns, no load	amp. turns	1040	3470	7300
Excitation amp. turns, full load	amp. turns	.....	5270	.....
Armature reaction	amp. turns	1390	2540	5500
Stability factor	.....	0.9	1.55	.....
Excitation to balance arm. reaction	amp. turns	.....	1090	.....
Excitation at 110% volts	amp. turns	1115	4200	.....
Volts per bar	volts	6.8	6.8	15.2
Reactance volts	volts	5.7	1.6	7
Friction loss, brush	watts	60	460	3800
Friction loss, other	watts	100	600	7000
Core-loss	watts	60	1680	8300
Armature res. at 25° C.	ohms	0.27	0.013	0.0016
Brush res. at full load, 25° C.	ohms	0.044	0.0072	0.00104
Series-field res. at 25° C.	ohms	0.05	0.0033	0.00018
Interpole res. at 25° C.	ohms	0.123	.....	0.00034
Shunt-field res. at 25° C.	ohms	150	9	25.2
Friction loss	per cent	6	2.6	2.
Core-loss	per cent	2	4.1	1.56
Shunt-field loss	per cent	3	2.2	0.42
Arm. copper loss	per cent	6.5	4.9	2.20
Efficiency at full load	per cent	82.5	86.2	93.8
Rise in temp. by thermometer:				
Armature	° C.	.....	.....	44
Field	° C.	.....	.....	24
Rise in temp. by resistance:				
Armature	° C.	.....	.....	44
Field	° C.	.....	.....	33

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ing the brushes so as to vary the voltage available and ture reaction balancing the field m.m.f.

NERATORS. — This type of machine is also some- was formerly incorrectly called uni-polar. Its method ne principle of the Faraday disk, which consisted of a t an axis and projecting between the poles of a magnet. netic field an e.m.f. is set up between the axis and the if brushes bearing on these two parts are connected rrent will flow. The peculiar characteristic of a homo conductor always cuts the flux in the same direction, duced in it is always in the same direction and is not al direct-current machine. Thus no commutator is

mutator is the feature which makes the homo-polar ne commutator presents many difficulties in high- en by steam turbines. It is for this application that a successful homo-polar machine have been directed. collector rings with brushes are used to collect the conductors. These collector rings, however, present and operation on account of the high peripheral speed The rings are subject to a considerable centrifugal ncy of the current to arc between the brush and the e high rubbing speed.

e of such a machine is not only unidirectional as in all ut is really constant. But since there can be only a he voltage generated is very low. The voltage gener- s

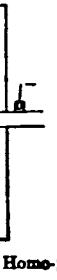
$$E = Blv\,10^{-8},$$

s per sq. cm., l = length of conductor in cm., v = n. per sec.,
expressed,

$$E = \frac{NZ\phi 10^{-8}}{60} \text{ volts},$$

r minute, Z = conductors in series, ϕ = total flux

es. — There are two types of homo-polar machines, The radial type (Fig. 22) is like the Faraday disc and



Homo-polar

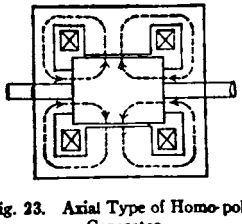


Fig. 23. Axial Type of Homo-polar Generator

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consists of a disc revolving between the two poles of a cylindrica
Brushes bear on the outer rim and the shaft to collect the current.
may be made of steel to reduce the reluctance of the magnetic pa
voltage of such a machine is limited to 10 or 15 volts, but the curre
very large. A variation of this type has two discs on the same shaf
magnetic path so arranged that the voltage of the two discs may be
series by brushes bearing on the peripheries of the two discs. The
(Fig. 23) consists of a cylindrical steel armature with copper bars in th
the whole revolving in a cylindrical field so arranged that the magnetic
outward from the armature in a radial direction at all points. The se
ductors on the armature are connected to slip-rings at both ends, and
of brushes and stationary conductors, these conductors are connected
The voltage of such a machine may be from 40 to 50 volts per conduc

Data on Large Axial Type Machine. — In the *Trans. A.I.E.*
Noeggerath describes a machine of the axial type rated at 300 kw. for
at 3000 r.p.m. The armature has 12 conductors connected in series for
The diameter of the armature is 19 inches and the length 12 inches.
pheral velocity is 15,000 ft. per min. The armature is of cast steel a
cast steel collector-rings on it. The stationary conductors conne
collector-rings together are placed in the face of the pole and thus th
may be used to balance the armature reaction.

Excitation. — The armature reaction of such machines is very hig
only a distorting effect. However, it weakens the field as the cross
tion weakens one part more than it strengthens another due to saturat
a proper arrangement of the movable connections between the coll
and stationary conductors a m.m.f. may be set up which will strengthe
and thus the machine may be compounded. These machines may
self-exciting but the resistance of the shunt fields must be very low in
the machine may pick up on starting as the resistance in the brush
high. The drop in voltage in each brush contact is about 0.8 volt a
but is higher before the current flows. It sometimes requires from
times the normal voltage of brush contact to start the current.

Losses. — Such a machine as described above has an efficiency o
mately 90 per cent at full load. The losses are made up principally
and I^2R in the brushes. The field I^2R is low as the air gap is small for
cal considerations. The armature I^2R is almost negligible due to the
The eddy losses are low if the flux density is constant in one zone a
armature but the density may vary along an element of the cylinder.
weight of the machine is about the same as for the usual d-c. machi
proportion of copper is much lower than in the usual machines.

SPECIFICATIONS FOR D-C. GENERATORS. — The
memoranda are intended to assist in writing specifications. See also
Specifications.

Principal Characteristics and Conditions of Service. — Service
it is to be used, such as railway, lighting, etc. Voltage. Rated ou
watts. Speed.

Style and Description, Details of Construction. — Type, whe
or compound wound. Whether interpole. Details of speed and
of prime mover and how generator is connected to prime mover, e.g.
belt driven by steam turbine, reciprocating engine, water wheel, wat
gas engine, oil engine, etc., with vertical or horizontal shaft. If fie
is to be supplied, its characteristics, including the effect upon the

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l of all steps: accessibility of armature. If belt driven,

by Other Contractors. — *See Generators, Alternating-*
ding.

Tests. — (*See Standardization Rules of the A.I.E.E.*).
which ratings are to be based. Details of overload
¼, ½, ¾, 1, and 1¼ loads. (Whether rheostat losses
lating efficiencies.) High potential tests of insulation.
effect of moisture upon insulation. When run at
he load may be varied from zero to a stated per cent
using more than a stated variation of voltage, the field
stant.

– In installing a d-c. machine the following precautions

es with foundations the foundation bolts must be pro-
n drawings.
ined up and well cleaned before being filled with oil.
st be properly centered so that the air gap is correct at
ges are used to measure the gap. The magnet frame
base.
ust be properly connected. Test for polarity with a
ake sure that no field coils are reversed. For a self-
is one particular connection of the field to the armature
ation.
must be smooth and polished; use sandpaper to polish
use emery cloth.
be properly and accurately spaced around the com-
be sandpapered and fitted to the curvature of the com-
on the brushes must be adjusted to the correct value
pounds per square inch of contact surface.
be thoroughly dried out by heating and the insulation

starting up a single generator it is sometimes necessary
y separately exciting the shunt fields for a moment to
m.
e to "pick up" or generate voltage by self-excitation it
or short-circuit most of the resistance of the regulating
eries with the shunt field. If the total resistance of the
eds a certain critical value the machine will not "pick
e is allowed.

— In order to operate a power station under economical
to have a number of machines whose aggregate capacity
m demand on the station. As the demand varies the
operation is adjusted so that the machines running are
their rating, and, therefore, at a good efficiency.

ors. — In order to operate shunt generators in parallel,
e bus-bars, it is only necessary to adjust them all to the
age, connect them to the bus-bars, and adjust the divi-
ening the field of the underloaded machine if the voltage
If the voltage of the bus-bars is high, weaken the field
ine.

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Compound Generators, Equalizer Connection. — In order t compound-wound machines in parallel it is necessary to provide an connection which makes a common connection on all the machines at between the armature and the series field as shown in Fig. 24.

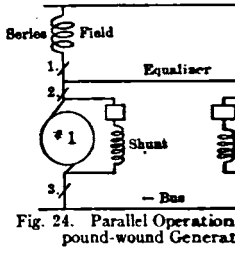


Fig. 24. Parallel Operation pound-wound Generat

The function of the equalizer is to divide the load current at all times in the proper proportion between the series fields of the different generators. This prevents the machines from acting as series generators or differential motors which would cause short-circuits.

For compound-wound machines to operate successfully in multiple all machines connected to one set of bus-bars must have the same amount of compounding as well as the same voltage at no load. Due to saturation in the circuit it is not always possible to make the compounding curve a stra i.e., the increase in voltage directly proportional to the load. It is, necessary to investigate the compounding curves of machines before operated in parallel. With unlike compounding curves one machine come overloaded while another is under-loaded, unless the field curre machine is adjusted.

In connecting a machine in parallel with those in operation it is ne see that it has the proper polarity and voltage, that the equalizer circui

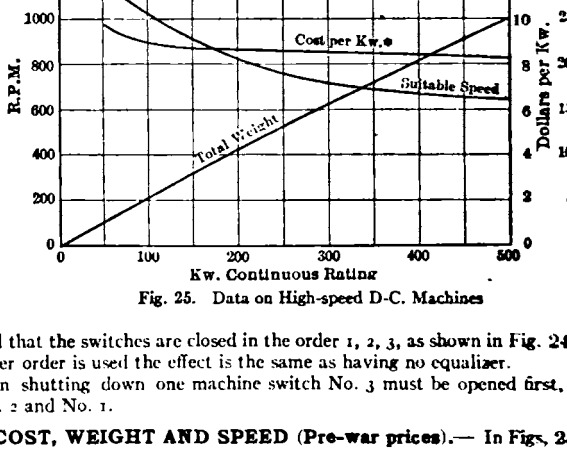


Fig. 25. Data on High-speed D-C. Machines

and that the switches are closed in the order 1, 2, 3, as shown in Fig. 24 other order is used the effect is the same as having no equalizer.

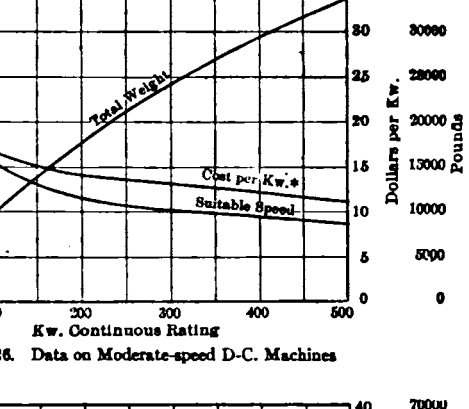
In shutting down one machine switch No. 3 must be opened first, No. 2 and No. 1.

COST, WEIGHT AND SPEED (Pre-war prices).— In Figs. 2 27 will be found the weight and cost per kilowatt of direct-current g for usual or standard speeds. Fig. 25 gives the weight and cost of high-speed machines for the suitable speeds shown by the curve. Fig the same information for a line of moderate-speed machines, gene

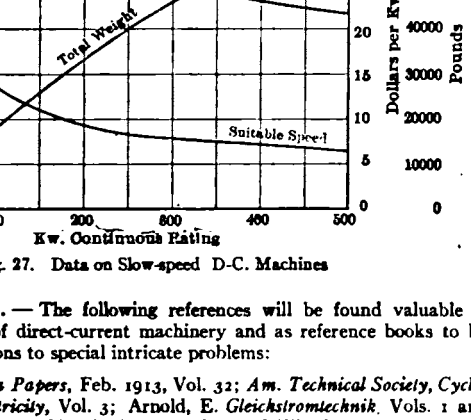
* 1922 prices about 50 per cent higher than given by this curve.

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r a line of slow-speed generators designed for direct con-
es.



6. Data on Moderate-speed D-C. Machines



. 27. Data on Slow-speed D-C. Machines

. — The following references will be found valuable in
f direct-current machinery and as reference books to be
ns to special intricate problems:

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tricity, Vol. 3; Arnold, E. *Gleichstromtechnik*. Vols. 1 and
Machine Design; Crocker and Wheeler, *Management of*
leming and Johnson, *Insulation and Design of El. Windings;*
rom Maschinen; Gray, A., *Electric Machine Design;* Haw-
Dynamo; Hobart. H. M., *Dynamo Design;* Hobart and
ruction; Hobart and Ellis, *High Speed Dynamo-Electric*
., *Dynamo Maschinenen;* Lamme, B. G., *A.I.E.E.* 1913,
; Langsdorf, A. S., *Principles of D.C. Machines;* Livings-

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... cent higher than given by this curve.

ton, R., *Mechanical Design and Construction of Generators;* Murdock, *Ventilation of Electric Machines;* Parshall and Hobart, *Electrical Design;* Smith, S. P., Design, *London Electrician,* June 1916; Smit *Choice of Brushes,* El. Journal, Vol. 13, p. 263; Still, A., *Principles of Design;* Thompson, S. P., *Dynamo-Electric Machinery,* Vol. 1; Tu Hobart, *The Insulation of Electric Machines;* Walker, M., *Specifica Design of Dynamo-El. Machinery;* Weaver, W. B., *Operation of Machines,* E Journal, Feb. 1917.

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ENERATORS, STATIC. — (*See also Generators, Alternating-current; Elyt.*) In electro-therapeutic and X-ray work a unidirectional high-frequency current is desired and is often obtained by a kind of electric generator led a static generator. There are two types of static generators available r the purpose, the frictional machine and the influence machine.

Frictional Machine. — In the frictional machine two dissimilar substances e rubbed together in some form rotating apparatus as shown in g. 1. A rotating glass plate *A* ubbed on both sides at *BB* by o pieces of leather which are ased and covered with the amal- m 1 Zn, 1 Sn, 2 Hg. The glass s electrified positively and the harge is drawn off by the metal oints *CC* which almost touch the lass. Two silk aprons *DD* cover he glass between the rubbers and he metal points, to prevent the ssage of the charge into the air. he rubbers are connected to ground remove the negative charge which cumulates upon them.

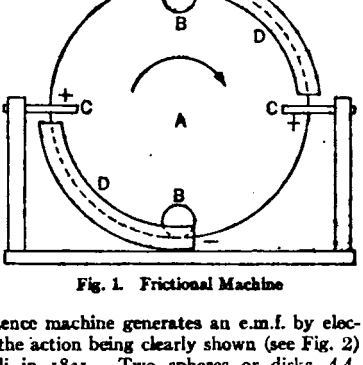


Fig. 1. Frictional Machine

Influence Machine. — The influence machine generates an e.m.f. by electrostatic induction, the principle of the action being clearly shown (see Fig. 2) in a machine invented by G. Belli in 1831. Two spheres or disks *AA*. called carriers and normally insulated from each other, are rotated about the shaft *B*. The two fixed plates *CC* are charged initially from some external source. When the carriers *AA* take the position shown in the figure, a momentary connection is made to the neutralizing wire *EE* at the spring contacts *DD*. As a result of this connection between *A* and *A*, the carriers are charged by induction, the charge on each being opposite to that of the adjacent plate. When the carriers rotate still further, the connections at *DD* are broken and the charges induced on the carriers become isolated. When the carriers are rotated through half a revolution from the position shown, they strike the prongs *FF* and add their charges to the field plates *CC*.

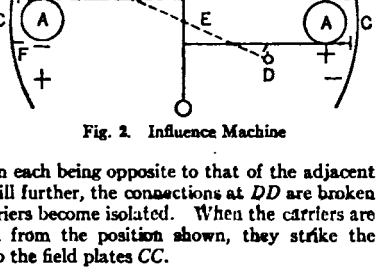


Fig. 2. Influence Machine

Wimshurst Machine. — Many forms of influence machines based upon the above principles have been devised. The most successful designs were made by Voepler, Holtz and Wimshurst. The Wimshurst machine, shown in Fig. 3, has superseded most of the other forms because of its self-exciting powers and suitability for work in all conditions of atmosphere. Two glass disks, *A* and *B*, are rotated close together and in opposite directions. A certain number of tin-foil carriers *CCC*, are mounted upon the outside surface of each plate. Neutralizing conductors *DD* for each disk are placed at right angles to each other. The collecting combs *EE* are connected to a condenser *F* and a spark gap G across which the discharge takes place. If two diametrically opposite

carriers on the back plate are charged positively and negatively re
opposite charges will be induced upon the adjacent carriers on the f
if they are connected by the neutralizing wire. The induced charges are isolated when this connection is broken and are drawn off at the collecting combs *EE*. In the Wimshurst machine induced charges in moving from the point of electrification to the collecting combs also serve to induce other charges on the back plate.

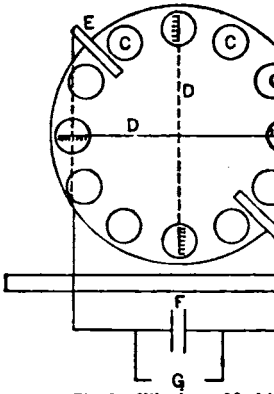


Fig. 3. Wimshurst Machi

After a few revolutions of the disks, half of the carriers on each plate are charged negatively and half positively, giving a machine of reliable service and high power. Unlike the Holtz machine the Wimshurst machine does not reverse its polarity when the distance between the terminals is made greater than the sparking distance. Large influence machines are constructed with several plates revolving in opposite directions and connected in pa whole being contained in a glass case to protect the plates from dust. plate Wimshurst machine gives a spark of eight inches and a twelve-plat will give a spark of 13⅝ inches. The plates in these machines ar mately 30 inches in diameter and the machines give 6 sparks for each of the disks.

BIBLIOGRAPHY. — Gray. J., *Electrical Influence Machines;* *Static Electricity;* Holtz, Dr. W., *The Priority of Invention of the D Influence Machine*, Elec. Tech., Zeit. 1904, Vol. 25, p.

GREEK ALPHABET.

A	α	Alpha.	N	ν	Nu.
B	β	Beta.	Ξ	ξ	Xi.
Γ	γ	Gamma.	O	ο	Omicro
Δ	δ	Delta.	Π	π	Pi.
E	ε	Epsilon.	P	ρ	Rho.
Z	ζ	Zeta.	Σ	σ	Sigma.
H	η	Eta.	T	τ	Tau.
Θ	θ	Theta.	Υ	υ	Upsilon
I	ι	Iota.	Φ	φ	Phi.
K	κ	Kappa.	X	χ	Chi.
Λ	λ	Lambda.	Ψ	ψ	Psi.
M	μ	Mu.	Ω	ω	Omega.

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OUND CONNECTIONS. — (*See also Grounding of Electric Circuits.*) ound connection is a conductor buried in the earth and connected by uctors to other conductors or apparatus which are to be maintained at h potential, irrespective of the current which may flow through it. Usually cuit is not grounded except at such points that under normal conditions peration no appreciable current flows to ground. A current may, however, stablished through a ground connection due (1) to a lightning discharge, to an accidental grounding of a live wire of a grounded circuit, and (3) a cross between the grounded circuit and a high voltage ungrounded circuit; the last instance the current through the ground connection is only the tively small charging current between the other wires of the high voltage tem and the ground (*see Capacity and Charging Current*).

SE OF GROUND CONNECTIONS. — Ground connections are used the following purposes: (1) for lightning arresters, to afford a path to ground the lightning; (2) for lightning rods on buildings, for the same purpose; steel transmission poles to give the current a short circuit to ground in se of insulator failure. Also as a lightning protection; (4) to bring the ural points of circuits to ground potential and thus reduce the potential sses of the system and minimize the danger of accident from shock; (5) to ing transformer cases, instrument cases, conduits, etc. to ground potential d thereby reduce the danger from shock; (6) to obtain an earth return for egraph circuits; (7) for wireless telegraph systems to obtain the use of the rth's electrostatic capacity.

GROUNDING TO CONDUCTORS USED FOR OTHER PURPOSES. — Where an extensive system of water pipes buried in the earth is ailable, a satisfactory ground connection can be made directly to the pipes. as pipes are not suitable for ground connections, as in case of broken joints he resulting arc might ignite the escaping gas. Steam heat pipes are ot insulated (and therefore partially electrically insulated) from the earth. here there are two ground connections, one to an electric railway track and he other to a water pipe, there is danger that railway current may thereby be troduced into the water piping system and produce electrolysis. Sheaths of ables are not good ground as the cables might be injured by the currents in heir sheaths, either from electrolysis or unforseen heating. In fact, cable heaths, like other buried conductors, have a tendency to collect stray currents from electric railways and special ground connections sometimes have to e made to permit these currents to escape without producing electrolysis. teel frames of buildings present only a limited surface to ground at the foundations and are therefore only good when the current to be discharged will be proportionally small.

Connections to Piping System. — The National Electrical Code contains he following requirements:

Size of Ground Wires. — Not to be smaller than No. 6 A.W.G. copper for ightning arresters and must be large enough to carry current caused by or following discharge of arrester (Rule 15*A*l); not to be smaller than No. 8 A.W.G. for irect-current systems and must have at least one-fifth the carrying capacity f the grounded conductor, and not to be smaller than No. 8 A.W.G. for alternating-current systems but must have at least one-fifth the carrying capacity f the wire to which it is attached, except that it need not be larger than No. 0 A.W.G. (Rule *Ak*).

Method of Making Ground Connections.—In connecting a ground wire to a piping system, the wire should be sweated into a lug attached to an approved clamp, and the clamp firmly bolted to the water pipe after all rust and scale

have been removed; or be soldered into a brass plug and the plug scre
a pipe or pipe fitting.

GROUNDING TO SPECIAL PLATES, PIPES, ETC. — When
buried conductors are not already available, direct connection to th
may be made (1) by burying a plate in the earth, (2) by burying a wir
bon in the earth, or (3) by driving a pipe vertically into the earth.
form of ground connection is now generally accepted as the best. Th
methods of direct grounding are described in detail in the section below o

Factors Affecting the Impedance of Ground Connection. The
impedance opposing the flow of current into the ground through a gro
nection depends (1) upon the extent of metal surface in contact with t
(2) the thoroughness of this contact, (3) the wetness of the earth, (4) the
between this ground connection and the ground connections (if any *)
the current leaves the earth.

The effect of the distance upon the impedance between the electro
important one, but is frequently overlooked. If the electrodes are
gether, the impedance will be low on account of the shortness of th
path. If the distance between electrodes be increased, the impedanc
increased until a certain point is reached, after which it will steadily
on account of the increase in the cross-sectional area of the earth
experiments by the Cunliffes (*Jour. I.E.E., 1909, Vol. 43, p. 449*) the
ance" (probably meaning impedance) reached a maximum when th
plates were about 25 feet apart, the decrease in "resistance" being c
den for smaller or greater distances, as shown in Fig. 1. A curve by
Creighton (*G. E. Rev., 1912, Vol. 15, p. 60*) shows the resistance betw
grounds at various distances apart, the maximum resistance being
tained at 25 feet.

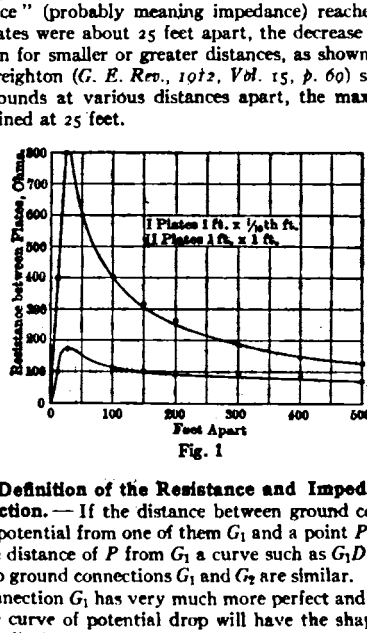


Fig. 1

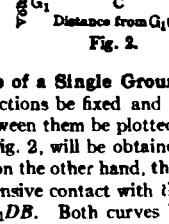


Fig. 2.

**Definition of the Resistance and Impedance of a Single Grou
nection.** — If the distance between ground connections be fixed and
of potential from one of them G_1 and a point P between them be plotte
the distance of P from G_1 a curve such as G_1DA, Fig. 2, will be obtain
two ground connections G_1 and G_2 are similar. If, on the other hand, th
connection G_1 has very much more perfect and extensive contact with t
the curve of potential drop will have the shape G_1DB. Both curves
peculiarity of being steep near the electrodes and of becoming flat betwe
indicating that the greater part of the resistance occurs near the el

* The circuit may be completed by a displacement current, through the air,
surface of the earth.

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the current is restricted to a limited area, practically no drop occurring ere the current spreads out.

The impedance of the ground connection G_1 is then defined as the ratio of the ential drop CD, to the current entering the ground at G_1, and similarly for ground connection G_2. The resistance may be approximated by measuring impedance at different frequencies, and by extrapolation, finding the impedce at zero frequency. This will be the resistance.

Resistance of Some Typical Ground Connections. — The resistance of ound connections varies so greatly with the condition and nature of the soil, at data on resistance have only local application. The following tests are sented merely to give a general idea of the results which are obtained in ctice.

Authority	Time of year	Description of soil	Type of ground connection	Dimensions	Depth	Ohms
					ft.	
Horie.....	Feb.–June	Surface loam	Plate	1 ft.×1 ft.	..	1940
	Feb.–June	Moist black loam	Plate	6 ft.×2 ft. 3 in.	6	113
	Feb.–June	River bottom	Plate	1 ft.×1 ft.	..	132
	Feb.–June	Gravelly soil	Pipe	1¼ in.	5	630
	Feb.–June	Gravelly soil	30 Pipes	1¼ in each	5	13
	Feb.–June	Swampy soil	7 Pipes	1¼ in each	5	15
Del Mar...	Summer	Rock & loam fill	Plate	15 in.×15 in.	6	155
Hayden...	Aug.–Sept.	Clay loam	Pipe	2½ in.	3¾	26.1
Hayden...	Feb.–Mch.	Clay loam	Pipe	2½ in.	3¾	120
Hayden...	June–July	Clay loam	Pipe	2½ in.	3.1	35.4
	Mch.–Apr.	Clay loam	Pipe	2½ in.	3.1	240

E. F. Creighton (*G. E. Review, 1912, Vol 15, p. 67*) says: "If an iron pipe inch in diameter is driven into normally moist earth to a depth of 6 or feet, it will usually have a resistance of about 15 ohms. Eight ohms may be sidered unusually low, while dry soils may give a resistance of 56 ohms and wards." Creighton also states that after a depth of several feet in the conting stratum has been reached, each additional foot decreases the total sistance by the factor $d/2$ where d is the depth in feet.

DESIGN OF GROUND CONNECTIONS. — It is as a rule impracticable to install a ground connection of sufficiently low conductivity to allow the assage of the maximum current it may have to carry without producing a siderable rise of voltage. The conductivity which a ground connection ould have is therefore largely a matter of experience and judgment rather an a matter of exact calculation. Cheapness and durability usually determine the material, usually iron or copper, and the thickness.

Copper Plates. — Formerly the most common form of ground connection sisted of a copper plate embedded in charcoal or coke in moist earth. The e of coke is questionable, for the reason that the sulphur in the coke is likely corrode the copper plate and thus increase its resistance. Some engineers e of the opinion that neither charcoal nor coke is of any particular use in conection with a ground plate. The corrosion of copper ground plates is greatly duced by coating with tin. As the conductance of a ground connection is

not proportional to the area of the metal plate, the use of a single la is an uneconomical method of obtaining a low resistance.

Copper Wire or Ribbon. — The wire or ribbon has the advantage resistance than a plate for the same area. The wire has the further a that no special material or connection is required. The wire may b in a straight line or coiled with turns wide apart into a plane spiral. form is sometimes made by wrapping a number of turns of wire a butt of a pole before setting it.

Pipes Driven into the Ground. — The driven pipe or rod is pro best of all forms of direct ground connections. The pipe is usually an often galvanized or sherardized, from ¾ inch to 2 inches in nominal si 6 feet or more into the moistest ground available. The diameter of a little effect upon its earth resistance; thus a pipe 2 inches in diame resistance only 6 to 12 per cent less than a pipe 1 inch in diameter Creighton, *G. E. Rev., 1912, Vol. 15, p. 14*). To facilitate driving, t sometimes provided with a pointed casting at the lower end and c upper end. The pipe has the advantage that it is cheap to install, as dug, and being driven vertically, it can tap any conducting stratum of which is practically accessible. It is highly efficient as regards cor per square foot of surface exposed to the earth, and while the resist single pipe will exceed that of a large plate, a higher and more perma ductivity can be obtained from several pipes driven at some dista and connected in multiple, than from an equal expenditure in mo single large ground plate. Ground pipes or plates in multiple shou less than 6 feet, and preferably 10 feet, apart, in order to avoid supe two zones of high current density.

If the ground available is naturally dry the conductivity may be by cupping out the soil around the pipe at the surface and adding a fe of salt and water. A neater form of earth unit is shown in Fig. 3. A of metal or earthenware of any available diameter is set around the pipe at the surface of the ground and covered by a lid. This receptacle will hold the salt. Its advantages lie in the easy construction of the connection and protection of surrounding vegetation from the saline water.

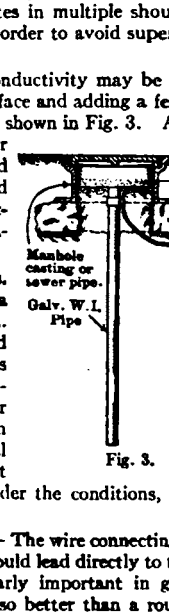


Fig. 3.

Pipe Grounds for Lightning Arresters. — The General Electric Company recommends a large number of grounds at each installation. These numerous ground connections are joined together by a copper connection. It sometimes happens that a good ground cannot be conveniently made near the arrester, or that a better one can be made at a more distant point. In this case it is recommended that the principal ground be made at the more distant point, but that a ground of some sort, the best possible under the conditions, directly underneath the arrester.

Connections to Ground Plates and Pipes. — The wire connectin paratus to be grounded to the buried conductor should lead directly to with as few bends as possible; this is particularly important in g lightning arresters, in which case a flat strip is also better than a rou All exposed joints and those buried in the ground should be made in su that they will not rust off. The buried connection from a ground pla surface should be so protected that it will not rust off or be cut off w

nections are made for other purposes. It is also necessary that the connections be protected from mechanical injury and theft, from the surface of the ground above the level at which it can be reached. To insure reliability, connections should as far as possible be made so that their continuity can be determined by inspection.

TESTS OF GROUND CONNECTIONS. — Ground connections should frequently tested to determine their continuity and occasionally to determine their impedance. Alternating current should be used, in order to avoid the effects of polarization. In order to pass a current through a ground connection it is necessary to have a second connection in order to complete the circuit. Where a large water-piping system is available for the return connection, an approximate measure of the resistance can be obtained by passing a current from the ground connection to an accessible part of the piping, say a hydrant, and computing the resistance by dividing the volts by the amperes. The resistance thus obtained includes both the resistance to be measured and that of the connection through the piping system. As the latter is probably much smaller and may be insignificant, the result gives an approximate idea of the resistance and locates a discontinuity as an infinite resistance, that is, no current flowing. Where there are two similar grounds, current may be passed from one to another and the sum of the two resistances, or the average resistance, obtained.

When a more accurate determination of the individual resistances of two or more ground connections is desired, the connections shown in Fig. 4 may be employed and a curve obtained by test, similar to that shown in Fig. 2. The apparatus required comprises a source of alternating current, a rod P which may be driven into the earth, a high resistance wire BD stretched between the two ground connections G_1 and G_2, an ammeter A and a telephone receiver T. The contact C is slid along the resistance wire until the telephone receiver is silent. The drop of potential between G_1 and the rod is then the same as between G_1 and the contact C. The drop between G_1 and P is therefore equal to

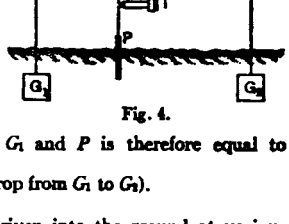


Fig. 4.

$$\frac{\text{(length of wire } BC)}{\text{(length of wire } BD)} \times \text{(total drop from } G_1 \text{ to } G_2).$$

By taking a series of observations with P driven into the ground at various points the curve of potential drop is readily plotted and the resistance of each ground connection, as defined above, readily obtained.

CARE OF GROUND PLATES AND PIPES. — The greatest trouble with ground plates and pipes arises from electrolysis, and periodic resistance measurements should be made as described above. When a ground connection shows an abnormally high resistance, it is usual to supplement it with a new ground connection, as it seldom pays to remove the old ones. Ground connections deteriorate rapidly if equipped with salt boxes; but even under the worst conditions they are likely to last many years. Practically no accurate measurements of the resistance of ground connections were made until quite recently, so that little is known about their life performance. J. L. R. Hayden cites the case of some pipe grounds which maintained the same average resistance for three years.

SPECIFICATIONS FOR GROUND PIPES AND PLATES. — (*See also* Article on *Specifications.*) In the case of ground plates, the following data

should be specified: Material of plate (usually copper); size of plat thickness; depth at which the plate shall be buried; amount of cha and above it; method of connecting the plate to its cable or wire (u dered and bolted); whether the plate shall also be connected to the and if so, how.

In the case of pipe ground connections, the following data should b Diameter of pipe; whether galvanized, sherardized, etc.; depth to pipe shall be driven; method of finishing the top of the pipe; heigh shall project above the ground; whether the pipe shall be connec track rails and if so, how.

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GROUND DETECTORS AND ARCING-GROUND SUPPRESSORS. — A ground detector is a device for indicating an accidental ground on a transmission line; an arcing-ground suppressor is an arrangement of switches and relays by means of which an arc tending to maintain an accidental ground is automatically extinguished

GROUND DETECTORS FOR NORMALLY UNGROUNDED SYSTEMS. — On ungrounded two-wire direct-current systems a voltmeter of the central-zero type connected between the ground and the middle point of a resistance joining the two line wires serves as a satisfactory ground detector. The direction of the deflection will indicate on which wire the ground has taken place, and the magnitude will indicate the nature of the ground. For alternating-current circuits, this method is unsatisfactory on account of capacity effects and also because of the higher voltages commonly involved.

Electrostatic Ground Detectors. — For single-phase ungrounded systems the simplest form of ground detector consists of two electrostatic voltmeters, each connected between one line wire and the earth. A ground on either wire causes an inequality in the readings of the two meters.

The more common form of ground detector operates as an electrostatic differential voltmeter. Fig. 1 shows diagrammatically the arrangement for a single-phase instrument. The movable vane V is connected to the earth, the fixed plates S_1 and S_2 are connected one to each of the two mains. Vane V will be equally attracted by the two plates unless the insulation resistances of the two line wires to ground are not equal, but will deflect from its normal position to one side or the other when a ground occurs.

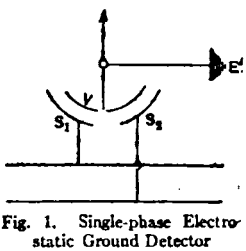


Fig. 1. Single-phase Electrostatic Ground Detector

The three-phase electrostatic ground detector for ungrounded circuits is made in two principal forms. One form consists of three separate elements, each similar to that used in the single-phase instrument, all three elements being in one case but having individual scales. Another form consists of a movable spherical vane, connected to the earth, and three fixed vanes, each of which is connected to one line wire. The movable vane in its normal position is equally distant from each one of the fixed vanes, but, in case of a ground on one line wire, it moves away from the fixed vane which is connected to the line wire on which the ground occurs. The principal parts of this instrument are clearly visible through the glass front of the instrument cover; hence no pointer and scale are needed. Two single-phase detectors will work satisfactorily on three-phase circuits, if the junction point of the two instruments is connected through a condenser to the third line wire.

Voltage Range. — Commercial sizes of electrostatic ground detectors range from 650 volts to 22,000 volts for single-phase circuits, and from 1150 volts to 22,000 volts for three-phase circuits.

Connections. — Electrostatic ground detectors are usually not connected directly to the line wires, especially if the voltage is above 3300. Some types are furnished with special terminal studs containing high-resistance rods of graphite through which the instrument is connected to the line wires. Other types are connected to the circuit through condensers, commonly of tubular form. Although, in this case, the condensers practically insulate the instrument from the line, the leads connecting the detector and the condensers must be treated as high-tension conductors, i.e., they should be properly separated and

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far enough from neighboring metal in order that disturbing capacity effe not be introduced. Therefore, the leads should be fairly short and must enclosed in metal conduit.

GROUND DETECTORS FOR NORMALLY GROUNDED TEMS. — The methods outlined above, depending on the variable p difference between mains and earth, do not apply to earthed systen three-wire circuits with grounded neutral, or four-wire, three-phase circu grounded neutral. The most usual method for earthed circuits is nect an ammeter in the earth circuit between the earth plate and t tem; hence any leakage current will have to pass through the amme low-range instrument is desired if slight grounds are to be detected. I to protect the instrument from excessive currents, an arrangement may by which the instrument is short-circuited as soon as the current reache tain value, or a resistance may be inserted in the circuit to reduce the to a safe value. By the second method a short-circuit due to a ground be suppressed without interruption of service on the line in question. same time, however, the pressure on the other line wires with respect t would be raised to a higher value.

ARCING-GROUND SUPPRESSORS. — Interruptions to servi damage to apparatus are frequently caused by grounds which tend to pc arcs, due to the burning away of the conductor. Arcs of this kind may b mittent, due, for example, to the swinging of the conductor back anc Arcing grounds may give rise to disastrous surges in the system. The ground suppressor, placed on the main bus at the generating station, r arcs to ground on a line wire by automatically grounding that line wirc power station, thereby short-circuiting the arc. It is obvious, from the of the device, that it cannot be used on earthed systems.

A three-phase arcing-ground suppressor consists of the following parts

(*a*) Three single-pole, motor-operated, oil circuit-breakers each con one phase of the power house main bus to the ground. These circuit-b are provided with interlocking relays, each of which has three contacts, which closes the tripping circuit of its own oil circuit-breaker while th two open the tripping circuits of the other two circuit-breakers. Hen impossible to have more than one oil circuit-breaker closed at the sam For use with overhead systems each circuit-breaker is equipped wi second-stroke lock device described later. The oil circuit-breakers are p with the usual remote-control switches with red and green lights to be on the station switchboard.

(*b*) Three single-pole, single-throw disconnecting switches for discon the oil circuit-breakers.

(*c*) An electromagnetic selective relay for detecting the ground pha operating the proper oil circuit-breaker. This selective relay is conne the main bus through three Y-connected transformers of which the neu the high-tension side is grounded.

Operation when used with Overhead Lines. — The arcing-groun pressor is suitable for overhead lines only when metal towers or poles of rel low resistance are used, as on a wooden pole line the resistance of the liable to prevent sufficient current flowing to ground to reduce the po sufficiently to operate the phase selective relay.

The operation is as follows: If a ground occurs on one wire in the syste unbalancing in the potentials of the grounded Y-connected transformers the phase selective relay to be operated in such a way that the proper int ing relay is thereby energized. This closes the corresponding oil circuit-b

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e wire, on which the arcing ground has occurred, Thus the arcing ground is almost instantly cleared, pens automatically after a fractional part of a second, l the normal state of insulation of the line is reëstab- of the arc to ground. Whenever an arc is established oscillations are set up, the duration of which depends g resistance in the circuit (*see Transmission Lines*). dangers from such oscillations, a damping resistance thrown in series before the switch rod closes the main r it has opened the main contact.

rmanently broken down by the arc, the line potential o ground as soon as the metallic ground through the second-stroke lock device then operates; it locks the ided the second closing of the switch occurs immedi- ned. In this case the system remains grounded on e to operate with the metallic ground. After the he oil switch is opened by the attendant.

with Underground Cables. — When the arcing- for the protection of cables, the second-stroke lock desirable for the oil circuit-breaker not to be opened d until the feeder has been cleared, the reason being e of a conductor from the sheath is usually so small lation produces a permanent fault, and the normal ufficient to reëstablish an arc, even if it were auto- he arcing-ground suppressor on cable systems, there- lue to a puncture in the cable and prevents the trouble esses dangerous high-frequency surges due to arcing d to clear short-circuits between line wires.

g-ground Suppressor. — The best location for the s at the power house, and directly connected to the nay be under the immediate observation of the station rrent supply is available, and where the more impor- n case of grounds are usually performed.

electrostatic ground detector costs from $30 to $60, ge, and a three-phase electrostatic ground detector A three-phase arcing-ground suppressor for voltages ts approximately from $2200 to $6000.

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GROUNDING OF ELECTRIC CIRCUITS. — (*See also Ge*
Alternating-current; Ground Connections; Transformers.) Some electric
are operated insulated, that is with no intentional electrical connecti
any point of the circuit to the ground, while others are grounded by
more conductors provided for the purpose.

Among the considerations influencing the decision of this point are: (1
of shock to persons touching the circuit; (2) danger of fire from escap
rent, spark, or arc; (3) elimination of electrical oscillations set up in
due to the sudden changes in current resulting from the making and
of an arc, usually to ground, usually referred to as an "arcing ground
grounds may give abnormal voltages particularly on a-c. circuits w
arc forms and is extinguished twice every cycle; (4) decreased strain o
insulation in case of accidental ground; (5) the utilization of the gro
conductors on or in the ground for carrying return currents; (6) the
of electrolysis and disturbance of telegraph and telephone systems by
escaping to the ground.

CURRENT PRACTICE REGARDING GROUNDING. — W
practice of different companies is not consistent with respect to insul
grounding of various classes of circuits, the following rules probably c
best practice at the present time.

(1) Low-voltage circuits should be insulated where they are in no way
to direct or indirect crossing with other circuits of higher voltage.

(2) Low-voltage circuits should be grounded if there is any danger of
with circuits of higher voltage.

(3) Intermediate voltage circuits should be insulated when practicabl

(4) Intermediate voltage circuits if grounded (600-volt railway circ
example) should be handled only by experienced people and should be
sible to the public.

(5) High-voltage circuits are always dangerous and may be insu
grounded according to other conditions than safety from shock.

The reasons for the above practice are discussed below.

**ELECTRIC SHOCK FROM GROUNDED AND UNGROU
CIRCUITS.** — Of the various considerations affecting the desira
grounding a circuit, that of shock is perhaps the most important. (
article on Shock, Electric.) A person touching a circuit at any two points
which there is a difference of potential will receive a shock. The d
severity of shock from touching simultaneously two line wires of a c
not affected by grounding the circuit, but the danger or severity of sho
touching simultaneously either wire and the ground does depend upon
the circuit is grounded or not.

It should be noted that the sensitiveness of different people to shoc
a great deal and that the severity of a shock depends as much on the
resistance of the skin (whether dry or wet), and on the parts and orga
body through which the current passes, as on the voltage. It is there
possible to say that any voltage used in practice is so low that under
dition can it give a dangerous shock. However, considering ordinary co
and the result of a majority of the shocks, circuits of voltages up to and i
220-volts may be considered as not liable to cause a serious shock,
grounded or ungrounded, and may be referred to as "low-voltage" circ

Voltage to Ground of Grounded Circuit. — When a circuit is inte
grounded, the voltage of the grounded point is made permanently the

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every other point of the circuit becomes fixed with may be readily calculated (*see Kirchhoff's Laws in* en carries a definite, predetermined risk, instead of y be nothing or may be very great.

Ungrounded Circuit. — Under normal conditions insulated circuit is the same as that of the ground, uit having a potential above and the negative parts These differences of potential cause the positive and l like the plates of condensers, the positive wire and r and the earth and negative wire the other. The ges on the wires will be equal and the resultant e zero in all cases. These condensers are in series trical the two condensers will have equal capacity. sitive wire will be as much higher than that of the wire is below earth potential. In an unsymmetrical positive and negative wires with respect to earth cities.

Ground Connection. — In case of a ground, either e grounded point of the circuit is brought to ground nade in the voltage to ground of the positive and , and the resultant charge on the earth is no longer me by conduction from the circuit and must there- the ground connection. As long as there is a change e circuit due to the ground connection a current will nection. Such a current is only momentary in the ows as long as the ground continues with alternat- le on *Capacity and Charging Current*.

which flows through such a ground connection is voltage of the system and its electrostatic capacity tic capacity is proportional to the extent of the the miles of line of commercial circuits ordinarily to the voltage, it follows that the amperes to ground f the voltage of the circuit. The energy which can ccidental ground will be proportional to this current that is, will vary as the cube of the voltage. In the capacity to ground there may be a leakage ulation.

ontact with High-voltage Circuits. — Circuits e of 11,000 volts or over are generally of sufficient ufficient electrostatic capacity) so that a fatal shock to ground, due to the current passing to ground gh the circuit be otherwise perfectly insulated from

e Voltage Circuits. — In general the power avail- nt escaping from an insulated circuit to ground is case of contact with the two wires of the circuit. ass of circuits whose voltages are high enough to where contact is made with two points of the cir- give serious (or sometimes even appreciable) shocks he circuit is ungrounded. These circuits are inter- voltage (220-volt) and high-voltage (11,000-volt) This class includes 440- and 550-volt power circuits 00-volt primary circuits, if leakage is small.

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Shock from Low-voltage Circuit Crossed (in Contact) With l tage Circuit. — When an insulated circuit becomes crossed with a higher voltage it becomes charged to the voltage of the latter circ point of contact. It becomes practically a part of the higher volt and is equally dangerous to touch. As its insulation is not designe such abnormally high voltage, there is danger of shock even throu sulation of the conductor.

When a grounded circuit is crossed with one wire of a higher volta this wire tends to come to ground potential, and the voltage of t parts of the low-voltage circuit with respect to the ground remains In cases where a very large amount of current escapes from the hi circuit, this will be appreciably modified by the addition of a volta the resistance or impedance drop in the low-voltage circuit due to t from the high-voltage circuit from point of contact to ground. If, fo an outside wire of a three-wire, 110/220-volt, alternating-current circuit, with grounded neutral, should become crossed with a grounded circuit, a large amount of current may flow into it, whic escape to the ground after passing through the lamps on one side of or through the transformer secondary. The impedance of the pat the lamps and transformer may be high enough so that the volt crossed outside wire of the secondary may be raised to a dangerous vol that of the grounded neutral.

Conclusions regarding Effect of Grounding with respect to The considerations on which above classification is based lead to the c

(1) The insulating of low-voltage (under 220 volts) circuits dec danger of shock under normal conditions, but as such shocks woul serious, there is little gain in safety through the insulation of the circ

(2) The grounding of low-voltage (under 220 volts) circuits greatly the danger of fatal shocks in cases where the low-voltage circuits beco with one of higher voltage.

(3) The insulating of intermediate voltage circuits (440 to 2 greatly decreases the danger of shock under ordinary conditions be shocks are obtained from touching one conductor, and in such c electrostatic capacity is ordinarily so small that no appreciable cu to ground.

(4) The grounding of intermediate voltage circuits (440 to 2 does not greatly decrease the danger of fatal shock in case the circu crossed with one of higher voltage because the normal voltage of when grounded is itself dangerous.

(5) Neither the insulating nor grounding of a high-voltage circ 11,000 volts) materially changes the danger of shock which is ver either case.

DANGER OF FIRE FROM GROUNDED AND UNGR CIRCUITS. — In general, conditions which diminish the danger shocks also diminish the danger of fire.

The Rules and Requirements of the National Board of Un is the principal authority on the subject of grounding from the sta fire hazard. These rules, given in the National Electrical Code (19 are abstracted in the following table.

GROUNDING OF HIGH-VOLTAGE CIRCUITS. — The of low-voltage circuits is governed by considerations of danger of fire, while that of high-voltage circuits is for the purpose of increasin bility (continuity of service over the line), or of decreasing the co

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it	Grounding	Point of attachment of ground
	Prohibited	At one station only
	Optional	At one station only
	Optional	Neutral, at one or more supply stations but not at individual services or within buildings served
unded other ircuit, 150 V.	Compulsory	Each service is near the transformers but not otherwise within buildings. Single-phase three-wire systems should have their neutrals grounded. Single-phase two-wire systems may have the ground on either conductor. In the case of two- or three-phase systems the ground should be on the point of the system which causes the lowest voltage from ground of unguarded current carrying parts of connected devices
unded other uit ex-	Optional	
	Optional	
	Optional	

induction from aerial circuits of higher voltage
or induction from aerial circuits of higher voltage.
or induction from aerial circuits above 600 V.
induction from aerial circuits above 600 V.
induction from aerial circuits, etc., above 600 V.
or induction from aerial circuits, etc., above 600 V.

miting the voltage strain on the line insulator and also article on *Generators, Alternating-current* and *nections* in the article on *Transformers*.

rounds by Metallic Grounding. — In normally rcuits the current to ground is sometimes sufficient n one of the wires and a grounded conductor near t with it, producing a so-called "arcing" ground. und to produce destructive voltages on the circuit. the neutral or one wire of the circuit the rise of s perhaps the main reason why many high-voltage

ain by Grounding the Neutral. — In high-voltage ors is an important element. In an ungrounded be large enough to stand full line voltage (between become grounded accidentally. Where the neutral the maximum voltage on any insulator can never to ground. The voltages to neutral of a single- er cent of the voltage between lines, and the voltage system is 58 per cent of the voltage between lines. utral therefore requires insulators of from 50 to 58

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per cent of those for same circuit with insulated neutral, or for the s insulator the line voltage can be from 73 to 100 per cent higher with neutral than without. These figures neglect the fact that the maximu is constant for grounded neutral, and occurs only for a short time at intervals with insulated neutral. In practice the same insulators ar used whether the neutral is grounded or not, the factor of safety beir when the neutral is grounded.

Limiting Short-circuit Current by Resistance.— In a grounde every accidental ground becomes a short-circuit. As such short-circ be destructive to generating machinery, the current is sometimes li a resistance in the ground connection (usually made at the neutr amount of resistance required depends on the per cent of short-circui which is permissable. The resistance has, however, the disadvant it increases the strain on the insulation, so that as the short-circuit reduced, the benefit to the insulation is also reduced. Where the grounded as a remedy for arcing grounds and no increased factor of the insulator for normal condition of operation is desired, the use of in the ground connection is allowable.

Use of Ground for Return Circuit. — Connections to ground are as return paths for the normal current of the circuit, except for railw Formerly many 500-volt direct-current power circuits, operated fron circuits which were necessarily grounded, used the ground as a re cuit, though usually only for small or outlying motors. Such connect cause electrolysis in underground pipes and arcs, in cases where the other foreign conductors over which the currents are returning, ar Present practice on light and power distribution is to provide complet circuits for all currents which will flow in a circuit under normal oper ditions. Where one conductor is to be intentionally grounded the current into the ground may be prevented by grounding it at only or where, on account of great extent of circuit, grounds on same cond necessary at several points, the escape of current will be reduced to a by making the ground connection on the neutral instead of an outside

BIBLIOGRAPHY. — *National Electric Code; Reports of Com Grounding Secondaries*, Trans. N.E.L.A., Lincoln, P. M., *The Grounded With and Without Series Resistance, in High-Tension Systems*, Trans. 1907, Vol. 26; Clark F.G., *The Grounded Neutral*, Trans. A.I.E.E., 26; Rhodes, Geo. I., *Experience with a Grounded Neutral on the Hig System of the Interborough Rapid Transit Company*, Trans. A.I.E.E., 26; Allen, C. W., *Grounding of Neutrals with Particular Reference to the and Transformer Connections*, G. E. Rev., 1911; Rice, C. W., and Tho *Grounded Y versus Isolated Delta from the point of View of the Systems in west*, G. E. Review, 1913, Vol. 16; Steinmetz, C. P., *The Grounding mission Lines*, G. E. Review, 1913, Vol. 16; Ricker, C. W., *Exper Grounded Neutral in a High Tension Plant*, Electric Journal, 1906, Vol. J. S., *Grounded and Ungrounded Transmission Circuits*, Electric Jour Vol. 8; Jollyman, Downing and Baum, *Experiences of the Pacific Gas an Company with the Grounded Neutral*, Trans. A.I.E.E., 1914, Vol. 33.

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(*See also Insulating Materials; Telegraph Instru- and Cables, Insulated.*) Gutta-percha is derived r latex of the bark of certain trees of the order of Dichopsia Gutta, found chiefly in the Straits Settle- pelago. The trees are felled immediately after the or gum collected as it exudes from incisions in the ed from the leaves by digesting them in toluol. How- the latex is boiled in water and it is then ready for ecoming quite scarce and practically the whole avail- ish cable makers.

on of gutta-percha is represented by the formula brown leather at temperatures between 0° C. and ratures it softens, and at 65° C. it is plastic and or rolled. On cooling it returns to the non-plastic

hen exposed to the air, changing from dark brown or d becoming brittle.

GUTTA-PERCHA INSULATION. — For insu- ha is shredded and squeezed in warm water. It is through fine-wire gauze and rolled into sheets. Its ed on differently by various manufacturers, the proc- rade secrets. Like rubber it is applied to the wire e or by strips. Unlike rubber it is used in the pure minerals. Gutta-percha is less porous than rubber roof, a quality which makes it the best material for cific gravity is just above unity.

NCE. — The constant K in the formula

$$M = K \log \frac{D}{d}$$

nately, at 75° F. after one minute electrification. See

ent of Resistance. — The temperature coefficient ha is of the same nature as that of rubber (*see article*

$$R_T = R_{75} \epsilon^{(75 - T)C},$$

at 75° F., R_T the resistance at $T°$ F. and C a constant o 0.085. For values of ϵ^x see *Exponential Functions.*

pon Resistance. — Gutta-percha being used prin- ples, the effect of pressure upon its resistance is im- sistance at atmospheric pressure, R_p = resistance ad per square inch.

$$R_p = R\,(1 - 0.00023\,p).$$

Brannt, W. T., *India Rubber, Gutta-Perchas and India Rubber, Gutta-Percha and Balata*, Cologne, 1903; n, L. and Falconnet, H., *India Rubber and Gutta-* H. K. *Dielectric Characteristics of Various Insulating* vol. 10, p. 114.

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HEAT AND THERMAL PROPERTIES. — (*See also Tem and Thermometers; Thermodynamics, Principles of.*) Heat is said to b to a body, or the body is said to absorb heat, (1) whenever its temp rises, (2) whenever it passes from a solid to a liquid state, or (3) whe passes from a liquid to a gaseous state; when the reverse of these chang place the body is said to lose or to give out heat. A body can also (or give out) heat without any of these changes taking place, provided out (or absorbs) at each instant an amount of energy of some oth equivalent to that absorbed (or given out) as heat. The heat abso given out by a body in virtue of a change in its temperature is called "s heat; heat absorbed or given out in passing from one state to another "latent" heat. Experiment shows that heat may be considered as a energy.

Symbol for Heat (H). — Both H and Q are commonly used to d quantity of heat. The symbol H is used throughout this article.

UNITS OF HEAT. — There are several arbitrarily chosen units of he

15° Gram-Calorie or Small Calorie. — The heat necessary to r temperature of 1 gram of water from 14.5° C. to 15.5° C. This is the un monly employed in scientific work.

Mean Gram-Calorie or Small Calorie. — The $\frac{1}{100}$th part of the heat to raise the temperature of 1 gram of *water* from 0° C. to 100° C., the lat of fusion and boiling not being included. According to Marks and Davis *Tables and Diagrams, N. Y., 1912*), the 15° calorie and the mean smal differ by less than one-tenth of one per cent.

Kilogram-Calorie or Large Calorie. — The heat required to raise t perature of 1 kilogram of water from 14.5° C. to 15.5° or the $\frac{1}{100}$th pa heat required to raise the temperature of 1 kilogram of water from 100° C. The relation between the gram-calorie and the kilogram-calori

1 kilogram-calorie = 1000 gram-calories.

Ostwald Calorie. — The heat required to raise the temperature of of water from 0° C. to 100° C. This unit is frequently used by electroc

1 Ostwald calorie = 100 mean gram-calories.

British Thermal Unit (B.t.u.). — The heat required to raise the tem of 1 pound of water 1° F. There is no general agreement as to *which* d temperature shall be used; Peabody uses the degree from 62° F. to 63° F. and Davis define the British thermal unit as the $\frac{1}{180}$th part of the heat to raise the temperature of 1 pound of water from 32° F. to 212° F. Th as defined by Marks and Davis is about 0.13 per cent greater than th as defined by Peabody. Marks and Davis's definition is adopted thr this book; the difference between the two is negligible for ordinary work. The relation between the B.t.u. and the mean kilogram-calori

1 B.t.u. = 0.25200 kilogram-calories.

Mechanical Equivalent of Heat. — This is the name given to the mentally determined conversion factor between any heat unit and a of mechanical work; see *Units and Conversion Factors*. The fundame lation is

1 mean gram-calorie = 4.1834×10^7 ergs.

This is the value given by Marks and Davis.

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Y AND SPECIFIC HEAT.—The "thermal capa- as the heat absorbed by the body per unit increase ring during this change in temperature no change of solid to liquid or from liquid to gaseous form or no ransfer of heat energy from the body in question to l capacity *per unit mass* of a substance is approx- eases slightly with increase in temperature; in the vith temperature is quite marked. Calling C the mass of a substance the heat absorbed by a homo- emperature increases from t_1 to t_2 is

$$H = CM\,(t_2 - t_1) \qquad (1)$$

ity per unit mass of water (between 0° C. and 100° ean gram-calories per gram per degree centigrade, nity. The ratio of the thermal capacity per unit the mean thermal capacity of water is called the stance. The specific heat of a substance does not nich the various quantities are measured; its thermal es. When heat is expressed in mean gram-calories, rature in degrees centigrade, the thermal capacity its specific heat; compare with density and specific

osorbed or Given Out.—
gram-calories per gram per °C.),

rature.
ıe heat absorbed is (2)

$$H = kCM\,(t_2 - t_1),$$

values:

VALUES OF k

gy	Unit of mass	Temperature scale	Value of k
	Gram	Centigrade	1.000
	Kilogram	Centigrade	1 000
	Pound	Centigrade	1.800
	Pound	Fahrenheit	1.000
	Gram	Centigrade	4.183
	Pound	Fahrenheit	1054
	Kilogram	Centigrade	1.162×10^{-3}
	Pound	Fahrenheit	2.928×10^{-4}

at. — In the table below are given the values of the ommon substances used in engineering work. These the thermal capacity per unit mass, when mass is ature in degrees centigrade and heat in gram-calories.

onstant Volume and Constant Pressure. — In osorbs heat an expansion (contraction in a few does work on whatever opposes this expansion, part g thus converted into mechanical work; see *Ther-*

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TABLE I.—SPECIFIC HEAT OF SOME COMMON SUBST

(From Landolt-Börnstein Tables; see also article on Pyrometers.

Substance	Temperature, ° C.	Specific heat C.	Substance	Temperature, ° C.
Air (*a*)	−102 to 440	0.237	Ice	− 78 to − 1
Aluminum	15 to 435	0.236	Iridium	0 to 10
Ammonia	23 to 216	0.520	Iron, cast	18 to 10
Antimony	22 to 600	0.052	Lead	17 to 10
Asbestos	20 to 98	0.195	Manganin (*e*)	18
Bismuth	−79 to 100	0.029	Manganin (*e*)	100
Brass (*c*)	20 to 100	0.092	Marble	0 to 10
Bronze (*c*)	20 to 100	0.104	Mercury	0
Carbon (gas carbon)	20 to 1040	0.315	Mercury	100
Carbon (graphite)	0 to 3000	0.535	Mica	20 to 9
Carbon dioxide(*a*)	− 78 to 7	0.184	Molybdenum	20 to 55
Carbon dioxide(*a*)	0 to 200	0.215	Nickel	0 to 10
Carbon monoxide (*a*)	23 to 198	0.243	Nitrogen (*a*)	0 to 20
Cement (Portland)	28 to 30	0.271	Nitrous oxide (*a*)	13 to 17
Chlorine	13 to 202	0.124	Oxygen (*a*)	20 to 44
Cobalt	15 to 350	0.109	Osmium	19 to 9
Concrete, tamped	20 to 100	0.156	Palladium	0 to 10
Concrete, tamped	800	0.219	Palladium	0 to 126
Constantan (*a*)	18	0.098	Paraffin	25 to 3
Constantan (*a*)	100	0.102	Petroleum	21 to 5
Copper	−188 to 20	0.080	Petroleum	18 to 9
Copper	0 to 100	0.094	Platinum	0 to 10
Copper	300	0.098	Rhodium	10 to 9
Copper	900	0.126	Silver	0 to 26
Cork		0.485	Steam (*g*)	
Cotton	0 to 100	0.362	Steel	20 to 10
Ebonite		0.339	Tantalum	−185 to 2
German silver	0 to 100	0.095	Tin	17 to 10
Glass	0 to 19	0.171	Tungsten	20 to 10
Glass	56 to 78	0.192	Wax (yellow)	26 to 4
Gold	0 to 100	0.032	Wood's metal (*f*)	5 to 5
Hydrogen (*a*)	− 28 to 198	3.41	Wool	
			Zinc	20 to 10

(*a*) At constant pressure of 1 atmosphere.
(*b*) 60 Cu + 40 Zn.
(*c*) 88.7 Cu + 11.3 Al.
(*d*) 60 Cu + 40 Ni.
(*e*) 84 Cu + 4 Ni + 12 Mn.
(*f*) 25.85 Pb + 6.99 Cd + 52.43 Bi + 14.73 Sn.
(*g*) See article on *Steam*.

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In the case of solids and liquids the external work ble. In the case of gases and vapors, however, the reciable. The specific heat of a gas or vapor when , so that it can do no external work, is called the olume, and is usually designated by the symbol C_v. or vapor when it is allowed to expand at constant ific heat at constant pressure, and is usually desig- The ratio

$$\gamma = \frac{C_p}{C_v} \qquad (3)$$

value, 1.40 approximately, for all ordinary (diatomic)

$\gamma = \frac{C_p}{C_v}$ FOR SOME GASES AT ATMOSPHERIC PRESSURE

rom Landolt-Börnstein Tables.)

n-ure,	$\gamma = \frac{C_p}{C_v}$	Gas	Tem-perature, ° C.	$\gamma = \frac{C_p}{C_v}$
81	1.34	Chlorine.....	20–340	1.32
o	1.40	Hydrogen.....	.....	1 40
oo	1.39	Nitrogen.....	.....	1.40
oo	1.30	Nitrous oxide.....	0–100	1.29
oo	1.30	Oxygen.....	.....	1.40
oo	1.40			

heat is supplied at a uniform rate to a piece of iron e rate of increase of temperature gradually increases specific heat) until a certain temperature is reached rature is suddenly and in most cases greatly retarded l. The reverse of this effect occurs when the sample nperature above this point, and under certain con- ntaneous reheating during the cooling. Any point ot change in the slope of a heating or cooling curve. point; there is a very marked recalescence point nd also one or more points at which the same effect ree. The major recalescence point of ordinary iron 750° C. and 850° C.

EZING POINT AND HEAT OF FUSION. — substances when heated to a definite temperature liquid state with no increase in temperature during ded the solid and liquid are kept thoroughly mixed, nied by a considerable absorption of heat. The tem- ge takes place is called the melting point or freezing takes place at the same temperature), and the heat called the heat of fusion or heat of liquefaction; this iven out when the body solidifies. In the case of , there is no definite melting point, the change from g gradual; such substances begin to melt at a lower

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tempera ure than that at which solidification begins during coo melting points and heats of fusion for some common substances ar Table III. The values printed in bold face type are recommend Bureau of Standards as suitable for pyrometer calibration.

TABLE III.—FUSION AND VAPORIZATION

(*At Atmospheric Pressure, i.e., 760 mm. Mercury.*)

Substance and References	Melting point, ° C.*	Heat of fusion, gr-cal. per gr.†	Boiling pt., ° C.*
Aluminum (2)	**658.7**	76.8	1800
Ammonia (2, 3)	−75	108	−33.5
Antimony (2)	630	....	1440
Bismuth (2)	271	12.64	1430
Brass	900 ±	....	....
Bronze	900 ±	....	....
Cadmium (2)	321	13.66	778
Carbon (1, 3)	over 3600	....	over 3600
Carbon dioxide (3)	−79	....	−79
Carbon monoxide (2, 3)	−203	....	−190
Chlorine (2, 3)	−102	22.96	−33.6
Chromium (2)	1610	....	2200
Cobalt (2)	1480	....	....
Copper (2)	**1083**	42.0	2310
German silver	1100 ±	....	....
Glass, flint	1300	....	....
Gold (2)	**1063**	....	....
Gutta percha	100	....	....
Hydrogen (1, 3)	−259	....	−252.6
Iridium (2)	2350(?)	....	....
Iron (2)	1530	23.0 to 33.0	2450
Lead (2)	**327**	5.36	1525
Manganese (2)	1230	....	1900
Marble	2500 ±	....	....
Mercury (2)	−38.87	2.82	357

* Let t_c be the value in ° C.; then the value in ° F. is $t_f = 32 + 1.$

† Let H be the value in gram-calories per gram; then the correspo of fusion or of vaporization

In kg-cal. per kg. is	$1.000\ H$,
In watt-seconds per gram is	$4.183\ H$,
In kw-hr. per kg. is	$1.162 \times 10^{-3} H$,
In kw-hr. per lb. is	$5.271 \times 10^{-4} H$,
In kw-hr. per ton (2000 lbs.) is	$1.054\ H$.

References: (1) Bureau of Standards, Cir. No. 35; (2) Smithsonian Tables, 1920; (3) Landolt-Börnstein-Roth, Physikalisch-Chemische 1912.

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HION AND VAPORIZATION — Continued

heric Pressure, i.e., 760 mm. Mercury.)

	Melting point, ° C.*	Heat of fusion, gr-cal. per. gr.†	Boiling pt., ° C.*	Heat of vap't'n gr-cal. per gr †
....	2535	....	....	....
....	1452	4.64	2325	....
....	−211	....	−195	47.65
....	−160.6	....	−153	....
....	−218	....	−182.7	50.97
....	2700	....	2600	....
....	1545	36.3	2535	....
....	52.4	35.1	....	....
....	1755	27.2	3910	....
....	1950	....	2500	....
....	100	....	....	....
....	217	....	690	....
....	1420	....	....	....
....	961	21.07	1955	....
....	1300 to 1475	....	....	....
....	106.8 to 112.8	9.37	444.7	362.0
....	2900	....	....	....
....	231.9	14	2270	....
....	3400	....	5830	....
....	1720	....	....	....
....	62	42.3	....	....
....	75.5	8.40	....	....
....	419.4	28.13	930	....

° C.; then the value in ° F. is $t_f = 32 + 1.8\,t_c$.

gram-calories per gram; then the corresponding heat

	$1.000\,H$,
gram is	$4.183\,H$,
	$1.162 \times 10^{-3}\,H$,
	$5.271 \times 10^{-4}\,H$,
2000 lbs.) is	$1.034\,H$.

of Standards, Cir. No. 35; (2) Smithsonian Physical
t-Börnstein-Roth, Physikalisch-Chemische Tabellen,

The addition of an impurity to a liquid lowers the
example of which is the lowering of the freezing point
f salt. Also, when certain substances go into solution
olution is lowered. Some common freezing mixtures
om *Halle*.

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FREEZING MIXTURES

Mixture	Parts by weight	Decrease of temp., ° C.		Parts by weight	Dec tem
		From	To		Fro
Snow	3	0	−17.7	1	0
Common salt (NaCl)	1			1	
Snow	2	0	−33	1	0
Calcium chloride ($CaCl_2$)	3			2	
Snow	3	0	−37	..	..
Potassium hydrate (KOH)	4				
Water	1	+10	−16	..	..
Ammonium nitrate (NH_4NO_3)	1				
Water	16			1	
Sal ammoniac (NH_4Cl)	5	+10	−12	1	+8
Saltpeter (KNO_3)	5			1	

VAPORIZATION. — Above the surface of any liquid there alway certain amount of the substance in a gaseous form, i.e., as a vapor, the of which depends upon the nature of the substance and upon the tem and the pressure in the space occupied by the vapor and such other ga air) as may be present. In the case of a simple liquid evaporatin space from which all other gases and vapors have been removed, the tion ceases when a definite pressure is established in this space, this equ pressure depending only upon the temperature at which this space is ma This statement is true only when there always remains some unev liquid; if all the liquid evaporates, then the equilibrium pressure also upon the mass of the vapor and the space which it occupies; as long liquid remains, the equilibrium pressure depends only upon the tem and is independent of the volume of the space and the mass of the vap occupies it. This equilibrium pressure for any given temperature is c (normal) "vapor pressure" or "vapor tension" at that temperature, vapor is said to be "saturated," i.e., each unit volume of the space the greatest possible mass of vapor which can occupy it at this particu perature. Diminishing the volume of the space (at constant temp occupied by a saturated vapor causes some of the vapor to condense, a is left remains saturated at the same pressure and temperature. Increa volume of the space (at constant temperature) causes more of the l evaporate and the vapor still remains saturated at the same pressure a perature, provided always that some liquid is left.

Boiling Point and Heat of Vaporization. — The temperature cor ing to any given pressure at which a vapor is completely saturated is c "boiling point" of the liquid at this pressure. The temperature of which is "boiling" in the ordinary sense of the term is in general grea the temperature of the saturated vapor above it, since the vapor in the formed is under a greater pressure than the vapor above the surfa quantity of heat required to convert unit mass of a liquid into vapor a pressure is called the heat of vaporization or heat of evaporation of t at this pressure; the same quantity of heat is given out by unit mas vapor when it condenses at this same pressure. The boiling points a of vaporization generally given are for normal atmospheric pressure, viz

two quantities for some common substances are

ated Vapors; Gases. — When the pressure exerted of the containing vessel is less than the saturation the vapor is said to be unsaturated or superheated. brought about either (1) by increasing the volume ere is no longer any liquid left to evaporate, keeping (2) by raising the temperature of such a saturated constant, or (3) by a proper combination of (1) alled "permanent" gases are superheated vapors, ing very great. The distinction ordinarily made that a gas is far removed, with respect to tempera- saturated state, whereas a comparatively small in- rease in the temperature of a vapor will saturate it.

ses. — Ordinary gases, such as air and superheated erheat the more nearly do the relations hold), are the following "law,"

$$pV = \frac{MRT}{\mu}, \qquad (4)$$

e of the gas,
by it,

ture; see Table V below,
of the gas;* see Table IV below,
all gases, called the "gas constant," whose value ts in which the various quantities are expressed;

OLECULAR WEIGHTS OF GASES

	μ	Gas	μ
.	28.98	Chlorine (Cl_2).....	70.92
.	26.02	Hydrogen (H_2).....	2.016
.	17.03	Nitrogen (N_2).....	28.02
.	44.00	Nitrous oxide (N_2O).....	44.02
.	28.00	Oxygen (O_2).....	32.00

be deduced from purely thermodynamic relations *ples of)* on the assumptions: (1) that the product is a constant for any particular gas (*Boyle's or Mari-* nsic energy per unit mass of a gas depends only on endent of the volume and nature of the gas (*Joule's* onstant volume the specific heat of the gas is inde-

emical reaction) of perfect gases of different molecular lar weight of the mixture is

$$= \frac{M_1 + M_2 + M_3 + \dots}{\frac{M_1}{\mu_1} + \frac{M_2}{\mu_2} + \frac{M_3}{\mu_3} + \dots},$$

masses of the individual constituents and μ_1, μ_2, μ_3, etc.,

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pendent of its temperature. A gas which satisfies the above condition a "perfect" gas; all ordinary gases and highly superheated vapo these conditions approximately.

As a consequence of the above law the following relations must perfect gas; they also apply approximately to ordinary gases. In a the symbols above, let

C_v = specific heat at constant volume,
C_p = specific heat at constant pressure,
$\gamma = \frac{C_p}{C_v}$,
W_{12} = work done on the gas when its pressure changes fro
H_{12} = heat absorbed by the gas when its pressure changes fr
J = mechanical equivalent of heat.

Then for a perfect gas, for an *isothermal change*, i.e., a change at cons perature ($T_1 = T_2$)

$$W_{12} = p_1 V_1 \log_e \left(\frac{p_2}{p_1}\right), \quad H_{12} = \frac{W_{12}}{J},$$

and for an *adiabatic change*, i.e., no heat passes in or out of the gas

$$\frac{p_1}{p_2} = \left(\frac{V_2}{V_1}\right)^{\gamma}, \quad \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}}.$$

$$W_{12} = JC_vM\,(t_1 - t_2) = \frac{p_1 V_1\,(t_1 - t_2)}{T_1\,(\gamma - 1)}.$$

Any one of the four sets of units given in the following table (or *consistent* set) may be used in these formulas.

TABLE V. — VALUES OF THE GAS CONSTANT R AND MEC EQUIVALENT J

Notation	Units and constants			
M = mass	kg.	grams	lb.	
V = volume	cu. meter	cu. cm.	cu. ft.	
p = absolute press.	kg. per sq. m.	dyne per sq. cm.	lb. per sq. ft.	c
t = temperature	° C.	° C.	° F.	
H = quantity of heat	kg-cal.	gm-cal.	B.t.u.	g
W = work	m-kg.	erg	ft-lb.	me
T = absolute temp. =	t+273	t+273	t+460	
R = gas constant =	849	0.832×10^8	1547	
J = mechan. equiv. =	427	4.19×10^7	778	

Gas Saturated with Vapor. — Experience shows that when a evaporates into a space already occupied by a gas (e.g., water evapo the atmosphere), evaporation ceases for any given temperature when pressure (depending upon the temperature and the nature of the the gas) is established in the mixture; or, if the pressure and temp maintained constant, then evaporation ceases when a definite amou has been produced. When a mixture of a gas and a vapor contains mum mass of vapor per unit volume of the mixture, the gas is said rated with the vapor. Such a mixture may contain less of the vap

amount; the ratio of the mass of vapor per unit
he maximum possible mass per unit volume at any
ure is called the "relative humidity" of the mixture.
ixture (e.g., air and water vapor) can be determined
t- bulb thermometer. (*See the Hygrometric Tables of*

Amount of Moisture in Saturated Air.— The
approximate but sufficiently accurate for practical
re of any gas and vapor which do not act chemically

of the mixture,
sure of the mixture,
erature corresponding to t, see Table V above,
from Table V above,
ght of air; see Table IV above,
pressure of steam at the temperature t, to be taken
m steam tables, see article on *Steam*,
olume of steam at the pressure p_w; also to be taken
tables,

mass of unit volume of air at the pressure $(p - p_w)$

ature t,
ss of unit volume of the mixture.

at is the weight (mass) in lb. per cu. ft. of air satu-
pressure (14.70 lb. per sq. in.) with water vapor at
eight in lb. of the water contained in 1 cu. ft. of the
formulas $p = 14.70 \times 144$ lb. per sq. ft.; $p_w = 0.946$
0.002851 lb. per cu. ft.; $T = 460 + 100 = 560°$ F.;
$\frac{.946) \times 144}{\times 560} = 0.06630$ lb. per cu. ft.; $\delta_m = 0.002851$
r cu. ft. Answer: The mixture weighs 0.06915 lb.
02851 lb. of moisture per cu. ft.

rtial Pressures. — The above calculation is based
etermined relation, known as Dalton's Law, that,
ses or vapors which do not react chemically upon
ure for a given volume of the mixture is approxi-
f the individual pressures which each gas or vapor
ed this volume. For example, if a mixture of three
fill, when mixed, a volume V and produce a pressure
A by itself would exert a pressure p_a when it alone
nd gas B by itself would exert a pressure p_b when
e V, and similarly for gas or vapor C, then

$$p = p_a + p_b + p_c. \qquad (7)$$

are called "partial" pressures. Dalton's Law holds
sufficiently accurate for most practical calculations.

substance passes directly from a solid to a gaseous
lled sublimation. A common instance of this is the
nic acid, which passes from solid to gaseous form
a temperature of − 79° C. and absorbs 140 gram-
m-calories per kilogram.

T. — When a body is at a higher temperature than
ergy is transferred from the hotter to the colder

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bodies, as is manifested by the changes in temperature or state whic or actually do, take place, even though the intervening space is en of matter. The energy thus transferred from one body to anoth empty space is called "radiant energy," or "radiant heat," and is nature to the energy radiated in the form of light waves and elect waves. The waves of radiant heat have a length greater than th waves and less than that of the ordinary electromagnetic wave wireless telegraphy. Radiant heat is absorbed by, transmitted th reflected by, ordinary matter in much the same way that light wav sorbed, transmitted and reflected. Matter which is transparent to li however, may be practically opaque to heat waves; e.g., water ab tically all the heat waves which fall upon it.

When a hot and a cold body are separated by a fluid which is free t heat is transferred from the hot to the cold body by currents of the flowing from one to the other; similarly, all parts of a fluid whic heated quickly come to approximately the same temperature. Th of heat by currents of the fluid itself is called "convection."

In the case of a hot and a cold body separated by a solid the heat, which may be very rapid, particularly when the separating a metal, is probably due to an extremely rapid to-and-fro motion o cules which constitute the medium. In any event, the process is different from the transfer of heat either by radiation or by convec described by the term "conduction" of heat. In a fluid heat is both by conduction and convection.

An excellent brief treatment of Heat Transmission is given by I. *A.I.E.E., Trans. 32, p. 301, Feb. 1913*, including numerical data on conduction and convection.

Radiation, Absorption and Reflection of Heat. — The rate hotter body radiates heat, and a colder body absorbs heat, dep the state of the surfaces of the bodies as well as on their ter The rate of radiation and of absorption are increased by darkness ness of the surfaces of the bodies, and diminished by smoot polish. For this reason the covering of steam pipes and boilers smooth and of a light color; uncovered pipes and steam-cylin should be polished.

The heat radiated by a body at a given temperature T to surroun at a lower temperature is equal to the heat which this body would this same temperature T from surrounding bodies at a higher te When a given quantity of radiant heat strikes a body, only part of as a rule, absorbed, the rest being reflected.

Let H_i be the incident heat, H_r the reflected heat, and H_a the abs at temperature t, and let H_e be the heat which the body would emit a temperature to bodies at a lower temperature; then

$$H_i = H_r + H_a,$$

$$H_a = H_e.$$

Definition of "Black Body"; Stefan-Boltzman Law. — body" is defined as one that absorbs all radiations falling upon it, nei ing nor transmitting any. The radiation of such a body is a func temperature alone, and is identical with the radiation inside an i parts of which have the same temperature. By heating the walls of a as uniformly as possible and observing the radiation through a opening, a practical realization of a black body is obtained.

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a body is found to obey the following law

$$= K\left[\left(\frac{T}{1000}\right)^4 - \left(\frac{T_0}{1000}\right)^4\right] At, \qquad (8)$$

y radiated in time t from such a body at an *absolute* ding bodies maintained at an *absolute* temperature rface of the body and K is a constant. This relation ltzman Law. When the *absolute* temperature T is te temperature T_0, this relation may be written

$$K\left(\frac{T}{1000}\right)^4 At.$$

he Smithsonian Physical Tables (1914) is 1.374 when ories, T in centigrade degrees and t in seconds. For ing values

VALUES OF K

it of a (A)	Unit of time (t)	Temperature scale	Absolute zero	K =
m.	second	Centigrade	−273	1.374
meter	hour	Centigrade	−273	0.000495
t.	hour	Fahrenheit	−460	0.00174
m.	second	Centigrade	−273	5.75
n.	hour	Centigrade	−273	370.

lecting Powers. — The ratio of the heat radiated ce at a given temperature T to the heat radiated per black surface at this same temperature T is called ative emissivity, of the surface at that temperature. ratio and unity is a measure of the heat which would at the same temperature, and is defined as the reflect- The radiating power of a surface depends upon the e; at very high temperatures the radiating power es the value of unity, i.e., at high temperatures the any surface approaches in value the total energy black body. The table on page 738, taken in part *Engineer's Pocketbook* and in part from Langmuir's 913) gives the approximate value of the radiating faces at ordinary temperatures.

may increase its radiating power from 2 to 3 times, y affect the radiating power of a rough surface.

— Whenever a difference of temperature is main- rts of the same body there is a transfer of heat from t by the process described by the term "conduction," tion and convection.

thin a substance, the two sides of the layer being small compared with its area. Let one side of this t temperature T, the same at all points of this surface, layer be maintained at a constant temperature T_1;

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TABLE VI.—APPROXIMATE RADIATING AND ABSORBING

Surface	Radiating or absorbing power	Surface	
Lampblack	1.00	Zinc, polished	
Water	1.00	Steel, polished	
Carbonate of lead	1.00	Platinum, polished	
Writing-paper	0.98	Platinum in sheet	
Ivory, jet, marble	0.93–0.98	Tin	
Ordinary glass	0.90	Brass, cast, dead polished	
Ice	0.85	Brass, bright polished	
Gum lac	0.72	Copper, varnished	
Silver-leaf on glass	0.27	Copper, hammered	
Cast iron, bright polished	0.25	Copper, oxidized	
Cast iron, oxidized	0.65	Copper, calorized	
Aluminum paint on cast iron	0.47	Monel metal, polished	
Gold enamel on cast iron	0.39	Monel metal, oxidised	
Mercury, about	0.23	Gold, plated	
Wrought iron, polished	0.23	Gold on polished steel	
		Silver, polished bright	

let A be the area of the layer (i.e., of one of its flat surfaces) and x th of the layer. Then the amount of heat transferred through the lay t is,

$$H = \frac{K A (T - T_1)t}{x},$$

where K, called the "thermal conductivity," is approximately a con given material, and is independent of the temperature difference $T -$ this difference is small; K is not constant, however, for wide temper ations, particularly in the cases of gases (see paragraph following Ta Values of K are given in Tables VII and VIII. The reciprocal of t conductivity, viz., $\rho = 1/K$, is called the thermal resistivity.

The values of K given in the tables below are the values of this fa H is expressed in gram-calories, A in sq. cm., x in cm., $(T - T_1)$ in ° C seconds; i.e., K is the number of gram-calories transmitted per secon

Unit of heat	Unit of area	Unit of thickness	Unit of time	Unit of temp. diff.	
Gram-calorie	sq. cm.	cm.	second	° C.	1.
Kg-calorie	sq. m.	cm.	hour	° C.	3.
B.t.u	sq. ft.	inch	hour	° F.	29
Watt-seconds	sq. cm.	cm.	second	° C.	
Watt-seconds	sq. ft.	inch	second	° F.	85
Kw-hr	sq. m.	cm.	hour	° C.	4
Kw-hr	sq. ft.	inch	hour	° F.	

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hen a difference of temperature of 1° C. is maintained his cube. For other units the value of K as given factor noted in the table at bottom of preceding

h Other than Thin Layers. — The formula for H ly *when the lines of flow are straight and perpendicu-* T *and* T_1 *are temperatures of the surfaces of the sub-*peratures of a fluid, for example, in contact with take these facts into consideration accounts for s in the reported values of thermal conductivity he flow of heat in other cases, formulas analogous nce and conductance must be employed; see *Resist-* Langmuir, Adams and Meikle, *Trans. Am. Electro-*

fficient of Thermal Conductivity. — In the case the internal thermal conductivity with temperature ir degree of approximation by the relation

$$K = K_0 (1 + at), \qquad (10)$$

ity at 0° C., say, and K is the conductivity at any and a is a constant. The coefficient a may be either value for some of the common metals is given in

al Conductivity (K) of Materials. — In the fol-III, are given the thermal conductivity of certain metallic substances respectively. The data are from dolt-Börnstein, *Physikalish-Chemische Tabellen*, 1912; *ch. Eng.*, June, 1908; Hering, Carl, *Trans. A.I.E.E.*, *ans. Am. Electrochem. Society*, 1912; Ordway, *Trans.* 4–85; Coleman, J. J., *Engineering*, Sept. 5, 1884; ; Wolff, *Jour. Frank. Inst.* 1893; Peclet, *Practical Chem. Eng.*, Feb. 1909, p. 72; Brill, G. M., *Trans.* l. 16, p. 827; *Smithsonian Physical Tables*, 1920; ., 32, p. 301, Feb. 1913.

ivity of Laminated Steel. — The thermal conduct-core perpendicular to the laminations depends upon n and the oxide scale or varnish on the laminations e on the laminations. G. E. Luke (*El. World*, 70, ves the following values for K in gram-calories per

	Pressure, pounds per square inch			
	25	50	75	100
thick, ...	0.00096	0.00115	0.00125	0.00132
, 18.35 varnish	0.00094	0.00098	0.00109	0.00120

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TABLE VII.—THERMAL CONDUCTIVITY OF NON-META
SUBSTANCES

Substance	Temp. range, ° C.		Therm. conduct. K **		Te tu ef pe
	From*	To	From †	To†	
Air (see paragraph following Table VIII.)					
Asbestos	100	500	0.00016	0.00043	
Asbestos paper	.....	.....	0.00043	0.00060	
Brick building	15	1100	0.00149	.....	
Brick, dust	15	30	0.000461	.....	
Brick, fire	0	1300	0.00140	0.0054	
Carborundum, brick	150	1200	0.0032	0.027	
Cardboard	Below 0	....	0.000394	.....	
Cement, Portland	35	90	0.000712	0.00217	
Chalk	.....	....	0.00219	.....	
Cloth, empire	.....	....	0.00060	.....	
Concrete, slag	50	....	0.00081	.....	
Cork	20	20000	0.000153	0.000717	
Cotton batting, loose	.....	....	0.000096	.....	
Cotton batting, tightly packed	.....	....	0.000072	.....	
Ebonite	6	90	0.00038	.....	—
Eiderdown, loose	.....	....	0.000107	.....	
Eiderdown, tightly packed	150	....	0.000045	.....	
Feathers	20	155	0.000163	.....	
Felt	21	175	0.000087	0.000225	
Flannel	50	....	0.00012	.....	
Fullerboard	.....	....	0.00034	.....	
Glass	.....	....	0.0026	0.0036	
Glycerine	.....	....	0.00057	.....	
Granite	100	200	0.0045	0.0097	
Hair	20	155	0.000148	.....	
Ice	−160	0	0.0066	0.0050	
Infusorial earth	20	450	0.000216	0.00354	
Lampblack	100	500	0.0000756	0.000109	
Leather	.....	....	0.00015	0.00042	
Limestone	40	350	0.0046	0.0035	
Linen	.....	....	0.00021	.....	
Liquids, hydrocarbons, oils, etc	.....	....	about 0.0003	.....	
Magnesia, carb	20	188	0.000175	.....	
Magnesia, calcined	20	155	0.000165	0.000173	
Magnesia, asbestos	100	400	0.000162	0.000178	
Marble	15	30	0.00770	0.00910	—
Mica, pure	.....	....	0.00086	.....	
Mica, paper	.....	....	0.00038	.....	
Micanite	.....	....	0.00024	0.00029	
Oil, paraffin	.....	....	0.00033	.....	

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RMAL CONDUCTIVITY OF NON-METALLIC UBSTANCES—*Continued*

Temp. range, ° C.		Therm. conduct. K^{**}		Temperature coefficient per° C.
From*	To	From†	To†	a
.....	....	0.000425	.....	.....
0	34	0.000355	0.000382	+0.0110
13	....	0.000325	.....	+0.0067
.....	....	0.00029	0.00031	.....
.....	....	0.00034	0.00041	.....
.....	....	0.000473	0.00062	.....
.....	....	0.000450	.....	.....
.....	....	0.00130	.....	.....
20	155	0.000425	.....	.....
20	155	0.00100	.....	.....
200	500	0.0000920	0.000162	.....
95	....	0.00249	.....	.....
20	155	0.000428	.....	.....
.....	....	0.0036	.....	.....
.....	....	0.00038	.....	.....
.....	....	0.00034	0.00054	.....
20	155	0.000855	0.000867	.....
.....	....	0.000123	0.000152	.....
.....	....	0.00060	.....	.....
50	100	0.000095	0.000141	.....
50	....	0.00264	.....	.....
94	....	0.0048	.....	.....
.....	....	0.000060	0.00115	.....
.....	....	0.000330	.....	.....
.....	....	0.00036	0.00065	.....
.....	....	0.00103	.....	.....
0	25	0.00150	0.00136	.....
.....	....	0.0000878	0.00038	.....
.....	....	0.000117	.....	.....
.....	....	0.000055	.....	.....
0	175	0.0000930	0.000128	.....
100	....	0.000192	0.000216	.....
100	....	0.0000553	0.000119	.....

ature is given the measurement was made at that

by different experimenters except where only one
h case the range is that to which the given value of

centimeter-cube per degree centigrade per second;
ultiplying factors when other units are employed.

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TABLE VIII.—THERMAL CONDUCTIVITY OF METALS VARIOUS FORMS OF CARBON

Substance	Temp. range, °C.		Therm. conduct. K*		Temp. per
	From†	To	From‡	To‡	
Aluminum	18	100	0.480	0.492	+0
Aluminum	200	400	0.545	0.760	+0
Aluminum	500	600	0.885	1.01	+0
Brass, yellow	0	100	0.204	0.254	+0
Brass, red	0	100	0.246	0.283	+0
Calorite	20	250	0.038	.....	.....
Carbon, amorphous	100	360	0.089	.....	.....
Carbon, amorphous	100	842	0.129	.....	.....
Carbon, Ach. Graph.	100	390	0.338	.....	.....
Carbon, Ach. Graph.	100	914	0.291	.....	.....
Carbon, graphite brick	300	700	0.024	.....	.....
Charcoal	20	155	0.00019	.....	.....
Coal	.....	.....	0.00030	.....	.....
Constantan	18	100	0.054	0.064	+0
Copper	−54	−14	0.921	1.059	+0
Copper	74	167	0.914	1.024	+0
Copper	100	197	1.043	.....	.....
Copper	100	837	0.858	.....	.....
Copper, commercial	18	.....	0.835	.....	.....
German silver	0	100	0.070	0.089	+0.
Gold	100	.....	0.703	.....	−0.
Iron	0	.....	0.167	0.207	−0.
Iron	100	.....	0.142	0.163	0.
Iron	200	.....	0.136	.....	.....
Iron	100	727	0.202	.....	.....
Iron	100	1245	0.191	.....	.....
Iron, cast	100	.....	0.096	.....	.....
Lead	0	100	0.0836	0.0764	−0. −0.
Manganin	18	100	0.52	0.63	+0.
Mercury	0	50	0.0148	0.0189	+0.
Nickel	18	.....	0.142	.....	−0.
Nickel	300	.....	0.126	.....	.....
Nickel	1200	.....	0.058	.....	.....
Platinum	18	100	0.166	0.173	+0.
Platinoid	18	.....	0.060	.....	.....
Silver	18	100	1.006	0.992	−0.
Steel	.....	.....	0.062	0.111	−0.
Steel, transformer (a)	20	250	0.077	.....	.....
Tin	0	100	0.155	0.145	−0.
Zinc	18	100	0.265	0.262	−0.

* In gram-calories per centimeter-cube per degree centigrade per sec
table on page 738 for multiplying factors when other units are employ
† When only one temp. is given the measurement was made at that
‡ Range of determinations by different experimenters except where
value of K is given, in which case the range is that to which the given
K applies.

(a) See also paragraph *Thermal Conductivity of Laminated Steel* on p

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tivity of Gases. — The thermal conductivity of a
the nature of the gas but also upon its specific heat
d its absolute temperature T. Langmuir (*Phys. Rev.*
following values for the *watts* conducted from a plane
g film A sq. cm. in area and B centimeters thick

$$W = \frac{A}{B}(\phi_2 - \phi_1), \qquad (11)$$

ions of the absolute temperatures at the two surfaces
following table.

VALUES OF ϕ

ydrogen	Air	Mercury Vapor
0.0000	0.0000	
0.0329	0.0041	
0.1294	0.0168	
0.278	0.0387	
0.470	0.0669	
0.700	0.1017	0.0165
1.261	0.189	0.0356
1.961	0.297	0.0621
2.787	0.426	0.0941
3.726	0.576	0.1333
4.787	0.744	0.1783
5.945	0.931	0.228
7.255	1.138	0.284
8.655	1.363	0.345
0.18	1.608	0.411
1.82	1.871	0.481
3.56		0.556
5.54		0.636
7.42		0.719
9.50		0.807
1.79		0.898

ng to Langmuir (*Trans. A.I.E.E., 31, p. 1229, 1912;*
n in a gas or liquid consists essentially in conduction
of the fluid of definite thickness, in which the heat
fluid is negligible compared to that carried by con-
hich the temperature is maintained uniform because
n the case of a vertical plane surface in air, when
above the surrounding air, the heat loss by "free"
ulation of the surrounding air) is equal to that con-
till air 4.3 millimeters thick adhering to the surface,
the two faces of the film the temperature of the sur-
f the room air respectively. Equation (11) should be
king $x = 0.43$.

urface radiating upward the convection loss is about
for a horizontal plan surface radiating downward
less, than from a vertical surface.

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According to H. T. Gillette (*Eng. and Cont.*, 47, p. 573, June 27 equivalent film thickness for water is 1.27 millimeters when the w stirred mechanically. The equivalent film thickness for steam is also much less than that for air.

The film thickness of 4.3 millimeters for air is for air at ordinary perature and barometric pressure, with no forced ventilation. The ness is directly proportional to the absolute temperature of the s air, and varies approximately inversely as the square root of the abs sure.

The free convection from a round wire or cylinder of any diameter r calculated in a similar manner, except that the thickness of the air fi upon the diameter of the wire, and account must be taken of the fa lines of heat flow are radial. Langmuir gives the following formu watts carried off by convection from a length of 1 cm. of wire

$$W = s(\phi_2 - \phi_1),$$

where ϕ_2 and ϕ_1 correspond to the absolute temperature T of the w absolute tenperature T_1 of the surrounding air (see table on p. 7 is the shape factor, defined by the relation

$$\frac{a}{B} = \frac{s}{\pi}\epsilon^{-\frac{2\pi}{s}},$$

where a is the diameter of the wire, in centimeters, B the film thicl plane surface, in centimeters, and ϵ the Napierian base. The val space factor for wires in air at ordinary room temperatures and a pressure are given in the following table.

VALUES OF s

$\frac{a}{B}$	s	$\frac{a}{B}$	s	$\frac{a}{B}$	s
0.02	1.85	0.5	5.21	5.0	
0.04	2.22	1.0	7.40	6.0	
0.06	2.47	1.5	9.30	7.0	
0.08	2.67	2.0	11.1	8.0	
0.10	2.85	2.5	12.8	9.0	
0.20	3.60	3.0	14.5	10.0	
0.30	4.20	3.5	16.1	12.0	
0.40	4.75	4.0	17.8	14.0	

Forced Convection. — Langmuir finds (l.c.) that the conve plane surfaces in a stream of air is equal to that in still air multipl factor $\sqrt{\frac{v+33}{33}}$, where v is the velocity of the air in cm. per sec.

Total Heat Transfer. — Numerous formulas have been propose years for the total transfer of heat (radiation, conduction and convec pipes to the surrounding gas or vapor; see C. H. Herter, *Am. Soc. R J.*, 4, p. 308, Nov. 1917; L. H. Fry, *A.S.M.E.J.*, 39, p. 843, Oct. 1917; and Barkley, *Bur. of Mines, Tech. Paper*, No. 114, 1915; E. E. W *M.E.J.*, 37, p. 546, Sept. 1915.

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HEATING. — Most substances expand when
o° degrees and 4° C., quartz glass below − 84° C.
contract with increase of temperature. When the
anged by rapid cooling, slow changes in its dimen-
it has attained the same uniform temperature
hich is particularly marked in glass, is known as
n be largely eliminated by prolonged heating at a
a very gradual cooling, i.e., by annealing.
ly homogeneous substance which is not subjected
nore or less permanent changes in its structure,
temperature and the pressure or tension in it. In
ssure or tension the amount of expansion caused
rature depends upon both the material of the body

n of Gases. — In the case of gases, however, there
all the so-called permanent gases expanding about

me at o° C. per degree centigrade increase of tem-

pressure, provided this remains constant through-
e ordinary gases,

$$V = V_0\left(1 + \frac{t_c}{273}\right),$$

° C., and V the volume at any other temperature
e same at both temperatures. If the temperature
egrees and V_0 is the volume at o° F., then

$$V = V_0\left(1 + \frac{t_f}{460}\right).$$

60 are the absolute zeros on the centigrade and
y.

Expansion of Liquids and Solids. — Let l_0 be
n of liquid, at any standard temperature, say o° C.,
other temperature t. Then the exact relation be-
ssed as a series of the form

$$= l_0 (1 + at + bt^2 + \ldots),$$

coefficients for any given material and *fixed reference*
coefficients of the powers of t above the first are
coefficient, and for small ranges of temperature the

$$l = l_0 (1 + at)$$

oefficient a in this formula is practically a constant
e not exceeding 100° C.; it is sometimes called the
xpansion" between the limits of temperature chosen.
and 100° C., the mean coefficient of linear expansion

$$a_0 = \frac{l_{100} - l_0}{100\, l_0},$$

e change in length produced by increasing the tem-
C.
r each value of the standard or reference tempera-
ust be used. For example, if a rod has a length l_1

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TABLE IX. — COEFFICIENTS OF LINEAR EXPANSI

$l = l_0 (1 + at + bt^2)$, temperature in °C.*
a_{20} = "true" coefficient at 20°C.

(From Landolt-Börnstein's Tables, 1912 Edition.)

Substance	Temp., ° C.		a	b	
	From	To			
Aluminum	0	610	0.235 $\times 10^{-4}$	0.707 $\times 10^{-8}$	0
Brass (73.7 Cu+24.2 Zn +1.5 Sn+0.6 Pb)	0	80	0.179 $\times 10^{-4}$	0.456 $\times 10^{-8}$	0
Bronze (81.2 Cu+8.6 Zn +9.9 Sn+0.2 Pb)	0	80	0.176 $\times 10^{-4}$	0.469 $\times 10^{-8}$	0
Carbon, gas-carbon	40	....	0.054 $\times 10^{-4}$	.....	
Carbon, graphite	40	....	0.079 $\times 10^{-4}$	.....	
Constantan (60 Cu+40 Ni)	0	500	0.148 $\times 10^{-4}$	0.402 $\times 10^{-8}$	0
Copper	0	625	0.167 $\times 10^{-4}$	0.403 $\times 10^{-8}$	0
Glass, Jena	0	100	0.077 $\times 10^{-4}$	0.350 $\times 10^{-8}$	0
Glass, French	2	100	0.072 $\times 10^{-4}$	0.544 $\times 10^{-8}$	0
Gold	9	95	0.136 $\times 10^{-4}$	1.12 $\times 10^{-8}$	0
German silver	0	100	0.184 $\times 10^{-4}$	.....	
Ice	−27	−2	0.514 $\times 10^{-4}$	.....	
Iron, cast	0	625	0.098 $\times 10^{-4}$	0.566 $\times 10^{-8}$	0
Iron, wrought	0	500	0.117 $\times 10^{-4}$	0.525 $\times 10^{-8}$	0
Lead	14	94	0.273 $\times 10^{-4}$	0.74 $\times 10^{-8}$	0
Marble; white	15	100	0.117 $\times 10^{-4}$	.....	
Mica, parallel to cleavage	5	80	0.077 $\times 10^{-4}$	1.200 $\times 10^{-8}$	0
Mica, perpendicular to cleavage	4	82	0.076 $\times 10^{-4}$	0.490 $\times 10^{-8}$	0
Nickel	0	1000	0.135 $\times 10^{-4}$	0.332 $\times 10^{-8}$	0
Nickel steel (24% Ni)	0	38	0.175 $\times 10^{-4}$	0.711 $\times 10^{-8}$	0
Phosphor bronze (97.6 Cu +2.2 Sn+0.2 P)	0	80	0.167 $\times 10^{-4}$	0.462 $\times 10^{-8}$	0
Platinum	0	1000	0.0887 $\times 10^{-4}$	0.1324 $\times 10^{-8}$	0
Porcelain, Berlin	20	100	0.027 $\times 10^{-4}$	0.306 $\times 10^{-8}$	0
Porcelain, Bayeux	0	600	0.034 $\times 10^{-4}$	0.107 $\times 10^{-8}$	0
Rubber, hard	17	25	0.77 $\times 10^{-4}$	.....	
Rubber, hard	25	35	0.84 $\times 10^{-4}$	.....	
Silver	0	750	0.1827 $\times 10^{-4}$	0.4793 $\times 10^{-8}$	0
Steel	0	300	0.092 $\times 10^{-4}$	0.336 $\times 10^{-8}$	0
Tin	8	95	0.203 $\times 10^{-4}$	2.63 $\times 10^{-8}$	0
Vulcanite	0	18	0.636 $\times 10^{-4}$	.....	
Zinc	9	96	0.274 $\times 10^{-4}$	2.34 $\times 10^{-8}$	0

* When the temperature is expressed in Fahrenheit degrees, the formulas l

$$l = l_{32}\left[1 + \frac{a(t_f - 32)}{1.8} + \frac{b\,(t_f - 32)^2}{3.24}\right],$$

$$a_{32} = \frac{a_{20}}{1.8},$$

where a, b and a_{20} have the values given in the above table.

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l at t degrees, and a_0 is the mean coefficient of linear
., then $l_1 = l_0(1 + a_0 t_1)$ and $l = l_0(1 + a_0 t)$, whence

$$l = l_1[1 + a_1(t - t_1)],$$

$$a_1 = a_0/(1 + a_0 t_1).$$

t_1 is appreciable compared with unity then a_1 is not

of Linear Expansion. — The "true" coefficient of
mperature t is defined as the *rate* of increase of length
ure divided by the length at this temperature t, or

$$a = \frac{1}{l} \cdot \frac{dl}{dt}.$$

any temperature depends on the temperature.

l Expansion of Liquids and Solids. — The volume
quids and solids may be expressed in exactly the same
nsion, viz.,

$$= V_0(1 + \alpha t + \beta t^2 + \ldots)$$

$$V = V_0(1 + \alpha t),$$

any temperature t is defined as

$$\alpha_t = \frac{1}{V}\frac{dV}{dt},$$

olumes at t degrees and at the reference temperature

on, when the coefficient of linear expansion is small
not excessive, the volume coefficient may be taken
coefficient.
nts, determined from direct experiment, are given in
article on *Weights of Materials*.

EFFICIENTS OF CUBICAL EXPANSION

$V_0(1 + \alpha t + \beta t^2)$, temperatures in ° C.
true" coefficient at 20° C.
Landolt-Börnstein's Tables, 1912 edition.)

Temp., ° C.		α	β	α_{20}
From	To			
0	75	6.62×10^{-4}	24.2×10^{-8}	6.80×10^{-4}
0	40	4.96×10^{-4}	496×10^{-8}	6.94×10^{-4}
0	33	5.84×10^{-4}	99.2×10^{-8}	5.88×10^{-4}
24	120	8.99×10^{-4}	140×10^{-8}	9.55×10^{-4}
10	57	10.7×10^{-4}	-5580×10^{-8}	3.06×10^{-4}

C.):
$5553 \times 10^{-4} t + 1.2444 \times 10^{-6} \beta + 2.539 \times 10^{-21} \beta^6$)

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FLASH POINT OF OILS.—The flash point of an oil is the temp which the oil must be raised before the vapor immediately above it fire upon the application of a flame. This temperature depends to a able extent upon the size of the flame, the method of applying it, and and dimensions of the containing vessel; see *Oil, Transformer*. T ing values of the flash point for various oils are taken from J. Lew *Chemical Technology and Analysis of Oils, Fats and Waxes*.

TABLE XI. — FLASH POINT OF OILS

Oils	Spec. grav. at 60° F.	Flash °
Mineral oils:		
Refined American	0.875 to 0.920	325
Refined Russian	0.895 to 0.915	300
Scotch	0.875 to 0.895	300
Natural (dark) American	0.880 to 0.895	325
Natural (dark) Russian	0.910 to 0.915	250
Natural filtered American	0.885 to 0.905	450
Animal oils:		
Sperm	0.8804 to 0.8807	446
Lard	0.9172	
Tallow	0.951	
Neat's foot	0.9178	
White whale	0.9207	
Vegetable oils:		
Castor	0.963	
Linseed	0.930	
Olive	0.914	
Rape, crude	0.920	
Rape, refined	0.911	

HEATS OF FORMATION, COMBUSTION AND SOLU

When two or more substances react chemically heat is generally eit out or absorbed. When heat is given out the reaction is called "ex and when heat is absorbed the reaction is called "endothermic." T ing tables give the heats of reaction for some of the more important processes; see *Landolt-Börnstein's Tables* for more complete tables. sign indicates an endothermic reaction; i.e., an absorption of heat. values are given these refer to independent measurements.

The values given are the total amounts of heat in kilogram-calories or absorbed per mol (*see Electrochemistry, Principles of*) of the produc with the proportions of the reacting substances represented by the member of the reaction equation, the temperature at the beginning end of the reaction being the same, i.e., room temperature. For exam ing with 1 gram-atom of oxygen (16 kilograms, say) and 1 gram-atom (40.07 kilograms) both at room temperature, then the net amount of out in the formation of one mole (16 + 40.07 − 56.07 kilograms) oxide when its temperature is brought back to room temperature is gram-calories or 2.33 kilogram-calories per kilogram of calcium oxide.

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OF FORMATION OF IMPORTANT COMPOUNDS

m temperature unless otherwise stated.)

Equation	Kilogram-Calories* evolved per mol of product
$2C+2H=C_2H_2$	−47.8 to −58.1
$2Al+3O+3H_2O=2Al(OH)_3$	194.5 to 196.5
$Al+3O+3H=Al(OH)_3$	297.0
$2Al+3O=Al_2O_3$	380.2
$N+3H=NH_3$	11.9 to 12.2
$BaO+O=BaO_2$	18.4
$Ba+2O=BaO_2$	145.5
$Ba+2O+2H=Ba(OH)_2$	217.0
$Ba+O=BaO$	133.4 to 126.4
$Ca+2C=CaC_2$	−7.25
$Ca+O=CaO$	145.0 to 151.9
C amorphous $+2O=CO_2$	96.96-97.65
C graphite $+2O=CO_2$	94.8
C amorphous $+O=CO$	29.0
$Cu+2Cl=CuCl_2$	51.63- 51.4
$Cu+S+4O=CuSO_4$	182.6
$Cu+O=CuO$	37.2
$2Cu+O=Cu_2O$	40.8 -43.8
$2Fe+3O+3H_2O=2Fe(OH)_3$	95.6
$2Fe+3O=Fe_2O_3$ (dried at 400°)	65.2
$2Fe+3O=Fe_2O_3$ (heated to 1000°)	64.8
$Fe+2Cl=FeCl_2$	82.2
$Fe+O+H_2O=Fe(OH)_2$	68.3
$Fe+O=FeO$	65.7
$Fe + S + 4O + 7H_2O = FeSO_4 \cdot 7H_2O$	240.1
$PbO+O=PbO_2$	12.6
$Pb+O=PbO$	50.3
$Pb+S+4O=PbSO_4$	216.2
$Mg+2Cl=MgCl_2$	151.0
$Mg+2O+2H=Mg(OH)_2$	217.5
$Mg+O=MgO$	143.3
$Ni+2Cl=NiCl_2$	74.5
$Ni+O+H_2O=Ni(OH)_2$	60.8
$Ni+O=NiO$	57.9
$Ni + S + 4O + 7H_2O = NiSO_4 \cdot 7H_2O$	233.6
$N+O=NO$	−21.6
$N+H+3O=HNO_3$ liquid	41.5
$N+H+3O=HNO_3$ dissolved	49.1

-cal. = 3.968 B.t.u. = 4183 watt-seconds (joules) = 1.162 ×

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TABLE XII. — HEATS OF FORMATION OF IMPORTANT COMPOUNDS — *Continued*

(*At room temperature unless otherwise stated.*)

Product	Equation	Kilo Calo ev per pro
Nitrogen dioxide	$N+2O=NO_2$ at 22° C.	—
" "	$N+2O=NO_2$ at 200°	—
Ozone	$1\frac{1}{2}O_2=O_3$	−3
Potassium chlorate	$K+Cl+3O=KClO_3$	95.8−
" chloride	$K+Cl=KCl$	10
" hydroxide	$K_2O+H_2O+Aq.=2\,KOH$ (Aq.)	6
" "	$K+O+H=KOH$	103.2 t
" hypochlorite	$K+Cl+O+Aq.=KClO$ (Aq.)	89.4 t
" oxide	$2K+O=K_2O$	9
" perchlorate	$K+Cl+4O=KClO_4$	11
Silver nitrate	$Ag+N+3O=AgNO_3$	2
" oxide	$2Ag+O=Ag_2O$	5.9−
Sodium chlorate	$Na+Cl+3O=NaClO_3$	86.7 t
" chloride	$Na+Cl=NaCl$	9
" hydroxide	$Na_2O+H_2O+Aq.=2\,NaOH$ (Aq.)	63.9 t
" "	$Na+O+H=NaOH$	101.9 t
" hypochlorite	$Na+Cl+O+Aq.=NaClO$ (Aq.)	83.4 t
" oxide	$2\,Na+O=Na_2O$	100.3 t
" perchlorate	$Na+Cl+4\,O=NaClO_4$	10
Sulphuric acid	$S+4\,O+2\,H=H_2SO_4$ liquid	19
Sulphurous oxide	S solid $+2O=SO_2$ (gas)	7
" "	S solid $+2\,O=SO_2$ (dissolved)	7
Tin (stannous) chloride	$Sn+2\,Cl=SnCl_2$	8
" " oxide	$Sn+O=SnO$	67.6 t
Water	2 H gas $+O$ gas $=H_2O$ at 18° C.	6
"	2 H gas $+O$ gas $=H_2O$ at 0° C.	68.25
Zinc chloride and H	$Zn+2\,HCl(aq.)=ZnCl_2(aq.)+H_2$	3
" oxide	$Zn+O=ZnO$	85.0 t
" sulphate	$Zn+S+4\,O=ZnSO_4$	231.1 t

* 1 Kg-cal. = 1000 gram-cal. = 3.968 B.t.u. = 4183 watt-seconds (joules) = 10^{-3} kw.-hr.

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OF COMBUSTION (COMPLETE) OF SOME
NT INORGANIC SUBSTANCES*

erature 18° C. and constant pressure.)

	Formula	Heat of combustion in kilogram-calories per mol
.....	CH_4	213.5
.....	C_2H_2	315.7
.....	CH_3OH	170.7
.....	C_2H_5OH	326.1
.....	$C_3H_5N_3O_9$	361.2
.....	$CH_3-CO-CH_3$	427.3

* See also article on *Fuels*.

XIV. — HEATS OF SOLUTION

ure; anhydrous salts unless otherwise noted.)

	Formula	Mols of water per mol of compound dissolved	Kilogram-calories evolved per mol of compound dissolved
.....	$CuCl_2$	600	11.1
.....	$CuSO_4$	400	15.8
.....	$CuSO_4 \cdot 5\,H_2O$	400	−2.75
.....	$FeCl_2$	350	17.9
).....	$FeSO_4 \cdot 7\,H_2O$	400	−4.5
.....	$MgCl_2$	800	35.9
.....	$NiCl_2$	400	19.2
.....	$NiCl_2 \cdot 6\,H_2O$	400	−1.16
.....	$NiSO_4 \cdot 7\,H_2O$	800	−4.25
.....	KCl	200	−4.4
.....	$KClO_3$	400	−10.02
.....	$KClO_4$	200–400	−12.1
.....	NaCl	100	−1.03
.....	$NaClO_3$	180–360	−5.6
.....	$NaClO_4$	200–400	−3.5
.....	$AgNO_3$	200	−5.44
.....	$ZnCl_2$	300	15.6
.....	$ZnSO_4$	400	18.4
.....	$ZnSO_4 \cdot 7\,H_2O$	400	−4.26

See references in text.

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HEATING OF BUILDINGS. — (*See also Railways, Energy Requ for.*) The problem of determining the amount of heat necessary to ma room at a given temperature above the out-door temperature resolves it the determination of the amount of heat transmitted through the walls and floor; and the amount of heat necessary to raise the incoming ve air to the temperature of the air in the room.

HEAT REQUIRED TO WARM INCOMING AIR.— When t is occupied by a number of people, the quantity of ventilating air re often calculated on the basis of 1800 cu. ft. per person per hour. If th is greater than that which leaks in through the cracks at doors, windo forced ventilation should be employed. 1/50 B.t.u. is required to heat 1 air 1° F.

Let

t = temperature of incoming air, ° F.,
T = temperature of room, ° F.,
Q = cubic feet of air per hour leaving room at room temperature

Then the B.t.u. per hour required to heat this air to room temperatur is also the amount of heat carried off by this air, is

$$H_v = \frac{Q(T - t)}{56}$$

Infiltration of Air. — The heat required to warm the air which through cracks at windows and doors may be determined either by fin volume of air Q which enters in this manner and applying equation (1) heat required may be expressed directly in terms of the size and le cracks. Following the first method Carpenter proceeds as follows: Let

C = cubical contents of room in cubic feet,
N = number of air changes per hour,

then

$$Q = NC$$

where, for well constructed buildings, N has the values given in the f table.

Kind of room	N
Halls	3
Rooms on first floor	2
Rooms on second floor	1
Offices and stores, first floor	2 to 3
Offices and stores, second floor	1.5 to 2
Churches and public assembly rooms	0.75 to 2
Large rooms with small exposure	0.5 to 1

By far the greater portion of the infiltration is due to loose-fitting sash actual sash clearance determines the infiltration loss in any given ca the general run of well constructed buildings this clearance should not 1/32" while for poor construction the clearance may be as much as 1/16" heat loss by infiltration may be approximately determined by the use following values:

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clearance . 1.2 B.t.u. per hr. per ft. of crack per ° F.
clearance . 2.4 B.t.u. per hr. per ft. of crack per ° F.
. . . . . 0.15 B.t.u. per hr. per ft. of crack per ° F.

y this method is determined by the total lineal existing in the one outside wall having the greatest rface, and not upon the total number of feet of outside walls.

D DIRECTLY THROUGH WALLS, CEIL-

is heat may be conveniently referred to as the ough it is of course conducted through the walls ried off both by radiation and convection. Let

quare feet,
outside air,
nside air,
r square foot of radiating surface (wall, window,
° F. difference in temperature.
ation is

$$H_T = \Sigma KS(T - t),$$

es all the radiating surfaces. Certain additions of H_T as thus calculated to allow for the nature

he total heat lost by radiation may be made by face, $K = 1$ for all window surfaces and neglect- r's rule).

o use the proper value of K for each kind of wall ly the most accurate values of K are those given o take into account not only the nature of the made, but also the nature of both the inside and l the wind velocity of the outside air at the wall. re and having a thickness of x inches, Harding ue

$$K = \frac{1}{\frac{1}{K_1} + \frac{1}{K_2} + \frac{x}{C}}, \qquad (3)$$

d C $\left(\text{or } \frac{x}{C}\right)$ are given in the following tables.

al plates, building paper or glass is so small that e calculations. If the wall is composed of several contact with one another (no air spaces) then

$$\frac{1}{\frac{1}{K_1} + \frac{1}{K_2} + \left(\frac{x_1}{C_1} + \frac{x_2}{C_2} + \frac{x_3}{C_3} + \text{etc.}\right)}, \qquad (4)$$

the thickness of the various materials in inches, onding values of C.

S OF K_1 FOR STILL AIR

5 to 1.40	Glass Window	1.50
1.30	Sheet Asbestos	1.40
1.25	Magnesia Board	1.45
0.93	Wood (finished surface)	1.40

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The average value of K_1 from above data is 1.34.

The value of K_2 increases with the velocity of air over the surfa value of K_2, for brickwork and wood, for various velocities of air or wi ment may be obtained by multiplying the values of K_1 from the ab by the following factors:

Velocity, miles per hour	Multipliers of K_1	
	Brickwork	Wood
5	2.38	2.19
10	3.20	2.71
15	3.76	2.95
20	4.22	3.02

In practice the exposed walls of a building are not subjected to a wind movement of more than 15 miles per hour in extremely cold wea

VALUES OF C AND $\frac{x}{C}$

Material	Condition	Weight pounds per sq. in.	C	$\frac{x}{C}$
Asbestos board, corrugated	Dry	20.4	0.48	....
Asbestos sheet	Dry	48.3	0.29	....
Brickwork	Dry	132	4.00	....
Brickwork	Moist	.....	5.00	....
Brickwork	.....	.....	3.42	....
Concrete, cinder, 1 : 2 : 4	.....	.....	2.35	....
Concrete, stone, 1 : 2 : 4	Dry	140	8.30	....
Concrete, stone, 1 : 2 : 4	.....	.....	6.25	....
Cork, granulated	Packed	6.25	0.35	....
Cork, board	Dry	9.7	0.32	....
Glass 0.085 in. thick	.....	.....	....	24.3
Hollow tile, 2-inch	Note (*a*)	.....	....	0.99
Hollow tile, 4-inch	Note (*b*)	.....	....	0.61
Hollow tile, 6-inch	Note (*a*)	.....	....	0.47
Magnesia board	Dry	13.5	0.51	....
Mineral wool	Packed	16.3	0.35	....
Mortar	.....	.....	8.00	....
Sandstone	.....	.....	9.00	....
Window, 76.3 per cent glass	.....	.....	....	8.64
Window, double	½-in. air	.....	....	1.04
Wood (fir)	Dry	33.4	1.00	....

* Authorities: (1) Harding and Willard; (2) Norton; (3) Poensge

NOTES —(*a*) Plastered both sides; (*b*) Plastered both sides with r pared gravel roofing applied to one side only.

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Air at Ceiling. — It is recommended that an
er cent be made to the specified inside temperature
eiling for ceiling or wall heights not exceeding 15
ling heights of 20 feet or more in estimating the
5° is the specified inside temperature to be main-
of which is 20 feet, the temperature of the air in
of the roof may be assumed as 65° + 30 per cent

ompensate for other than southern exposures, the
ary factors, by which the calaulated heat trans-
be multiplied, are quire commonly used:

northwest exposure where winds
on as an important factor..... = 1.15 to 1.30
derately exposed..... = 1.10 to 1.20

RED. — If there are no sources of heat already
er of B.t.u. which must be supplied per hour by

$$H = H_0 + H_r,$$

values given above, H_r including the allowances
re a number of people in the room, or a number
y (as in a power house or substation) the additional
e heat given off by the people or apparatus is

$$H = H_m,$$

out by the people and apparatus, and is calculated

PERSONS, LIGHTS, MOTORS, MACHIN-
est gives off about 400 B.t.u. per hour., and at
hour. This quantity of heat is not of sufficient
account except in assembly halls and theaters.
ed by the electric lamps in a room is equal to
ts per lamp) × (number of lamps)
ps may be calculated from the following data:

..... 150 B.t.u.
as..... 700 B.t.u.
..... 1000 B.t.u.

es 3 cu. ft. of gas per hour and a fish tail burner 5

— Motors and the machinery which they drive,
n, convert all of the electrical energy supplied into
e room if the product being manufactured is not
the same as the room temperature. In this case

$$\text{r hour} = 2550 \left(\frac{\text{H.P. Output to Motor}}{\text{Efficiency of Motor}} \right).$$

the machinery from the outside, then only the
horsepower supplied is used, in which case

r hour = 2550 × (Brake Horse-power).

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In high-powered mills the heat given out by the machinery is the ch of heating and is frequently sufficient to overheat the building eve weather, thus requiring cooling by ventilation the year round.

In a transformer substation, or other room from which electric transmitted, the heat supplied by the electric apparatus is of course losses in the apparatus. Note that a loss of 1 kw. is equivalent to 34 per hour.

HEATING APPARATUS. — For dwellings, shops, etc., hot-air, or steam-heating systems are usually employed; for large buildings two only. In substations or power houses (e.g., a hydro-electric static the heat losses are not sufficient to provide enough heat, either steam heaters are used.

Harding and Willard give the following values of K (= B.t.u. rad square foot per hour per ° F. difference in temperature between st room air) for direct steam radiators. These values of K were determi tests on such radiators standing exposed in air at 70° with steam at a standard temperature difference of 150°.

VALUES OF K FOR DIRECT RADIATORS

Type Radiator	Height of Radiators		
	20 and 22 ins.	26 ins.	32 ins.
1 column	1.95	1.90	1.85
2 column	1.80	1.75	1.70
3 column	1.70	1.65	1.60
4 column	1.60	1.55	1.50
Flue, 42 square feet	....	....	....
Window	1.85	....	....
Pipe coils	2.00	....	....
Wall (horizontal)	1.95	....	....
Wall (vertical)	1.90	....	....

* Air entering flues at 70 and leaving same at 152°. (Allen.)

K increases (1) as height of radiator is reduced and (2) as numbe umns or width of radiator decreases. The variation in the value of K is mately 0.2 per cent per degree F. above or below the standard range of Thus if a 3-column, 38-in. high, direct radiator is to be used in a room 60° with steam at 230° we would have a temperature difference of 170 above standard, and the value of K would become $(1.55 + 0.002 \times 20$ $= 1.61$, and each square foot of radiation would give off 1.61×17 B.t.u. per hour.

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HEATING AND COOKING BY ELECTRICITY. — (*See also Heat and Thermal Properties; Insulating Materials; Resistance and Conductance; Wires, Resistance.*) Electricity may be used to generate heat for any heating or cooking operation that can be performed with any other source of heat. The readiness with which the heat can be applied to exactly the place needed, and in exactly the quantities needed, usually gives results so far superior to those obtained with other heating agents, that the increase in the cost of the heat is often overbalanced by the increased benefits obtained in other directions.

DESIGN OF HEATING UNIT. — Let R be the resistance of the unit in ohms, and I the current, in amperes. Then the rate at which heat is developed in the unit is

$$P = 3.413\, R\, I^2 \quad \text{B.t.u. per hour.} \qquad (1)$$

Let ρ = resistivity of the wire of which the device is made, in ohms per mil-foot, l = length of wire in feet, and s = cross-section of wire in circular mils. Then

$$R = \rho \frac{l}{s}. \qquad (2)$$

Values of ρ for some of the metals commonly used in heating units are given in Table I (*see also article on Wires, Resistance*).

Temperature Elevation for Given Power Input. — When a given heating device reaches a constant temperature, the rate at which heat is carried off

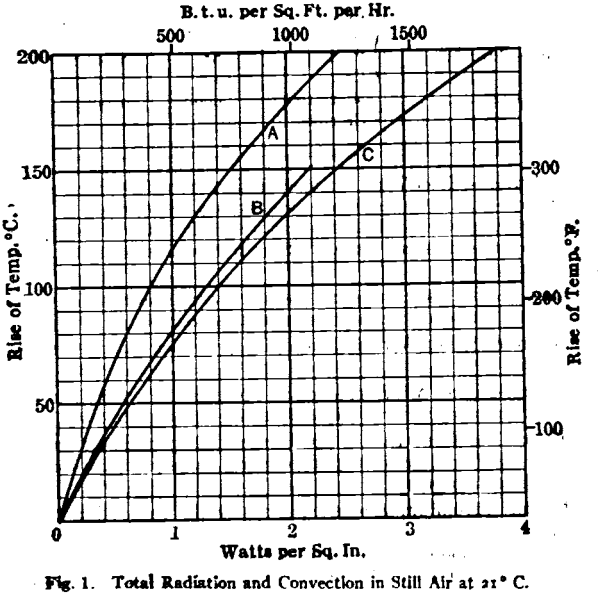


Fig. 1. Total Radiation and Convection in Still Air at 21° C.
A = Dull Nickel: *B* = Rough Black Body; *C* = 2.3 In. W.I. Pipe.

from its surface by radiation and convection (assuming the heat lost by thermal conduction is negligible) is equal to the rate at which heat is developed in the

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device. The rate at which heat is lost by radiation and convection both upon the extent and the nature of the surface and upon the difference perature between this surface and the surrounding air; see Fig. 1 and article on *Heat and Thermal Properties*.

Resistance Materials. — Metallic resistance materials are usua either in the form of rod, wire or ribbon, although cast shapes may be em The material chosen depends upon the temperature, the operating con space available and first cost. The following table contains some of the materials used.

TABLE I.—DATA ON RESISTANCE MATERIALS

Material	Chemical composition (approx.) per cent	ρ Spec. Res. ohms per cir-mil-ft.	Temp. coefficient per deg. F.
Pure nickel	.....	69	0.0039
Iron wire	.....	69	0.00625
30 per cent German silver	.....	280	...
Copper-nickel	Ni 60 to 70 Cu 40 to 30	280	0.000004
30 per cent nickel steel	Ni 70 Fe 30	500	0.0007
Nickel-iron-chrome	Ni 60 Fe 28 Cr 12	650	0.00020
Nickel-chrome	Ni 80 to 84 Cr 20 to 16	600	0.00006

Galvanized Iron Wire is a useful resistance material for electric applications in which the resistance element may be operated at a ve temperature and in which a large temperature coefficient is not a disadv It is sometimes used for air heaters. Plain iron wire is not suitable as rust too readily.

Cast Iron is useful in special cases of lower temperatures, parti where a heater with considerable mass in itself is desirable.

German Silver Wire is limited in application due to the da crystallization.

Copper-Nickel Alloys produce wire of great uniformity and fle capable of standing up under continuous heating at moderate temperatur

Thirty Per Cent Nickel Steel has a high specific heat and fai temperature coefficient, but is subject to rusting unless protected from m and from the atmosphere.

Nickel Chromium Alloys are probably the best resistance ma now available for electric heaters. The cheaper grades such as Chromel Nichrome, and Calido contain approximately 25 per cent iron, and this their resistance to oxidation as compared to the better grades, such as Kr Chromel "A," and Rayo, containing practically no other materials than and chromium.

Nickel-Chromium alloys are covered with a coat of oxide that p the material from further oxidation. This oxide does not scale off on re

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TABLE II.—NICKEL-CHROMIUM ALLOYS

B. & S. gauge	Diam. inches	Area, circular mils	Feet per pound	Resistance (75° F.) ohms per ft.	
				Nickel-iron chromium alloy	Nickel-chromium alloy
4	0.204	41,616	8.6	0.0157	0.0151
5	0.182	33,124	10.8	0.0198	0.0190
6	0.162	26,244	13.6	0.0250	0.0240
7	0.144	20,736	17.2	0.0316	0.0304
8	0.128	16,384	21.8	0.0400	0.0384
9	0.114	12,996	27.4	0.0504	0.0485
10	0.102	10,404	34.2	0.0630	0.0605
11	0.091	8,281	43.0	0.0791	0.0760
12	0.081	6,561	54.3	0.1000	0.0961
13	0.072	5,184	68.7	0.1263	0.1215
14	0.064	4,096	87.0	0.160	0.154
15	0.057	3,249	110	0.202	0.194
16	0.051	2,601	137	0.252	0.242
17	0.045	2,025	176	0.324	0.312
18	0.040	1,600	222	0.409	0.394
19	0.036	1,296	275	0.505	0.486
20	0.032	1,024	348	0.640	0.605
21	0.0285	812	439	0.800	0.765
22	0.0253	640	557	1.01	0.970
23	0.0226	510	699	1.27	1.215
24	0.0201	404	884	1.61	1.53
25	0.0179	320	1,110	2.03	1.90
26	0.0159	252	1,410	2.57	2.41
27	0.0142	201	1,770	3.78	3.03
28	0.0126	158	2,250	4.03	3.85
29	0.0113	127	2,700	5.02	4.77
30	0.0100	100	3,500	6.40	6.10
31	0.0089	79	4,500	8.09	7.70
32	0.0080	64	5,570	9.98	9.52
33	0.0071	50	7,070	12.7	12.06
34	0.0063	39	8,990	16.1	15.4
35	0.0056	31	11,380	20.4	19.5
36	0.0050	25	14,250	25.6	24.4
37	0.0045	20	17,600	31.6	30.1
38	0.0040	16	22,300	40.0	38.2
39	0.0035	12	29,100	52.2	49.8
40	0.0030	9	39,600	71.2	67.8

heating and cooling. The resistance of various grades and sizes is shown Table II.

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Insulating Materials. — Insulating material must be chosen with to the use to which it is to be put.

Mica is one of the best electrical insulators for heating purposes. must be exercised, however, in elements in which the resistor is to exceed 5 because of the effect of the heat in the mica. Mica, being a crystalline ma will dehydrate if heated to the proper temperature. Some grades of mica to dehydrate near 500° C., while others will stand up to 1000° C. dehydration, the electrical resistance of mica is reduced to such a low that it becomes a good conductor. Furthermore, the dehydrated mica its mechanical strength. During the process of dehydration water va given off which will attack the resistance material.

Mica is used in the form of solid plates of natural mica, and also in th of built-up plates, using small pieces of natural mica and binding them to with a suitable bond. Since natural mica can be obtained in quantitie in small sizes, any support or insulator larger than a few inches in either tion must be made of built-up mica.

The bonds for built-up mica are of two classes, volatile and non-volatile. tile bonds require heating to drive them out before the element is ready f Non-volatile bonds do not bake out and are to be preferred because they require this operation, and also because the small pieces of mica are held to more securely. The bond should be of such material as not to attack the ance material at the working temperature.

Porcelain possesses high electrical resistance, but only certain are suitable for high temperature uses, because of the danger of cracking undergoing the wide variations in temperature encountered. The insulato be designed with care to avoid such cracking, even with the best of materi

"Lava" is an excellent material but is much more expensive tha celain.

Asbestos is quite hygroscopic, which interferes with its use in h appliances, except in special cases. It is also incapable of withstandin temperatures.

Asbestos Lumber and Other Moulded Compositions cont asbestos and other fibers have various special uses, but none are suital high temperatures.

HOUSEHOLD APPLIANCES. — The following is a partial list usual household appliances and the energy required for each.

3-lb. flat-iron	250 to 300
6-lb. flat-iron	550
9-lb. flat-iron	635
Toaster	450 to 550
Table stoves	500 to 600
Table grills	600
Percolators	350 to 400
Waffle irons	600
Water cup	300 to 500
Reflector radiator	600
Warming pad	25 to 50
Hair curler	15 to 20
Immersion water heater	300 to 500
Ranges	5000 to 8000

Electric Flat-iron. — The heating element is usually of flat nicke chromium ribbon approximately 1/16 inch wide by 0.005 inch thick. Th

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for this ribbon is a flat plate of mica which is similar in shape to the bottom of the iron. The insulating plates are of mica also and are slightly larger than the ribbon form or support. The resistance ribbon is wound so as to distribute the heat over the ironing surface as desired. The usual ground test for this type of devices is 900 volts A.C. cold and 500 volts A.C. at working temperature. In elements of this type of construction the heat density of the ribbon is approximately 30 watts per square inch of total surface of the ribbon. The density of the heat distributed over the bottom area of the iron averages approximately 15 watts per square inch.

The usual working temperature of the bottom surface of a flat-iron is about 225° C. (437° F.) while the temperature of the element is about 350° C. (662° F.). If the iron is not used and the current left turned on, the temperature will rise until the heat radiated equals the input. This will occur when the bottom surface is near 600° C. (1112° F.), at which time the element will be near 700° C. (1292° F.).

Toasters. — Toasters of the vertical type usually have vertical heaters, similar in principle of construction to flat-iron heaters, except that the wire is exposed to radiate freely upon the bread.

Household Ranges. — Electric ranges are made in a variety of shapes and sizes to suit the various needs of the users. A range consists of one or more ovens and one or more open hot plates or burners. The type most generally used is the "Cabinet" type, having the oven on the same level as the top burners, and located at either end of the range. Other types have the oven beneath the open burners, and others the oven elevated above them corresponding to similar types of gas ranges.

Ovens are insulated with an insulating material such as mineral wool or air cell asbestos to prevent heat loss. They are equipped with one or two heaters according to the design. The maximum input per cubic inch varies from 0.40 to 0.70 watt per cubic inch for the ordinary sizes. Oven heaters are either of the open coil, enclosed coil, or sheathed wire construction.

Top burners for open cooking are from 6 to 12 inches in diameter, averaging about 8 inches. These burners operate at from 20 to 30 watts per square inch of upper surface. They are of various types, such as open coils supported in grooves in a porcelain disc, coils enclosed in a circular casting and insulated with mica or porcelain, or cast-in type of enclosed element.

The total capacity of the usual range is from 5000 to 8000 watts depending on the size of the oven and number of open burners.

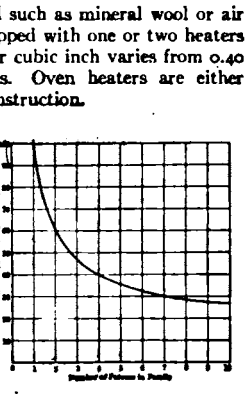


Fig. 2.

The Cost of Cooking depends on the number of persons in the family, the kind of meals served, the skill of the user, and the rate for current. The curve in Fig. 2 gives an idea of the power requirements for electric ranges under average conditions. This does not include the power required for lights, extra appliances, water heating, etc.

INDUSTRIAL APPLIANCES. — Electrically heated appliances have been developed for a very large number of uses. The following list contains only a few of the more common devices.

Tailor's Pressing Irons	Glue Pots
Solder Pots	Sealing Wax Heaters

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Soldering Irons	Hot Tables
Branding Irons	Press Blocks
Hatter's Irons	Chocolate Warmers
Velouring Stoves	

Usually the cost of the energy to operate such devices is immaterial in of the great advantage gained in speed, convenience, safety, and unifo of operation.

INDUSTRIAL APPLICATION UNITS. — These are small heater complete in themselves with supports and terminals which have been des to meet a wide variety of applications of heat to machines and applian which heated surfaces or spaces are essential to their successful oper Usually the application involves only minor changes in the construction machine to accommodate the electric units. Terminals are provided for r connecting up the units.

Such units are usually provided in standard voltages of 110 and 220 although the larger units for ovens are suitable for operation in series 550 volts. Some of the types and applications of these units are descrit the following paragraphs.

Cartridge Heaters. — A tubular unit having terminals at one or both and designed to be inserted in holes drilled in castings which require he such as embossing presses, hot moulding presses, shoe machinery iron machine irons, etc., is called a cartridge heater. Nickel chrome resis material is used for the heater and is wound on a central core of porcel lava and insulated from the outer tube of brass by cement or mica. Car heaters may be used in applications up to 300° C.

G. E. CARTRIDGE TYPE UNITS

Symbol No.	Length in inches	Diameter in inches	Watts
142	2.39	0.498	100
151	2.51	0.748	200
102	3.9	0.933	250
9	4.87	0.933	70
11	4.87	0.933	140
48	4.87	0.933	440
63	5.	1.291	300
103	5.	1.291	600
104	5.	1.291	900
162	8.5	1.291	1000

Steel-clad Heaters. — This is a flat type of element consisting of a form on which a resistance element is wound, insulated with flat plates of and enclosed in a casing of sheet steel pressed flat on the element. Tern are usually located at one end .

This unit is made in a wide variety of sizes and is suitable for hot-press he hot tables, heating rolls, small ovens, etc., in which the uniform distrib of heat is desired. A few of the standard sizes available are given listed i following table.

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WESTINGHOUSE STEEL-CLAD HEATERS

Length of heater, inches	Width, inches	Thickness, inches	Watts	Volts
10	2¼	5/16	350	55
12	2¼	5/16	500	110
15	2¼	5/16	650	110
21	2¼	5/16	1000	110
12	1⅛	⅛	175	110
24	1⅛	⅛	350	110

Space Heaters. — These are similar to the steel-clad heaters, except that one terminal is located at each end. The 24-inch length is a standard size and is suitable for a wide variety of applications, of which the following is a partial list. The unit is 1¼ inches wide, 5/16 inch thick, and is supplied in two designs, one for 110 volts and the other for 220 volts, the rating being 500 watts in either case.

Small Industrial Ovens
Blue-print Driers
Hoist Cabs
Ticket Booths
Watchmens' Houses
Elevator Cabs
Laundry Driers

Industrial Oven Heaters. — These heaters are designed for the larger sizes of industrial ovens. They are of nickel-chromium ribbon wound over porcelain bushings and assembled into a metal frame. Exposed heating ribbon is used to give free radiation into the oven space. The heating is done partly by radiation and partly by convection. Terminals are provided at the ends for connections. Units are usually made up for 110-volt and 220-volt service. Two 220-volt units may be connected in series for 440 volts. Complete sets of suitable connection straps and insulators are provided to accompany the heaters.

INDUSTRIAL ELECTRIC OVENS. — Electric heat has been applied to ovens for japanning, lithographing, paint drying, lacquer dyeing, core baking, armature baking and many other purposes requiring temperatures up to 600° F. The absence of fumes and gases, reduction in fire hazard, ease of control, and increased production have in many cases justified even increased costs of heat. Ovens are of the usual kiln type, the semi-continuous type, or the continuous type.

A Kiln-type Oven is usually rectangular in shape with a door at one end into which the material to be baked is loaded. When the oven has been loaded, the door is closed and current turned on. When the baking has been completed, the current is turned off, door opened and work removed.

A Semi-continuous Oven has doors at both ends and a new load is pushed in at one end while the finished load is removed from the other end.

In a Continuous Oven the work is carried through the oven on a continuous conveyor loading at one end and discharging at the other at a uniform speed.

Heaters are installed along the side walls or on the floor. A space of 8 to 10 inches from the wall or floor should be provided. Over the heaters a screen of expanded metal or wire mesh can be installed to prevent work dropping on the heaters and connections.

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Control is usually by magnetic switches. Door switches are sometime vided so that when the doors are opened the main switches also open. A mostat is usually used to regulate the temperature by turning the current off as may be needed. This thermostat operates through a relay to c the main magnetic switches.

110, 220, or 440 volts of any frequency and either single phase, two or three phase can be used. Direct current up to 550 volts can be used a

Heat Required for Industrial Oven. — In calculating the heat re ments, the following losses and uses of the heat must be carefully determ

Heat to Raise the Temperature of the Work, Including Truc The total weight of the material to be baked, the initial and final tempera and the specific heat must be known. Dividing the heat required by th gives the heat per hour needed. The japan or paint can be ignored. Th required to heat the trucks or hangers is calculated in the same way for eac

Heat to Raise the Temperature of Oven Walls. — The insu material in an oven wall absorbs heat in the period of heating up even t it be fairly good heat insulator. The usual method is to average the tem tures of the inner and outer surfaces, and subtract the initial temperat obtain the average temperature rise. This is multiplied by the weigh specific heat to obtain the total heat required. Dividing this by th allowed for the heating operation gives the rate at which heat must be su

The interior framework and oven lining of metal are heated on the a to the same temperature as the work in the oven, and can be calculated same way.

In the case of a kiln-type oven the interior cools down somewhat duri period when the doors are open for emptying and reloading. For this re portion of the heat must be replaced with each charge. This may be one-quarter to one-half of that required on the first bake.

Radiation Losses from the Oven. — This depends upon the wa door construction. It is of prime importance that the amount of metal e ing through the oven walls from the inner to the outer surfaces be reduce minimum. Average radiation loss from a metal oven with two inches of i tion (air-cell asbestos or magnesia) and door at one end only will be ap mately 50 watts per square foot of total outside surface of oven, with an temperature of 400° F. Exact figures for radiation losses cannot be giv it is controlled to such a great extent by the design of doors, corners, vents as well as by the thickness and character of the insulation.

Ventilation. — The amount of ventilation required depends upo product to be baked. Ovens for japanning, paint drying, core baking a other operations that give off gases or vapors require ventilation. Wh paint or japan is used that contains a volatile solvent of combustible n good ventilation is necessary to reduce the danger of fire or explosion. danger is much more remote with an electrical oven than with a gas or fuel-heated oven because of the uniform temperature regulation obtained an electric oven. Ventilation also removes the gases given off during b and improves the surface obtained.

For japanning ovens from ten to twenty changes of air per hour are u allowed. To calculate the heat required the volume of the oven is mul by the weight of a cubic foot of air at the oven temperature, times the tem ture rise, times the specific heat of air, times the number of changes per h

Totals. — Adding together the heats required for each of the throughout the time allowed will give the total heat. Dividing by the

the heat will be required. If the heat is calculated
y 3415 to get the power input in kw.
ve average figures of inputs for various oven sizes
ample, however, it may be stated that for japanning
baking period, the input would be around 100 watts
the oven.

– Electrically heated bread-baking ovens are made
reel type.
e with from one to five or six shelves. The greater
nore bread capacity per square foot of floor space is
ally placed in each shelf, although in the smaller
under the bottom shelf may be used. In the latter
the air in the oven are depended on to carry the
Ducts are provided at the sides or back to assist

eel carrying six to eight bread trays which rotates
s are placed on the bottom.
city from 30 to 600 loaves and from 4 kw. to 75 kw.
mption will be from 100 to 200 watt-hours per one
the size of oven, kind of bread and skill of operator.

NNEALING FURNACES. — Furnaces for these
atures up to 2000° F., are available in various sizes.
d of a fireclay lining, either solid or sectional, to
ed. This is surrounded by a wall of heat insulating
ly of the highest grade of nickel-chromium material
r rod. In order to utilize a heavy cross-section of
oltage lower than the usual 110 volts is provided by
r.
ize of furnace it is necessary to calculate the amount
e temperature of the material and also to estimate
nace. The frequency of opening and closing doors
ng, as the radiation through an open door is very

hould be consulted for more detailed information.

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HOISTS, ELECTRIC. — (*See also Cranes; Elevators; Motors, Ind Applications of; Telpherage.*) A hoist is a machine for raising and lo weights. The most common application is in mines, to which service t lowing article is devoted.

The hoists most generally used are of the drum type, the drums being cylindrical or conical or a combination of the two. As a rule two drum ating in balance are used for each hoist. The weight of the skip, or ca car carrying the ore, is balanced by a similar empty skip which is lower second compartment simultaneously with the hoisting of the loaded skip first, the loaded skip being dumped at the top and the empty one loaded bottom, and the cycle being repeated. The difference between balanc unbalanced hoisting is that the static load when working unbalanced is than when working balanced, and the change of load due to the rope is on as great.

Preliminary Data. — In dealing with hoisting problems the followin are required:

Present and ultimate depth of shaft.
If inclined, give angle of inclination with horizontal, or grade, in per c
Weight of material per trip.
Weight of skip or cage and car.
Diameter and weight of rope.
Size of tail rope, if used.
Rope speed.
Number of trips per hour.
Time required for loading and unloading.
Double or single drum.
Diameter and weight of drums.
Motor geared or direct connected.
Hoist balanced or unbalanced.
If balanced, will unbalanced operation ever be necessary?

Besides the above, the ordinary data of the power supply system m known; also the restrictions as to permissible peak loads, so as to make sible to decide whether a load equalizing set will be required.

For cylindrical hoists the power required for the various periods of th cycle can be figured directly in horse-power. For conical drums the prob somewhat more complicated and a moment diagram is usually first figur plotted, and then converted into horse-power.

SYSTEMS OF ELECTRIC HOISTING. — Of the large number tems of electric hoisting which have been proposed, by far the greater ma can be included in the three following systems:

1. Those driven by induction motors.
2. Those driven by direct-current motors, power for which is supplie motor-generator set.
3. Those driven by direct-current motors, power for which is supplie flywheel motor-generator set.

1. Induction-motor System. — In the first and simplest system the of the direct-connected induction motor is controlled by a variable resi in the rotor circuit. The advantages of this system are: simplicity, lo cost, high motor efficiency when the hoist is running at full speed (ap mately 90 per cent), no power consumed when the hoist is at rest. disadvantages are: low motor efficiency during acceleration (approxi 45 per cent), no power is returned to supply system during retard

ine power consumption for small movements of cage, fluctuation of power demand.

2. **Direct-current Motor System.** — In the second system the hoist is driven by a separately excited direct-current motor, receiving power from the alternating-current supply system through a synchronous or induction motor-generator set. The hoist motor is controlled by varying the voltage of the generator, which is separately excited, one generator being used for each motor. The advantages of the system are: high motor efficiency during acceleration, return of large portion of energy during retardation. The disadvantages are: low combined efficiency of the equipment when running at full speed (probably not better than 82 per cent), loss in motor-generator set when hoist is at rest, large initial rotor expense, fluctuation of power demand.

3. **Direct-current System with Flywheel.** — The thirds ystem takes advantage of the low first cost and efficiency of the flywheel (*see Flywheels for Load Equalization*) as a means for storing and returning large quantities of power for short intervals. This system is similar to the second, except for the addition of a flywheel to the induction-motor-generator set, and an automatic regulator for varying its speed. In its most common form this regulator consists of a water rheostat connected in series with the induction-motor rotor. The resistance is varied by means of movable electrodes suspended from an arm mounted on the shaft of a small induction motor, which is connected in series either directly or through series transformers, with the induction motor of the flywheel set. The regulator motor is so connected that its torque opposes the weight of the electrodes, which are partially counterbalanced to reduce the size of the *regulator* motor to a minimum, and to permit of an adjustment of the regulator for different values of line current. When the line current exceeds the value for which the regulator is adjusted, the torque of the motor overbalances the weight of the electrodes, lifting them and inserting resistance in the armature circuit of the induction motor. This causes it to slow down, and allows the flywheel to assist in driving the generator during the peak loads.

Steam vs. Electric Systems. — A comparison between a steam system and these three electrical systems is given in the following table, in which the fuel and ore ratios for each are given for a small installation hoisting from a 2000-foot level, and a large installation hoisting from a 6000-foot level.

In addition to the saving in fuel which may be realized by the use of electric hoists instead of steam hoists, there is a very material reduction in the labor, the

Installation	Hoisting system	Coal burned, tons per day	Ore hoisted, tons per day	Ratio tons ore to tons coal
Small, hoisting from 2000-foot level.	Steam	47	1780	40
	Electric, first system	13	1780	137
	Electric, second system	15	1780	119
	Electric, third system	16	1780	110
Large, hoisting from 6000-foot level.	Steam	65.5	1580	24
	Electric, first system	23	1580	69
	Electric, second system	24	1580	66
	Electric, third system	25	1580	63

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cost of which is chargeable against the hoist. This may amount to th
of one or two men in the boiler house if power is developed by the mini
pany, or of the whole boiler house force if power is purchased, and fre
the wages of one man in the hoist house.

Power Consumption. — So many factors enter into the cost of electr
ing that each individual case must be analyzed separately. An appr
estimate of the power consumption would be from 1 ¼ to 2¼ kilowatt-h
1000 ton-feet, the tonnage, in the case of unbalanced hoisting, includ
weight of the ore and skip. while for balanced hoisting only the ore.

SPECIFICATIONS FOR ELECTRIC HOIST. — The following
randa are intended to assist in writing specifications. See also article o
tors, Electric and the article on *Specifications*.

Principal Characteristics and Conditions of Service. — General
tion and use of hoist. Motor voltage and frequency (*see articles on*
Mechanical rating, i.e., load to be lifted a specified height in a specifi
Proportion of time above load will be carried and of time machine is at

Details of Construction. — Length of hoisting rope and whethe
rope is to supplied. If so, details of rope and of hook or other device.
requirements. Lubrication details. Materials of principal parts.

Performance and Tests. — Maximum load to be lifted. Maximu
descending. How tests are to be conducted.

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Sept., 1919.

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HYDRAULICS. — (*See also Dams; Hydrology; Pipes and Piping; Power Stations, Hydro-Electric Turbines, Hydraulic; Turbines, Hydraulic, Speed Regulation of.*) Hydraulics comprises the principles and laws governing the motion and mechanical reactions of liquid bodies. There are two general divisions of the subject: Hydrostatics, which refers to liquids at rest; and Hydrodynamics, which refers to liquids in motion. This article will be confined to that portion of the subject which relates more directly to the problems met with in the study of water-powers.

Head and Pressure. — In water power terminology the word *head* means the difference in level of water between two points. It is usually expressed in feet. The pressure of water in a pipe for instance, is usually given as so many feet head and not as so many pounds per square inch. The relation between head in feet, h, and pressure in pounds per square inch, p, is as follows:

$$h = 2.31\, p,$$

$$p = 0.433\, h.$$

These formulas assume 62.4 lb. as the weight of 1 cu. ft. of water. See also *Units and Conversion Factors.*

FLOW THROUGH PIPES. — See articles on *Pipes and Piping* and *Water Wheels, Speed Regulation of.*

FLOW THROUGH OPEN CHANNELS. — The term channel includes all forms of closed conduits when flowing partly full as well as ordinary stream beds or canals. The rate of flow in such a case depends upon the slope given to the water surface. It is difficult to treat analytically the flow in natural channels, because of the wide divergence in shape of cross-section and nature of sides and bottom of channel. Only artificial channels are considered here, although the same formulas apply to any section of natural channel which has the same cross-section throughout.

Velocity and Friction Head. — The total head required to transport water in an open channel is used in creating velocity and in overcoming friction.

The "velocity head," or head required to impart a given velocity of flow to water, may be expressed by the equation,

$$h_v = \frac{v^2}{2g},$$

where h_v is the head in feet, v is the average linear velocity in the channel in feet per second, and g is the acceleration of gravity, or 32.16. The theoretical head required to increase the velocity from v_1 to v_2 is therefore,

$$h_v = \frac{v_2^2 - v_1^2}{2g}.$$

All changes in velocity should be made gradually to prevent the formation of eddies which result in additional friction loss.

The difference in elevation between the water surface at any two points in a channel of constant cross-section is the "friction head" or head required to overcome friction between those points. The friction head per unit of length depends upon the cross-section, shape and roughness of the channel.

Chezy's Formula. — This formula gives the relation between the linear velocity of the water, hydraulic radius and the slope and a coefficient which must be determined experimentally, viz,

$$v = C\sqrt{rs},$$

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where v = linear velocity of water in feet per second, r = hydraulic radius in feet, s = slope of stream (i.e., the difference in elevation between two points on the water surface divided by the slope distance between the two points measured along the surface) and C is an experimentally determined coefficient which may also be expressed by the empirical formula given below.

Hydraulic Radius. — This term is used to designate the quotient of the area of a cross-section, e.g., $ABCD$ in Fig. 1, by the *wetted* perimeter of the channel walls and bottom, $AB + BC + CD$ in Fig. 1.

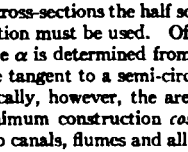


Fig. 1.

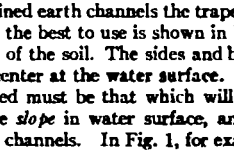


Fig. 2.

Best Section to Use. — Hydraulically, the most advantageous cross section to use is that having the maximum value of the hydraulic radius r. The semi-circle is therefore the best but is the most difficult to construct and to maintain. Of trapezoidal cross-sections the half hexagon is the best and of rectangular cross-sections the half square. In unlined earth channels the trapezoidal cross-section must be used. Of these sections the best to use is shown in Fig. 2. The angle α is determined from the character of the soil. The sides and bottom are made tangent to a semi-circle having its center at the water surface.

Practically, however, the area to be adopted must be that which will result in a minimum construction *cost* for the same *slope* in water surface, and this applies to canals, flumes and all other types of channels. In Fig. 1, for example, if the surface of the ground were considerably above the water surface, a minimum of excavation would correspond to a relatively deeper and narrower channel having a slightly larger area to retain the same slope for the given discharge.

Kutter's Formula. — This is the formula in common use for expressing the coefficient C in Chezy's formula in terms of the slope, hydraulic radius and the characteristics of the channel.

$$C = \frac{41.65 + \dfrac{0.00281}{s} + \dfrac{1.811}{n}}{1 + \left(41.65 + \dfrac{0.00281}{s}\right)\dfrac{n}{\sqrt{r}}},$$

where r and s are as above, and n is the "coefficient of roughness" depending upon the characteristics of the sides and bottom of the channel. Approximate values of n are given below. For a more extended list see *Bibliography*.

	Values of n
Best type of metal flumes	0.011
Concrete lining of smoothest kind, and well constructed clean wooden flumes with surfaced lumber	0.012
Clean wooden flumes of unplaned lumber, and average troweled concrete linings	0.015
Average concrete linings, not troweled, having prominent form marks, best conditions of canals in earth and best brickwork	0.016
Very rough concrete linings with deposits of gravel and moss, inferior brickwork, good rubble	0.018
Well constructed canals in firm earth or fine packed gravel free from vegetation	0.020
Worst type of ordinary metal flumes	0.022

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	Values of n
Average canals in earth	0.023
Canals in earth with occasional weeds and stones, and smoothest canals in rock cut	0.025
Canals in earth with a rather heavy growth of weeds and large rocks in bottom	0.030
Canals in bad condition and average canals in rock cut	0.035
Canals in rather rough rock cut	0.040

FLOW OVER WEIRS. — In hydraulics the term "weir" is used in general to designate any kind of a dam across a stream, and in particular to designate a vertical notch, usually rectangular, by means of which the quantity of water passing a given point may be determined, Fig. 3.

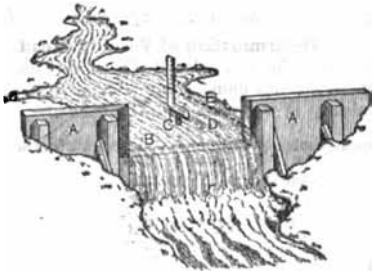


Fig. 3.

Definitions Regarding Weirs. — The "crest" is the horizontal edge of the weir. The "head" on a weir is not the depth of water over the crest, but is the difference in level between the crest and the reservoir surface, measured far enough away from the weir to avoid the surface curve or sharp slope near the crest. A "fully contracted" weir is one in which each end of the weir is at a distance of at least 3 times the head from the sides of the channel. A "suppressed" weir is one in which the sides of the channel (smooth and vertical) form the end of the weir. The "velocity of approach" is the velocity of the water in the channel leading to the weir. For a given head on the weir the quantity of water passing the weir depends somewhat upon the velocity of approach.

Weir Formulas. — The weir formulas of Francis, Bazin, Fletey and Stearns, Smith and others are each based on somewhat different experimental conditions. Therefore, to measure accurately the discharge over sharp-crested weirs, that formula should be used which is the result of experiments on weirs of the same general type and made under similar conditions.

Francis' formulas are given below. They are applicable only to vertical, rectangular weirs having

(1) Sharp, smooth, bevelled edges on the downstream side as shown in Fig. 3 (or a thin metal plate bolted to a wooden board may be used for the edge of the weir).
(2) The crest of the weir at least three times the head above the bottom of the channel.
(3) A length of crest at least three times the head on it.
(4) A head not greater than 2 feet nor less than 0.5 foot.
(5) A velocity of approach not greater than one foot per second.

Let Q = cu. ft. of water per sec. flowing over weir,
H = measured head on weir, in ft.,
h = head in ft., due to velocity of approach,
H_1 = "effective" head on weir, in ft.,
b = breadth of weir (length of crest) in ft.

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Then for a *fully contracted* weir

$$Q = 3.33\ (b - 0.2\ H)\ H_1^{3/2}$$

and for a *suppressed* weir

$$Q = 3.33\ bH_1^{3/2},$$

when the cross-section of the stream immediately above the weir is more tha 6 bH the effect of the velocity of approach is negligible and H_1 may be take equal to H. When the cross-section of the stream is less than 6 bH, then

$$H_1^{3/2} = (H + h)^{3/2} - h^{3/2}.$$

For the determination of the discharge over weirs having other than shar crests, the same general equations may be used; but the coefficient, 3.33 mu be altered as indicated by experiments (*see Horton's paper listed in Bibliography*

Determination of Velocity Head (h). — First take $H_1 = H$, and fro the above formula calculate Q. This value of Q divided by the cross-section of the channel immediately above the weir gives an approximate value for th velocity of approach V. The head due to the velocity of approach is the approximately $h = \frac{V^2}{64.32}$. Recompute the discharge Q, calculating $H_1^{\frac{3}{2}}$ fro the measured head H and this value of h. This will usually give the discharg very closely.

If desired, a new value of V may be found from this new value of Q and third value of Q computed, using for h a value based on the new value of V This method will be recognized as one of successive approximations. Generall one, and never more than two, recomputations are all that are necessary. I using the weir formulas given it is necessary to adhere to this method strictly, as the constants in the formulas were derived by using this method.

OTHER METHODS OF MEASURING FLOW. — The rate of discharge of a channel or natural stream may also be measured by means of floats, a Pitot tube, or a current meter. These devices are briefly described below.

Floats. — When a stream is of reasonably regular cross-section for a little distance, this method is applicable. Sticks about 1¼ inches in diameter, sufficiently weighted at one end so that they will float upright in the water, should be used. Surface floats are unreliable because of the influence of wind, skin friction of the water, etc. The floats are started at the beginning of a measured course and the time which they take to reach the end of the course is accurately taken. The velocity of the stream is thus obtained; this multiplied by the area of the cross-section gives the rate of discharge.

The floats should be started from various points in the width of the stream in order to obtain the average velocity as nearly as possible. They should be long enough to come as close as practicable to the bottom of the stream without touching, in order to average the velocities, which are variable throughout the depth of the stream. This method is less accurate than the use of the current meter.

Current Meters. — The ordinary current meter is essentially a wheel revolved by the water and held with its axis perpendicular to the direction of flow by means of vanes. Some means of recording the revolutions are provided. The meter must be rated by drawing it through still water at various measured speeds. Elaborate apparatus for meter rating is maintained by the Government and by various universities. Measurements of the velocity of the stream are made at frequent intervals across the stream and at varying depths, and the average velocity determined; this multiplied by the cross-sectional area of the stream for the height of water existing at the time gives the rate of discharge.

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Pitot Tube. — This is merely an open tube having a right-angle bend, the tube is placed in the stream in the position shown in Fig. 4, the lower end being directed against the current. The height h to which the water rises in the tube above the surface of the stream is equal to the velocity head, or the linear velocity of the stream is

$$v = \sqrt{2gh},$$

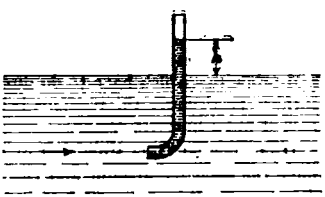


Fig. 4. Pitot Tube

where h is in ft., $g = 32.16$ ft. per sec. per sec., and v in ft. per sec. This formula does not apply to the flow through a pipe, since the pressure head must also be taken into account. For measuring the flow in pipes a differential gage of this type may be used, but the Venturi meter (see below) is better suited to such measurements.

Venturi Meter. — This meter, Fig. 5, serves as a simple and accurate means of measuring the discharge through a pipe. The meter consists essentially of an hour-glass-shaped section of pipe, with smoothly rounded internal walls, into which are fitted two gages as shown. The planes of the internal openings of gage pipes are at right angles to the direction of the current. Referring to Fig. 5, let

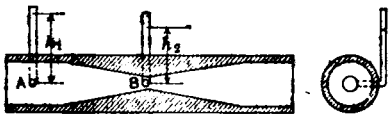


Fig. 5. Venturi Meter

a_1 = area, in sq. ft., of the cross-section at A,
a_2 = area in sq. ft., of the cross-section at B,
h_1 = reading of gage at A, ft. of water column,
h_2 = reading of gage at B, ft. of water column,
g = acceleration due to gravity, ft. per sec. per sec.,
C = a coefficient, ranging from 0.94 to 1.00, which takes into account the friction in the meter.

Then the discharge through the pipe in cu. ft. per sec. is

$$Q = C\frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}}\sqrt{2g(h_1 - h_2)}.$$

Ordinary pressure gages may be used at A and B, and their reading converted to feet of head, with a correction added for height of gage above center of meter.

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HYDROLOGY. — (*See also Hydraulics; Power Stations, Hydro-Electric.*) In the broadest sense, hydrology is the science of water, including its properties, the phenomena and natural laws associated with it, its distribution over the earth's surface, and in fact everything relating to water as a physical entity. As ordinarily employed, however, the term is limited to include only those laws and properties which have to do directly with its distribution over the earth's surface, particularly the relations between rain-fall, natural drainage, and the flow of water in rivers.

Hydrological Data Required in Water-power Engineering. — To determine the probable amount and character of power output of a water-power development, it is necessary to estimate the probable usable run-off of the stream and its flow characteristics. The characteristics of a stream are usually represented by its minimum flow and its variation from day to day and year to year.

ESTIMATING STREAM FLOW. — The probable discharge characteristics of a stream may be estimated in various ways depending upon the data available.

Long-term Stream Gagings. — The most accurate method of estimating the water available from a given stream is to make direct measurements of the discharge over a long enough period to be reasonably representative of what may be expected in the future. Records covering a period of ten to twenty years should be sufficient for all practical purposes, if rainfall records over a much longer period are available for comparison.

Such measurements are made at a suitable place and the elevation of water surface or "gage height" is recorded for a sufficient number of discharges to determine a "rating curve," see Fig. 1. It is then only necessary to make daily observations of the gage height to obtain a daily record of stream flow.

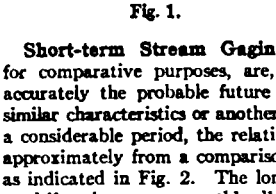


Fig. 1.

The U. S. Government has maintained gaging stations for a number of years on many streams in this country. These records are published in the Annual Reports of the U. S. Geological Survey (1888 to 1900) and in the Water Supply and Irrigation Papers (1896 to date) also issued by the U. S. Geol. Survey.

Short-term Stream Gagings. — Short-term stream gagings, while useful for comparative purposes, are, in themselves, of little value in estimating accurately the probable future discharge. If, however, a near-by stream of similar characteristics or another point on the same stream has been gaged over a considerable period, the relative discharge characteristics can be determined approximately from a comparison of simultaneous average monthly discharges as indicated in Fig. 2. The longer records of the nearby stream can then be used if each average monthly discharge is modified according to the curve.

In the absence of long-term records on a nearby stream, a rough estimate of future discharge can be obtained from a study of long-term rain-fall records, but the result so obtained is not satisfactory and should be used with caution.

No Stream Gagings. — If no gagings on the stream have been made, it becomes necessary to estimate the discharge from discharge records of nearby streams of similar characteristics. Such records, however, must be modified as indicated by a comparison of rain-fall records; or, in the absence of rain-fall records, a comparison of the rain-producing characteristics on the two water-

ards, and a study of the physical features of those areas which affect the "run-off," or percentage of rain-fall which finds its way to the stream.

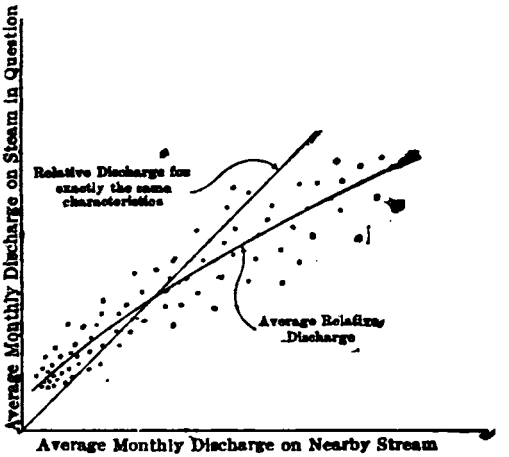


Fig. 2.

In the absence of discharge records on nearby streams, there is little hope of estimating accurately the probable future discharge. Even if long term rain-fall records are available, there is no satisfactory method by which the run-off can be determined even approximately.

RAIN-FALL AND RUN-OFF. — The discharge of a stream bears some relation to rain-fall on the tributary drainage area and depends upon the percentage of rain-fall which ultimately finds its way to the stream. Of the total rain-fall over a given period, a portion is lost by evaporation—directly to the atmosphere or utilized by vegetation. The rest appears as run-off.

As mentioned heretofore, it is necessary, in the absence of stream-flow records, to use the records of nearby streams modified in accordance with the relative rain-fall and run-off characteristics of the two drainage areas. The necessary modification is difficult to determine accurately, and becomes increasingly difficult the farther apart the two streams, particularly if on opposite sides of a large range of hills. A brief discussion of the numerous agencies affecting rain-fall and run-off are given in the following paragraphs.

Rain-fall.* — Rainfall varies materially in different localities, not only in annual precipitation but in its seasonal distribution. The U. S. Weather Bureau has published data and maps indicating the variation in mean annual precipitation throughout this country. The influences most affecting the deviations of local rain-fall from the general mean are the local topographical characteristics, the direction of prevailing winds and the altitude.

Moisture-laden winds, diverted upwards by mountain ranges, expand, cool, and condensation appears in the form of rain or snow. Thus the side of the range subjected to the prevailing winds will have the greater rain-fall.

In general, rain-fall seems to increase with the altitude; but in some cases

* Including snow, ice, etc., i.e., total precipitation.

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the effect of the topographical features on the prevailing winds may modi the general law. A knowledge of the conditions affecting local rain-fall a useful in the interpretation of published rain-fall data and particularly in cor paring the rain-fall characteristics of two areas where sufficient rain-fall gagi stations are not available for that purpose.

Rain-fall is usually expressed in inches, the number of inches being the dep of rain water which would be caught in a vessel with vertical sides set out the open. The records of rain-fall may be obtained from the United Stat Weather Bureau in Washington, D. C. Records covering as extended period and as wide a portion of the watershed under consideration as is pra ticable should be obtained. Too absolute dependence should not be plac on these results, as the intensity of rain-fall at different places in the drai age area of the stream under consideration may be quite variable, not on in general, but also in particular storms. It is conceivable that a station f recording rain-fall might be located at a point in an area where the annu precipitation is far above or below the average.

Run-off. — Among the many influences governing the relation betwee rain-fall and run-off and the distribution of run-off for a given period, the mo important are:

The geological formation,
The topography,
The nature of the vegetation,
The extent of lakes and swamps,
The amount of previous ground saturation,
The rate and amount of rainfall,
The mean temperature and wind velocity.

Run-off passes to the stream as surface flow or ground water flow. In rocky or clayey, hilly country the run-off passes quickly to the stream or its tributaries and a relatively small percentage of the rain-fall disappears in evaporation Such drainage areas therefore are characterized by a larger percentage of run-off but a considerable divergence between maximum and minimum flow. The latter characteristic makes them less attractive for power purposes unless large storage reservoirs are used.

Flat or rolling, impervious areas with many lakes or swamps are subject to considerable evaporation but the run-off is more uniform.

The best condition is a flat or rolling country with pervious soil. With such conditions a large part of the rain-fall seeps quickly underground with comparatively little evaporation. Ground water takes months in some cases to reach the stream and affords a supply during seasons of drought.

Evaporation is considerably more constant than run-off. Consequently the percentage run-off is usually much larger for high rain-falls than for low. Evaporation is known to increase with the temperature, although many other meteorological conditions affect it greatly.

The influences controlling run-off are so numerous and inter-connected that it is practically impossible to estimate closely the monthly or seasonal stream flow from rain-fall data; although a rough approximation of total annual run-off can be obtained. A knowledge of the factors affecting rain-fall and run-off are particularly useful if modified discharge records on one stream are to be used in estimating the probable discharge of another stream.

STORAGE RESERVOIRS. — "Primary" or uninterrupted power corresponds to the minimum flow of the stream. "Secondary" power corresponds to the flow above the minimum, or that power which is available only part of the time. Primary power is sometimes essential to the fulfillment of contracts.

The natural minimum flow of small streams is usually not large enough to permit of the successful installation of primary power developments. In such cases it becomes necessary to install turbines having a capacity considerably in excess of the minimum natural flow, and to provide steam or other auxiliary power to supplement the water power during periods of drought, or to provide storage reservoirs to hold back the excess or unusable flow until such times as the natural flow is insufficient. The reservoirs may be required to supply a deficiency extending over a few months or a series of years, depending upon the extent of the development in relation to the natural flow.

For use in fixing the required size of the reservoir, an investigation should be made to determine the minimum season, year or series of years, as the case may be, which may be expected to occur in the future.

Storage reservoirs are also used to partially regulate the flow of the stream. When thus used, they augment the primary power and increase somewhat the total available secondary power.

Allowance should always be made for evaporation from large storage reservoirs, which may modify the discharge records of previous years. Evaporation from free water surfaces varies from 20 to 100 inches, depending upon local conditions.

Load Factor. — All water is wasted which passes the water power plant in excess of the demand. The demand is fixed by the capacity of the installation and the load factor. The "load factor" is the ratio of the average load to the peak load, and ordinarily varies from 30 per cent to 80 per cent, depending upon the nature of the market. The load factor varies from day to day and from season to season. The daily load factor on Sundays is usually considerably lower than on week days, particularly in winter, when a large part of the load is used for lighting and all mills are shut down. Lighting, railway loads and many other loads vary considerably with the seasons. In most developments, the pond at the power dam is large enough to regulate the daily and week-end flow with in the capacity of the plant, so that it is only necessary to consider the average weekly or monthly load in determining the power available and the required capacity of storage reservoirs.

Hydrographs. — Fig. 3 represents a hydrograph of a stream showing a continuous graph of the discharge. The ordinates indicate the "second feet" or

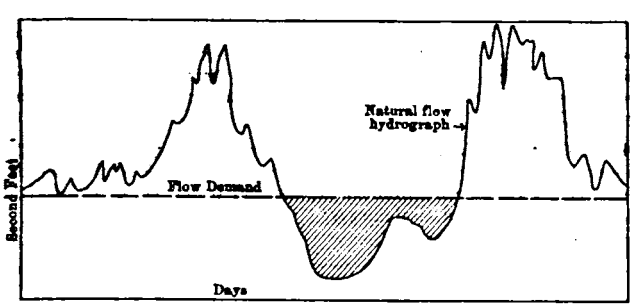


Fig. 3. Hydrograph.

cubic feet per second flowing at any time during the period covered. For large reservoirs, average monthly flow may be plotted instead of average daily flow with a considerable saving of labor. The period should cover a length of time

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sufficient to indicate the operation of the reservoir during the time of minimum flow. The flow demand, or flow corresponding to the average power demand is also indicated. This is not necessarily a straight, horizontal line as shown; but may vary with the seasons as hereinbefore explained. The shaded area represents the deficiency of natural flow and hence the amount of storage required to provide continuous or primary power. It is measured in "second-feet-days."

One second-foot-day requires 86,400 cubic feet of reservoir capacity. The maximum draft on the reservoir occurs at the end of the shaded area, after which there must be sufficient excess natural flow above the demand line to fill the reservoir again.

Mass Curves. — Another method of indicating storage requirements is by means of a mass curve, Fig. 4. Each ordinate indicates the total natural flow

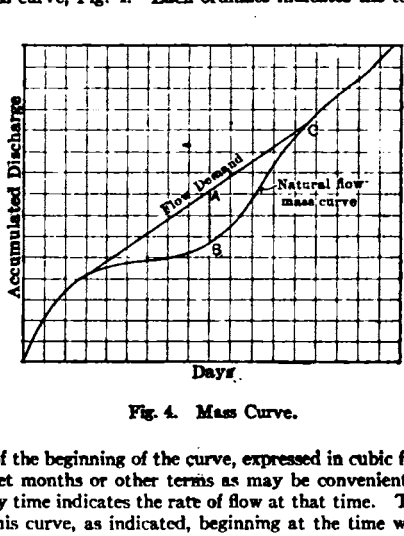


Fig. 4. Mass Curve.

since the date of the beginning of the curve, expressed in cubic feet, second-feet-days, second-feet months or other terms as may be convenient. The slope of the curve at any time indicates the rate of flow at that time. The flow demand is laid off on this curve, as indicated, beginning at the time when the natural flow is at the point of becoming deficient. The required capacity of the reservoir is indicated by the maximum difference, AB, between the ordinates to the two curves. The reservoir will have its maximum draft at B and will be full again at C where the two curves come together.

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HYPERBOLIC FUNCTIONS. — (*See also Derivatives; Integrals; Series, Mathematical.*) Hyperbolic functions are an extension of the trigonometric functions to those cases where the use of the latter gives rise to imaginary or complex angles. From the relations,

$$\cos x = \frac{e^{jx} + e^{-jx}}{2}$$

$$\sin x = \frac{e^{jx} - e^{-jx}}{2j}$$

where $j = \sqrt{-1}$, it follows that, putting $x = jz$:

$$\cos jz = \frac{e^{z} + e^{-z}}{2} \qquad (1)$$

$$-j \sin jz = \frac{e^{z} - e^{-z}}{2} \qquad (2)$$

Expressions (1) and (2) are both real quantities when z is real, that is, when the angle jz is imaginary. The first expression is called the hyperbolic cosine of z, abbreviated and pronounced "cosh"; the second expression is called the hyperbolic sine of z, abbreviated sinh and pronounced "shin." Hence, using x for the variable,

$$\sinh x = \frac{e^{x} - e^{-x}}{2}$$

$$\cosh x = \frac{e^{x} + e^{-x}}{2}$$

The hyperbolic tangent, cotangent, secant and cosecant are defined as follows:

$$\tanh x = \frac{\sinh x}{\cosh x}$$

$$\coth x = \frac{\cosh x}{\sinh x}$$

$$\operatorname{sech} x = \frac{1}{\cosh x}$$

$$\operatorname{csch} x = \frac{1}{\sinh x}$$

The hyperbolic angle x is a number analogous to radians in circular measure; it is never expressed in degrees.

Period of the Hyperbolic Functions. — Adding 2π to an angle does not change the value of the trigonometric functions; they are therefore said to have a period equal to 2π radians. Hyperbolic functions, however, have no true period, but adding $2\pi j$ to the hyperbolic angle does not change the values of the functions; hence these functions have an imaginary period, $2\pi j$.

Table of Hyperbolic Functions.* — Below is given a table of hyperbolic functions.

* More complete tables of hyperbolic functions may be found in the *Smithsonian Mathematical Tables*, by G. F. Becker and C. E. Van Orstrand, Washington, 1909 and in *Tables of Complex Hyperbolic and Circular Functions*, by A. E. Kennelly, Harvard Univ. Press, 1914.

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Angle		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
	sinh	0.0000	0.0100	0.0200	0.0300	0.0400	0.0500	0.0600	0.0701	0.0801	0.0901
0.0	cosh	1.0000	1.0001	1.0002	1.0005	1.0008	1.0013	1.0018	1.0025	1.0032	1.0041
	tanh	0.0000	0.0100	0.0200	0.0300	0.0400	0.0500	0.0599	0.0699	0.0798	0.0898
	sinh	0.1002	0.1102	0.1203	0.1304	0.1405	0.1506	0.1607	0.1708	0.1810	0.1911
0.1	cosh	1.0050	1.0061	1.0072	1.0085	1.0098	1.0113	1.0128	1.0145	1.0162	1.0181
	tanh	0.0997	0.1096	0.1194	0.1293	0.1391	0.1489	0.1587	0.1684	0.1781	0.1878
	sinh	0.2013	0.2115	0.2218	0.2320	0.2423	0.2526	0.2629	0.2733	0.2837	0.2941
0.2	cosh	1.0201	1.0221	1.0243	1.0266	1.0289	1.0314	1.0340	1.0367	1.0395	1.0423
	tanh	0.1974	0.2070	0.2165	0.2260	0.2355	0.2449	0.2543	0.2636	0.2729	0.2821
	sinh	0.3045	0.3150	0.3255	0.3360	0.3466	0.3572	0.3678	0.3785	0.3892	0.4000
0.3	cosh	1.0453	1.0484	1.0516	1.0549	1.0584	1.0619	1.0655	1.0692	1.0731	1.0770
	tanh	0.2913	0.3004	0.3095	0.3185	0.3275	0.3364	0.3452	0.3540	0.3627	0.3714
	sinh	0.4108	0.4216	0.4325	0.4434	0.4543	0.4653	0.4764	0.4875	0.4986	0.5098
0.4	cosh	1.0811	1.0852	1.0895	1.0939	1.0984	1.1030	1.1077	1.1125	1.1174	1.1225
	tanh	0.3800	0.3885	0.3969	0.4053	0.4136	0.4219	0.4301	0.4382	0.4462	0.4542
	sinh	0.5211	0.5324	0.5438	0.5552	0.5666	0.5782	0.5897	0.6014	0.6131	0.6248
0.5	cosh	1.1276	1.1329	1.1383	1.1438	1.1494	1.1551	1.1609	1.1669	1.1730	1.1792
	tanh	0.4621	0.4700	0.4777	0.4854	0.4930	0.5005	0.5080	0.5154	0.5227	0.5299
	sinh	0.6367	0.6485	0.6605	0.6725	0.6846	0.6967	0.7090	0.7213	0.7336	0.7461
0.6	cosh	1.1855	1.1919	1.1984	1.2051	1.2119	1.2188	1.2258	1.2330	1.2402	1.2476
	tanh	0.5370	0.5441	0.5511	0.5581	0.5649	0.5717	0.5784	0.5850	0.5915	0.5980
	sinh	0.7586	0.7712	0.7838	0.7966	0.8094	0.8223	0.8353	0.8484	0.8615	0.8748
0.7	cosh	1.2552	1.2628	1.2706	1.2785	1.2865	1.2947	1.3030	1.3114	1.3199	1.3286
	tanh	0.6044	0.6107	0.6169	0.6231	0.6292	0.6352	0.6411	0.6469	0.6527	0.6584
	sinh	0.8881	0.9015	0.9150	0.9286	0.9423	0.9561	0.9700	0.9840	0.9981	1.0122
0.8	cosh	1.3374	1.3464	1.3555	1.3647	1.3740	1.3835	1.3932	1.4029	1.4128	1.4229
	tanh	0.6640	0.6696	0.6751	0.6805	0.6858	0.6911	0.6963	0.7014	0.7064	0.7114
	sinh	1.0265	1.0409	1.0554	1.0700	1.0847	1.0995	1.1144	1.1294	1.1446	1.1598
0.9	cosh	1.4331	1.4434	1.4539	1.4645	1.4753	1.4862	1.4973	1.5085	1.5199	1.5314
	tanh	0.7163	0.7211	0.7259	0.7306	0.7352	0.7398	0.7443	0.7487	0.7531	0.7574
	sinh	1.1752	1.1907	1.2063	1.2220	1.2379	1.2539	1.2700	1.2862	1.3025	1.3190
1.0	cosh	1.5431	1.5549	1.5669	1.5790	1.5913	1.6038	1.6164	1.6292	1.6421	1.6552
	tanh	0.7616	0.7658	0.7699	0.7739	0.7779	0.7818	0.7857	0.7895	0.7932	0.7969
	sinh	1.3356	1.3524	1.3693	1.3863	1.4035	1.4208	1.4382	1.4558	1.4735	1.4914
1.1	cosh	1.6685	1.6820	1.6956	1.7093	1.7233	1.7374	1.7517	1.7662	1.7808	1.7956
	tanh	0.8005	0.8041	0.8076	0.8110	0.8144	0.8178	0.8210	0.8243	0.8275	0.8306
	sinh	1.5095	1.5276	1.5460	1.5645	1.5831	1.6019	1.6209	1.6400	1.6593	1.6788
1.2	cosh	1.8107	1.8258	1.8412	1.8568	1.8725	1.8884	1.9045	1.9208	1.9373	1.9540
	tanh	0.8337	0.8367	0.8397	0.8426	0.8455	0.8483	0.8511	0.8538	0.8565	0.8591
	sinh	1.6984	1.7182	1.7381	1.7583	1.7786	1.7991	1.8198	1.8406	1.8617	1.8829
1.3	cosh	1.9709	1.9880	2.0053	2.0228	2.0404	2.0583	2.0764	2.0947	2.1132	2.1320
	tanh	0.8617	0.8643	0.8668	0.8693	0.8717	0.8741	0.8764	0.8787	0.8810	0.8832
	sinh	1.9043	1.9259	1.9477	1.9697	1.9919	2.0143	2.0369	2.0597	2.0827	2.1059
1.4	cosh	2.1509	2.1700	2.1894	2.2090	2.2288	2.2488	2.2691	2.2896	2.3103	2.3312
	tanh	0.8854	0.8875	0.8896	0.8917	0.8937	0.8957	0.8977	0.8996	0.9015	0.9033

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HYPERBOLIC FUNCTIONS 1.50–2.99

01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
529	2.1768	2.2008	2.2251	2.2496	2.2743	2.2993	2.3245	2.3499
738	2.3955	2.4174	2.4395	2.4619	2.4845	2.5074	2.5305	2.5538
069	0.9087	0.9104	0.9121	0.9138	0.9154	0.9170	0.9186	0.9202
015	2.4276	2.4540	2.4806	2.5075	2.5346	2.5620	2.5896	2.6175
013	2.6255	2.6499	2.6746	2.6995	2.7247	2.7502	2.7760	2.8020
232	0.9246	0.9261	0.9275	0.9289	0.9302	0.9316	0.9329	0.9342
740	2.7027	2.7317	2.7609	2.7904	2.8202	2.8503	2.8806	2.9112
549	2.8818	2.9090	2.9364	2.9642	2.9922	3.0206	3.0493	3.0782
367	0.9379	0.9391	0.9402	0.9414	0.9425	0.9436	0.9447	0.9458
734	3.0049	3.0367	3.0689	3.1013	3.1340	3.1671	3.2005	3.2341
371	3.1669	3.1972	3.2277	3.2585	3.2897	3.3212	3.3530	3.3852
478	0.9488	0.9498	0.9508	0.9518	0.9527	0.9536	0.9545	0.9554
025	3.3372	3.3722	3.4075	3.4432	3.4792	3.5156	3.5523	3.5894
506	3.4838	3.5173	3.5512	3.5855	3.6201	3.6551	3.6904	3.7261
571	0.9579	0.9587	0.9595	0.9603	0.9611	0.9619	0.9626	0.9633
647	3.7028	3.7414	3.7803	3.8196	3.8593	3.8993	3.9398	3.9806
987	3.8355	3.8727	3.9103	3.9483	3.9867	4.0255	4.0647	4.1043
647	0.9654	0.9661	0.9668	0.6974	0.9680	0.9686	0.9693	0.9699
635	4.1056	4.1480	4.1909	4.2342	4.2779	4.3221	4.3666	4.4117
847	4.2256	4.2668	4.3085	4.3507	4.3932	4.4362	4.4797	4.5236
710	0.9716	0.9722	0.9727	0.9732	0.9738	0.9743	0.9748	0.9752
030	4.5494	4.5962	4.6434	4.6912	4.7394	4.7880	4.8372	4.8868
127	4.6580	4.7037	4.7499	4.7966	4.8437	4.8914	4.9395	4.9881
762	0.9767	0.9771	0.9776	0.9780	0.9785	0.9789	0.9793	0.9797
876	5.0387	5.0903	5.1425	5.1951	5.2483	5.3020	5.3562	5.4109
868	5.1370	5.1876	5.2388	5.2905	5.3427	5.3954	5.4487	5.5026
805	0.9809	0.9812	0.9816	0.9820	0.9823	0.9827	0.9830	0.9834
221	5.5785	5.6354	5.6929	5.7510	5.8097	5.8689	5.9288	5.9892
119	5.6674	5.7235	5.7801	5.8373	5.8951	5.9535	6.0125	6.0721
840	0.9843	0.9846	0.9849	0.9852	0.9855	0.9858	0.9861	0.9864
118	6.1741	6.2369	6.3004	6.3645	6.4293	6.4946	6.5607	6.6274
931	6.2545	6.3166	6.3793	6.4426	6.5066	6.5712	6.6365	6.7024
869	0.9871	0.9874	0.9876	0.9879	0.9881	0.9884	0.9886	0.9888
628	6.8315	6.9009	6.9709	7.0417	7.1132	7.1854	7.2583	7.3319
363	6.9043	6.9729	7.0423	7.1123	7.1831	7.2546	7.3268	7.3998
892	0.9895	0.9897	0.9899	0.9801	0.9903	0.9905	0.9906	0.9908
814	7.5572	7.6338	7.7112	7.7894	7.8683	7.9480	8.0285	8.1098
479	7.6231	7.6991	7.7758	7.8533	7.9316	8.0106	8.0905	8.1712
912	0.9914	0.9915	0.9917	0.9919	0.9920	0.9922	0.9923	0.9925
749	8.3586	8.4432	8.5287	8.6150	8.7021	8.7902	8.8791	8.9689
351	8.4182	8.5022	8.5871	8.6728	8.7594	8.8469	8.9352	9.0244
928	0.9929	0.9931	0.9932	0.9933	0.9935	0.9936	0.9937	0.9938
512	9.2437	9.3371	9.4315	9.5268	9.6231	9.7203	9.8185	9.9177
056	9.2976	9.3905	9.4844	9.5792	9.6749	9.7716	9.8693	9.9680
941	0.9942	0.9953	0.9944	0.9945	0.9946	0.9948	0.9949	0.9950

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HYPERBOLIC FUNCTIONS 3.00 – 4.4

Angle		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
	sinh	10.018	10.119	10.221	10.324	10.429	10.534	10.640	10.748	10.856	10.966
3.0	cosh	10.068	10.168	10.270	10.373	10.476	10.581	10.687	10.794	10.902	11.011
	tanh	0.9951	0.9952	0.9953	0.9953	0.9954	0.9955	0.9956	0.9957	0.9958	0.9959
	sinh	11.076	11.188	11.301	11.415	11.530	11.647	11.764	11.883	12.003	12.124
3.1	cosh	11.121	11.233	11.345	11.459	11.574	11.689	11.806	11.925	12.044	12.165
	tanh	0.9960	0.9960	0.9961	0.9962	0.9963	0.9963	0.9964	0.9965	0.9966	0.9966
	sinh	12.246	12.369	12.494	12.620	12.747	12.876	13.006	13.137	13.269	13.403
3.2	cosh	12.287	12.410	12.534	12.660	12.786	12.915	13.044	13.175	13.307	13.440
	tanh	0.9967	0.9968	0.9968	0.9969	0.9969	0.9970	0.9971	0.9971	0.9972	0.9972
	sinh	13.538	13.674	13.812	13.951	14.092	14.234	14.377	14.522	14.668	14.816
3.3	cosh	13.575	13.711	13.848	13.987	14.127	14.269	14.412	14.556	14.702	14.850
	tanh	0.9973	0.9973	0.9974	0.9974	0.9975	0.9975	0.9976	0.9976	0.9977	0.9977
	sinh	14.965	15.116	15.268	15.422	15.577	15.734	15.893	16.053	16.215	16.378
3.4	cosh	14.999	15.149	15.301	15.455	15.610	15.766	15.924	16.084	16.245	16.408
	tanh	0.9978	0.9978	0.9979	0.9979	0.9979	0.9980	0.9980	0.9981	0.9981	0.9981
	sinh	16.543	16.709	16.877	17.047	17.219	17.392	17.567	17.744	17.923	18.103
3.5	cosh	16.573	16.739	16.907	17.077	17.248	17.421	17.596	17.772	17.951	18.131
	tanh	0.9982	0.9982	0.9983	0.9983	0.9984	0.9984	0.9984	0.9984	0.9985	0.9985
	sinh	18.285	18.470	18.655	18.843	19.033	19.224	19.418	19.613	19.811	20.010
3.6	cosh	18.313	18.497	18.682	18.870	19.059	19.250	19.444	19.639	19.836	20.035
	tanh	0.9985	0.9985	0.9986	0.9986	0.9986	0.9987	0.9987	0.9987	0.9987	0.9988
	sinh	20.211	20.415	20.620	20.828	21.037	21.249	21.463	21.679	21.897	22.117
3.7	cosh	20.236	20.439	20.644	20.852	21.061	21.272	21.486	21.702	21.919	22.139
	tanh	0.9988	0.9988	0.9988	0.9989	0.9989	0.9989	0.9989	0.9989	0.9990	0.9990
	sinh	22.339	22.564	22.791	23.020	23.252	23.486	23.722	23.961	24.202	24.445
3.8	cosh	22.362	22.586	22.813	23.042	23.273	23.507	23.743	23.982	24.222	24.466
	tanh	0.9990	0.9990	0.9990	0.9991	0.9991	0.9991	0.9991	0.9991	0.9992	0.9992
	sinh	24.691	24.939	25.190	25.444	25.700	25.958	26.219	26.483	26.749	27.018
3.9	cosh	24.711	24.959	25.210	25.463	25.719	25.977	26.238	26.502	26.768	27.037
	tanh	0.9992	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993	0.9993	0.9993	0.9993
	sinh	27.290	27.564	27.842	28.122	28.404	28.690	28.979	29.270	29.564	29.862
4.0	cosh	27.308	27.583	27.860	28.139	28.422	28.707	28.996	29.287	29.581	29.878
	tanh	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9994	0.9994	0.9994
	sinh	30.162	30.465	30.772	31.081	31.393	31.709	32.028	32.350	32.675	33.004
4.1	cosh	30.178	30.482	30.788	31.097	31.409	31.725	32.044	32.365	32.691	33.019
	tanh	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995
	sinh	33.336	33.671	34.009	34.351	34.697	35.046	35.398	35.754	36.113	36.476
4.2	cosh	33.351	33.686	34.024	34.366	34.711	35.060	35.412	35.768	36.127	36.490
	tanh	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996
	sinh	36.843	37.214	37.588	37.965	38.347	38.733	39.122	39.515	39.913	40.314
4.3	cosh	36.857	37.227	37.601	37.979	38.360	38.746	39.135	39.528	39.925	40.326
	tanh	0.9996	0.9996	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997
	sinh	40.719	41.129	41.542	41.960	42.382	42.808	43.238	43.673	44.112	44.555
4.4	cosh	40.732	41.141	41.554	41.972	42.393	42.819	43.250	43.684	44.123	44.566
	tanh	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

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HYPERBOLIC FUNCTIONS 4·50–5·4

Angle		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
	sinh	45.003	45.455	45.912	46.374	46.840	47.311	47.787	48.267	48.752	49.24
4·5	cosh	45.014	45.466	45.923	46.385	46.851	47.321	47.797	48.277	48.762	49.25
	tanh	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.999
	sinh	49.737	50.237	50.742	51.252	51.767	52.288	52.813	53.344	53.880	54.42
4·6	cosh	49.747	50.247	50.752	51.262	51.777	52.297	52.823	53.354	53.890	54.43
	tanh	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.999
	sinh	54.969	55.522	56.080	56.643	57.213	57.788	58.369	58.955	59.548	60.14
4·7	cosh	54.978	55.531	56.089	56.652	57.221	57.796	58.377	58.964	59.556	60.15
	tanh	0.9998	0.9998	0.9998	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999	0.999
	sinh	60.751	61.362	61.979	62.601	63.231	63.866	64.508	65.157	65.812	66.47
4·8	cosh	60.759	61.370	61.987	62.609	63.239	63.874	64.516	65.164	65.819	66.48
	tanh	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.999
	sinh	67.141	67.816	68.498	69.186	69.882	70.584	71.293	72.010	72.734	73.46
4·9	cosh	67.149	67.823	68.505	69.193	69.889	70.591	71.300	72.017	72.741	73.47
	tanh	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.999
	sinh	74.203	74.949	75.702	76.463	77.232	78.008	78.792	79.584	80.384	81.19
5·0	cosh	74.210	74.956	75.709	76.470	77.238	78.014	78.798	79.590	80.390	81.19
	tanh	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.999
	sinh	82.008	82.832	83.665	84.506	85.355	86.213	87.079	87.955	88.839	89.73
5·1	cosh	82.014	82.838	83.671	84.512	85.361	86.219	87.085	87.960	88.844	89.73
	tanh	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.999
	sinh	90.633	91.544	92.464	93.394	94.332	95.281	96.238	97.205	98.182	99.16
5·2	cosh	90.639	91.550	92.470	93.399	94.338	95.286	96.243	97.211	98.188	99.17
	tanh	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	1.0000	1.0000	1.0000	1.000
	sinh	100.17	101.17	102.19	103.22	104.25	105.30	106.36	107.43	108.51	109.6
5·3	cosh	100.17	101.18	102.19	103.22	104.26	105.31	106.67	107.43	108.51	109.6
	tanh	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000
	sinh	110.70	111.81	112.94	114.07	115.22	116.38	117.55	118.73	119.92	121.1
5·4	cosh	110.71	111.82	112.94	114.08	115.22	116.38	117.55	118.73	119.93	121.1
	tanh	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000
	sinh	122.34	123.57	124.82	126.07	127.34	128.62	129.91	131.22	132.53	133.8
5·5	cosh	122.35	123.58	124.82	126.07	127.34	128.62	129.91	131.22	132.54	133.8
	tanh	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000
	sinh	135.21	136.57	137.94	139.33	140.73	142.14	143.57	145.02	146.47	147.9
5·6	cosh	135.22	136.57	137.95	139.33	140.73	142.15	143.58	145.02	146.48	147.9
	tanh	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000
	sinh	149.43	150.93	152.45	153.98	155.53	157.09	158.67	160.27	161.88	163.5
5·7	cosh	149.44	150.94	152.45	153.99	155.53	157.10	158.68	160.27	161.88	163.5
	tanh	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000
	sinh	165.15	166.81	168.48	170.18	171.89	173.62	175.36	177.12	178.90	180.7
5·8	cosh	165.15	166.81	168.49	170.18	171.89	173.62	175.36	177.13	178.91	180.7
	tanh	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000
	sinh	182.52	184.35	186.20	188.08	189.97	191.88	193.80	195.75	197.72	199.7
5·9	cosh	182.52	184.35	186.21	188.08	189.97	191.88	193.81	195.75	197.72	199.7
	tanh	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000

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Example. — $\sinh 0.83 = 0.9286$, $\cosh 0.83 = 1.3647$, $\tanh 0.83 = 0.6805$.

Approximate Formulas. — Note that for x less than 0.1,

$$\sinh x = x \text{ with an error of less than 0.2 per cent.}$$

$$\cosh x = 1 + \frac{x^2}{2} \text{ with an error of less than 0.09 per cent.}$$

For x greater than 6,

$$\sinh x = \cosh x = \frac{e^x}{2} = \frac{1}{2}\log_{10}^{-1}(0.43429\,x)$$

with an error of less than 0.01 per cent.

Anti-Functions. — If $a = \sinh x$, then x is the angle whose hyperbolic sin is a; this may be expressed symbolically

$$x = \sinh^{-1} a$$

which is read "x equals the angle whose hyperbolic sine is a." The angle is also called the "anti-hyperbolic sine" or the "inverse hyperbolic sine" of a. Similarly for the other hyperbolic functions. (See *Trigonometric Functions*, sub-heading *Anti-functions*.) The following relations exist between the anti hyperbolic functions and the natural logarithms:

$$\sinh^{-1} x = \log\left(x + \sqrt{x^2 + 1}\right)$$

$$\cosh^{-1} x = \log\left(x + \sqrt{x^2 - 1}\right)$$

$$\tanh^{-1} x = \frac{1}{2}\log\left(\frac{1 + x}{1 - x}\right)$$

Relations among Functions of the Same Angle. —

$$\cosh^2 x - \sinh^2 x = 1$$

$$1 - \tanh^2 x = \frac{1}{\cosh^2 x}$$

$$\coth^2 x - 1 = \frac{1}{\sinh^2 x}$$

$$\sinh(-x) = -\sinh x$$

$$\cosh(-x) = \cosh x$$

$$\tanh(-x) = -\tanh x.$$

See also the definitions given above.

Sum and Difference of Two Angles. —

$$\sinh(x + y) = \sinh x \cosh y + \cosh x \sinh y$$

$$\cosh(x + y) = \cosh x \cosh y + \sinh x \sinh y$$

$$\tanh(x + y) = \frac{\tanh x + \tanh y}{1 + \tanh x \tanh y}$$

$$\sinh(x - y) = \sinh x \cosh y - \cosh x \sinh y$$

$$\cosh(x - y) = \cosh x \cosh y - \sinh x \sinh y$$

$$\tanh(x - y) = \frac{\tanh x - \tanh y}{1 - \tanh x \tanh y}$$

Product of the Functions of Two Angles. —

$$\sinh x \sinh y = \tfrac{1}{2}[\cosh(x + y) - \cosh(x - y)]$$

$$\sinh x \cosh y = \tfrac{1}{2}[\sinh(x + y) + \sinh(x - y)]$$

$$\cosh x \sinh y = \tfrac{1}{2}[\sinh(x + y) - \sinh(x - y)]$$

$$\cosh x \cosh y = \tfrac{1}{2}[\cosh(x + y) + \cosh(x - y)]$$

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n Angle.—

$$\sinh 2x = 2\sinh x \cosh x$$
$$\cosh 2x = \sinh^2 x + \cosh^2 x$$
$$\tanh 2x = \frac{2\tanh x}{1+\tanh^2 x}$$

Angle.—

$$\sinh \frac{x}{2} = \sqrt{\frac{\cosh x - 1}{2}}$$
$$\cosh \frac{x}{2} = \sqrt{\frac{\cosh x + 1}{2}}$$
$$\tanh \frac{x}{2} = \sqrt{\frac{\cosh x - 1}{\cosh x + 1}}$$

imes an Angle.—

$$\sinh 3x = 3\sinh x + 4\sinh^3 x$$
$$\cosh 3x = 4\cosh^3 x - 3\cosh x$$
$$\tanh 3x = \frac{3\tanh x + \tanh^3 x}{1+3\tanh^2 x}$$

yperbolic and Trigonometric Functions.—

$\sin x$	$\sin(jx) = j\sinh x$
$\cos x$	$\cos(jx) = \cosh x$
$\tan x$	$\tan(jx) = j\tanh x$
$\sin^{-1} x$	$\sin^{-1} jx = j\sinh^{-1} x$
$\tan^{-1} x$	$\tan^{-1} jx = j\tanh^{-1} x.$

$$\cos^{-1} jx = \log(x + \sqrt{1+x^2}) - j\frac{\pi}{2}$$

of a Complex Angle.—

$$\sinh x \cos y + j\cosh x \sin y = Me^{j\theta}$$

$$\frac{\cosh 2x - \cos 2y}{2} \quad \text{and} \quad \tan\theta = \frac{\tan y}{\tanh x}.$$

$$\cosh x \cos y + j\sinh x \sin y = Ne^{j\phi}$$

$$\frac{\cosh 2x + \cos 2y}{2} \quad \text{and} \quad \tan\phi = \tanh x \cdot \tan y.$$

$$\frac{\sinh x \cos y + j\cosh x \sin y}{\cosh x \cos y + j\sinh x \sin y} = Pe^{j\psi}$$

$$\frac{\cosh 2x - \cos 2y}{\cosh 2x + \cos 2y} \quad \text{and} \quad \psi = \tan^{-1}\left[\frac{\sin 2y}{\sinh 2x}\right].$$

$$\tanh^{-1}(Ae^{j\alpha}) = B_1 + jB_2,$$

$$B_1 = \tfrac{1}{2}\tan^{-1}\left[\frac{2A\cos\alpha}{1+A^2}\right] \quad \text{and} \quad B_2 = \tfrac{1}{2}\tan^{-1}\left[\frac{2A\sin\alpha}{1-A^2}\right].$$

[W. A. Del Mar.]

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IGNITION, ELECTRIC, FOR INTERNAL COMBUSTION ENGINES. — (See also *Batteries, Primary; Batteries, Storage; Internal Combustion Engines; Starting and Lighting Systems.*) It is the function of the ignition system of an internal combustion engine to initiate the burning of the charge of fuel within the engine cylinder at the proper instant in the cycle, i.e., when the explosive mixture of gasoline vapor and air is at or near the point of maximum compression. The typical system, see Fig. 1, compris

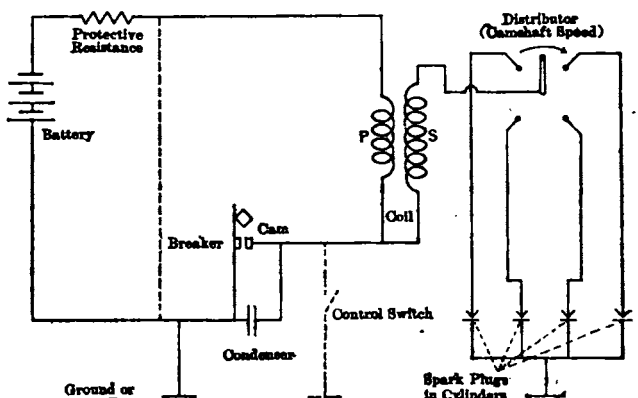


Fig. 1. Circuits of Typical Single-spark, Jump-spark Ignition System. Solid lines show battery system. If the battery and resistance are omitted, the dotted connections added, and the "coil" taken to represent the windings of a magneto, the circuits become those of a high-tension magneto ignition system.

(1) a source of electrical energy (battery or magneto generator); (2) a timer for correlating the production of the spark with the rotation of the engine (this may be either a "timer" or "commutator" which closes the primary circuit of a vibrator system at the proper instant, or a "breaker" which interrupts the primary circuit of an induction coil); (3) an induction coil (which may be incorporated as part of the magneto) for transforming the energy to a high voltage; (4) a distributor for leading the high voltage discharge to the successive cylinders in the proper sequence; and (5) a spark plug in each cylinder to provide a fixed insulated gap at which the igniting spark is produced.

IGNITION OF GASES. — Combustible gases and vapors when mixed with air in the proper proportion (15 of air to 1 of gasoline by weight is approximately the theoretical combining ratio) become explosive. That is, a flame started in the mixture is self-propagating with a velocity which varies greatly with the material and the proportions of the mixture, and is greater as the pressure and temperature of the mixture are increased, but so far as is now known is independent of the character of the igniting source. For gasoline engines the velocity is of the order of 10 meters per second, and consequently the spark should be timed to occur several thousandths of a second before the piston reaches upper dead center, so that the charge may be practically all ignited at the beginning of the power stroke. Since this desired *time* interval corresponds to a different *angular* interval at different engine speeds, means are usually pro-

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or automatically advancing the angular position of increase of speed. At starting the spark should o dead-center to avoid "back firing."

eous mixture a certain intensity of spark is required *Proc. Phys. Soc., London, 31, p. 168, 1919*), which id to a fixed amount of energy. At high voltages assing the gap may be made much less than in inverse and still produce ignition. The intensity needed of gasoline and air is 0.002 joule at 5000 volts. s the electrostatic energy stored in a capacity of hich is roughly the capacity of the usual spark plug when charged to a sparking voltage of 5000 volts. n system produces a spark at all, ignition is practi- the supposed advantages of a "hot" or "fat" spark ses where carburetion is imperfect, as with heavy d engine, much of the charge is in the form of spray such conditions it is quite possible that a spark of ergy content may be advantageous by vaporizing be noted that the hottest magneto spark (0.2 joule) aporize only 0.0007 cu. cm. of gasoline, and that an plied by the combustion of only 0.000006 cu. cm. of

electric spark may be defined as the passage of an gaseous medium and the distinction between it and here. There are two main types of spark:

er or Disruptive Spark, such as is produced f a condenser through a circuit of small resistance ent in such cases is of great amplitude, oscillates in cy and is rapidly damped out, the entire discharge ns of a second. The sparks in air are bluish white, sure effects, but will not readily ignite solid materials t is, however, as effective as the other type of spark

Spark or Arc is produced by the discharge of . The current is of small value (0.1 ampere or less, irectional, and may last for several thousandths of a sh or orange, quiet, of greater apparent "thickness" nsity, readily ignite paper or cotton.

ve a combination of both kinds of spark. The coil and spark plug form a condenser which discharges a owed by a type (b) spark from the coil.

N SYSTEMS. — Electric ignition systems may be

Low-tension Systems, in which the current gh a coil of high inductance and through a pair of ylinder. At the proper point in the cycle the con- ltable mechanism and the resulting arc ignites the agneto with a single winding is often used in place nce coil. The mechanical complexity of this system compression engines. It is now little used.

-tension Systems, in which a sufficiently high condary winding of an induction coil or magneto, by

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the breaking of current in a primary winding, to produce a spark acro fixed length inside the cylinder. Jump spark systems may be furt fied as:

Vibrator Systems, in which the primary current is interrupted rep a vibrating contact during the part of the stroke when a spark is The contact is vibrated as in an electric bell or buzzer either by the flux from the core of the main induction coil, or by a small auxiliary relay. The frequency of the vibrations is of the order of several hu second, but even then in high-speed engines there would be time for vibrations during the entire expansion stroke, and the net result is th in a single-spark system.

Single-spark Systems are those in which a single spark is produc engine cycle by the mechanical opening of the primary circuit conta is by far the most common type of system.

Ignition systems may also be classified according to the primary energy as battery, magneto, and dual:

Battery Systems draw current (0.5 to 5 amperes) at low voltag volts; usually 6) from a battery of storage or dry cells through the p an induction coil and the "breaker" contacts (see Fig. 1). In the **closed circuit** type the breaker is closed for a fixed fraction of cycle which, at moderate engine speeds, gives a time of closure abou the electrical time constant $\left(\frac{L}{R}\right)$ of the primary circuit. Consequ primary current has time to build up to nearly its final value $\frac{E}{R}$ before is broken. At higher speeds this final value is not reached and the "break" and the spark energy are correspondingly decreased. At the full value of current would flow continuously and produce excessi in the circuit. This is obviated in some systems by a series resistan temperature coefficient which is so heated by the excess current that ing increase of resistance limits the standstill current to a moderate v

In the **open-circuit** type the breaker is closed for a period short compared to the time constant of the primary circuit and whic pendent of engine speed. The maximum current would be very la never attained and the spark energy is independent of engine speed.

MAGNETOS are electric generators which have a permanent ma structure and are supplied with mechanical energy from the drivin the engine. Magnetos are classified as "low tension" or "high tens the former a single winding generates current at relatively low voltag transformed to high voltage by an external coil as with a battery sy the latter a secondary winding is placed over the primary and the serves the double function of generator and transformer.

Magnetos are also classified as **one-spark** or **two-spark.** In t one end of the secondary is grounded through the primary and the ot connected through a single distributor to one spark plug at a time. I spark" magneto both ends of the secondary winding are highly insu connected through the two parts of a double distributor to two spar the same cylinder. The ignition of the charge from two widely separa in the combustion space, secured either in this way or by two separate hastens the rapidity of inflammation of the charge and may increase power several per cent.

Magnetos may be classified according to their construction as follo

ture Type.—This most widely used construction permanent magnet *M* is provided with soft iron or S each of which subtends an rmature core is of the cross- laminated as much as pos- e ends of the winding extend th of rotor about three times yoke. Ball-bearings are uni- gaps reduced to a minimum. a primary coil of few turns ire (No. 22) and outside of any turns (approx. 10,000) of ayers are insulated with oiled ith oiled silk. The outside additional insulation because n turns which is produced at the spark. The circuits of losely analogous to those in a hown dotted in Fig. 1. The ary is connected by a well- arbon brush to the central

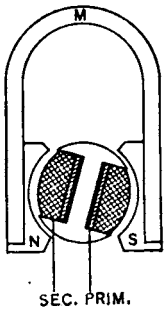


Fig. 2. Cross-section of Shuttle Armature, High-tension Magneto.

e either of the **brush type**, in which a carbon brush central arm rubs in succession against metal inserts ating block which are in turn connected to the spark inders; or of the **jump type** in which the arm passes (about 0.010 inch clearance) the fixed projecting struction avoids trouble from the accumulation of and the resulting flashing of the spark between inserts. ck is preferably made of a molded phenolic material r heat, but the surface over which the brush rubs mpound to reduce arcing troubles.

imary winding is connected to the armature core and f the machine by a carbon brush. The other end is d block which supports one of the breaker contact t point is carried on a grounded lever which is actuated er cam-follower so as to open the circuit abruptly at ach revolution. The contact surfaces are usually of hough tungsten is used to a considerable extent in denser of 0.1 to 0.2 microfarad capacity mounted in ed in parallel with the contacts and serves to reduce l otherwise occur. This condenser is usually of mica, some extent. It should be capable of withstanding a a-c. A brush bearing on the insulated block may be ontrol switch to ground, thus permanently short-cir- rendering the device inoperative when it is desired to ype of magneto furnishes two sparks per revolution cle engine must be driven at crankshaft speed.

. — In this type (Fig. 3) the coils are stationary nated core with extended pole pieces. Between these ft iron blocks which are carried on opposite sides of a e blocks are enlarged at opposite ends to form disks ximity to the respective poles of the U-shaped perma- f rotation is along the line joining the poles of the mag-

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net and perpendicular to the axis of the coil and to the line joining pieces of the inductor. This type has the advantage of having the coil st and it is consequently easier to insulate the high voltage leads. The described gives two sparks per revolution, but constructions using four

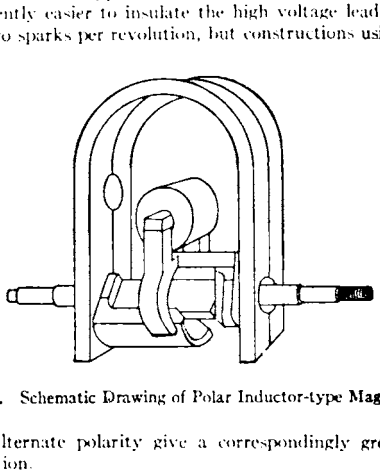


Fig. 3. Schematic Drawing of Polar Inductor-type Magneto.

rotor blocks of alternate polarity give a correspondingly greater nu sparks per revolution.

Sleeve-inductor Type. — This machine contains a field system an armature like the shuttle type but the armature is fixed in position magnetic axis at right angles to that of the field. Between the two st in what corresponds to the greatly widened air gap, there rotates a c non-magnetic sleeve containing two soft iron segments subtending mately 90°. A complete rotation of the sleeve reverses the flux thr armature core four times, so that by a proper cam four sparks per r can be produced.

Oscillating Magnetos. — Among the other numerous types there mentioned the oscillating magnetos in which the armature is rotated t fraction of a revolution against a set of springs which on release snap quickly across the position of flux reversal, and thus produce a spark.

Still another type of igniter properly classed as a magneto has only winding of many turns of fine wire. The translatory motion of a pa iron cores into and out of magnetic contact with the poles of a perman net reverses the flux through the coil so rapidly that sufficient voltage is p to produce a spark. Both of these devices are, however limited in s are used mainly on stationary engines.

Impulse Starter Coupling. This attachment is often inserted in connecting the engine with any of the foregoing types of magneto to starting, by producing a sudden rotation of the magneto armature at t time when the engine is being cranked slowly. At low speeds a latch the motion of the magneto rotor until the driving shaft has rotated t considerable angle and has wound up a spring located between th member and the rotor. When the engine has turned to upper dead c latch is displaced by a cam. The released rotor is spun rapidly by t past the firing position and a spark is produced in the cylinder. A c device renders the latch entirely inoperative at speeds above 150–2 and the magneto is then directly driven from the engine. The angula during the impulse is equivalent to a speed of about 800 r.p.m.

DUAL IGNITION SYSTEMS involve the combination of two more or less independent ignition systems on a single engine. The terms "dual," "duplex," and "double" are used in different senses by different makers to designate such combinations the purpose of which is to provide: (1) The addition to magneto ignition of some auxiliary to assist in starting; (2) A factor of safety in case of failure of one system, and (3) a slight increase of engine power resulting from two sparks in a single cylinder. Among the many possible combinations are the following:

(a) A high-tension magneto system with a battery which can be connected in series with the magneto primary and breaker for starting.

(b) A high-tension magneto with a small auxiliary hand-driven magneto delivering their secondary current through the same distributor segments. With this arrangement, which is widely used on heavy truck and airplane engines, the hand magneto is usually connected to an auxiliary distributor arm which is retarded one segment behind the regular arm, thus avoiding back-fire.

(c) A low-tension magneto and a battery feeding a common induction coil, distributor and plugs.

(d) A high-tension magneto fitted with an additional breaker mechanism. This is in series with a battery and induction coil, the secondary of which supplies the same distributor as the magneto, only one system being operative at a time.

(e) Two completely independent systems supplying separate sets of spark plugs. These may be two similar magnetos or battery systems as on most airplane engines or a magneto and a battery system.

(f) Battery systems having both vibratory and single-spark breakers but with other elements in common are sometimes called "dual," and if the vibrator is of high pitch are called "high frequency."

HIGH-FREQUENCY SYSTEMS, properly so called, such as the Lodge and the Dean systems, utilize the oscillating discharge of a condenser to produce frequencies of several thousand cycles per second. The former system is closely analogous to the series gap system and is very effective in firing spark plugs which are heavily shunted by carbon deposits.

CYCLE OF OPERATION. — The detailed operation of any type of jump spark ignition system can be most clearly understood by splitting up the complete cycle of operation into a number of separate periods during each of which the phenomena proceed under fairly definite electrical conditions, each period in turn being separated from the preceding and following one by an abrupt change of conditions.

Period 1 includes the building up of primary current and the consequent storage of magnetic energy, as a result of either the impressed voltage from the battery, or the voltage generated by the rotation of the magneto armature. In the former case the current builds up exponentially and gradually approaches its closed circuit value. In the case of the magneto, although the e.m.f. wave generated by the rotation is very peaked, the short circuit current wave at moderate and high speeds is rather flat-topped and sufficient current exists to produce a spark if "break" occurs over a range of about 90 electrical degrees in each half wave. At slower speeds the current wave is much more peaked and a spark can be produced over only a narrow timing range. To obviate this limitation magnetos are frequently so constructed that the pole pieces (or in polar-inductor types the coil and core) can be rotated with the breaker cam, and the "break" occurs always at the same point in the electrical cycle, though it is shifted with respect to the engine cycle.

The normal current at break is usually about 5 amperes in either battery or

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magneto systems. The inductance of the latter is, however, usually
ably greater, so that the available magnetic energy $\frac{1}{2}L_b i_b^2$, and henc
energy in the spark is correspondingly larger.

The discharge of the battery on closed circuit, or the operation of th
as a short-circuited a-c. generator, is suddenly interrupted by the
the breaker contacts by the cam and Period 2 begins.

Period 2. — This is of extreme'y short duration (of the order
second), and extends from the opening of the primary contacts to the
of the spark at the spark plug, but is of great importance, since the
or failure of the spark is determined by whether or not the induced
voltage during the period rises to a value equal to the breakdown volt
spark plug gap.

At the beginning of the period the primary current continues to flow
but into the primary condenser instead of through the breaker conta
current rapidly charges the condenser, raising the voltage at its term
introducing a back e.m.f. into the primary circuit. This causes a d
the primary current and in the magneto-motive force acting on the core
in the resultant flux. This decrease in flux induces a voltage in the
which is greater than that in the primary in approximately the rati
$\left(u = \frac{S_2}{S_1} = 50 \text{ to } 60\right)$; and this voltage in turn sets up a seconda
which charges the secondary condenser (capacity 2×10^{-4} microfara
mately) of which the secondary winding, distributor and spark plug
one "plate," and the grounded frame and engine the other "plat
transformation of energy from magnetic to electrostatic form, and i
In primary and secondary condenser, continues until either the
voltage is high enough to jump the spark gap, or until all the energ
electrostatic form. In normal operation the former result occurs wh
small part (about 10 per cent) of the magnetic energy has been tr
When, however, the system by reason of too small current at break
spark gap is just at the limit of sparking, the following relation holds:

$$E_s = I_b u \sqrt{\frac{L_1}{C_1 + u^2 C_2}}, \qquad \text{approx.}$$

Where
E_s = limiting secondary voltage (volts)
I_b = primary current at break (amperes
u = ratio of turns secondary to primar
L_1 = self-inductance of primary (henries
C_1 = capacity of primary condenser (fa
C_2 = capacity of secondary condenser (f

The above equation is useful as indicating the variation of E_s with
and C_2 but, in computing absolute voltages, the result must be corre
factor of from 0.5 to 0.7 to allow for losses

In most magnetos

$$C_2 = \frac{C_1}{u^2} \qquad \text{roughly}$$

In case the secondary terminals are shunted by a resistance, as is the
the spark plugs are fouled with carbon deposits, the maximum voltag
is much less than that given by equation (1), but can be roughly
from the following considerations: If the secondary were short-circ
a current equal to $\frac{I_b}{u}$ were induced in it after "break," the magnetomo

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e the same as before "break," and there would be no-
uced e.m.f. Consequently this current $\frac{I_b}{u}$ is the limit-
dary winding can ever supply. A fouling resistance
oduce misfiring practically constitutes such a short-
cross such a resistance is therefore always somewhat
g *IR* drop, viz.,

$$E_s = \frac{I_b}{u} S. \qquad (3)$$

rrent $\frac{I_b}{u}$ is about 0.1 ampere and hence a 3000 volt
f shunted by 30,000 ohms.

ttainment of breakdown voltage of the spark gap dur-
nes conducting and the secondary condenser discharges
enser type of discharge, which, as explained above, is
nough to produce ignition.

completion of the condenser spark the magnetic energy
es to deliver an inductive spark for a duration of several
until the entire energy is dissipated. The secondary
decreases linearly with time, giving a wave roughly
spark delivered by a magneto is usually of decidedly
for a battery system, both because of the greater
ic energy, and also because the voltage generated in
otation may (in case the spark is fully advanced) force
ent across the gap.

The function of the spark plug is to maintain within
a gap of definite breakdown voltage between two
is almost universally grounded on the cylinder wall.
irements are that the sparking voltage should not
the insulation resistance should be at least 100,000
d be practically gas-tight. In the most severe cases
e plug must satisfy these requirements while under
ounds per square inch, while immersed in a medium
in temperature between 0 and 2500° C., and in an
o deposit soot on the surface of the insulator.

— The various manners in which a spark plug may

Carbon Deposit Causing a Short Circuit. — This
uent cause of trouble and results from excess oil, too
whose insulator operates at too low a temperature. It
a) so shaping the insulator that part of it is hot enough
shielding the insulator with baffles that it is not exposed
xiliary Gap below.)

Oil Causing Open Circuit. — The breakdown
greater than that of an equal thickness of compressed
ation of a drop or film of oil on the electrodes may
oltage of the gap to a value in excess of that generated
develops at light loads and on starting, where an excess
linder. Small electrodes so shaped as to drain the oil
o reduce this trouble.

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(3) **Cracking of Insulator.** — This may result from mechanical shoc or differential thermal expansion. The trouble is absent in mica plugs, and ca be greatly reduced in others by the use of the special porcelains recently develope for spark plugs, which have relatively high mechanical strength and therma conductivity and small thermal expansion.

(4) **Pre-ignition.** — This occurs in hot high-compression engines an results in loss of power and overheating. The remedy is short thick electrode and thorough cooling of the plug.

(5) **Conduction through the Insulator.** — At high temperatures a ceramic bodies become to some extent conductors of electricity and differen varieties of porcelain differ greatly in this property. The better grades, however show so little of this effect that it is seldom of serious importance in engin operation.

(6) **Minor Troubles,** such as warping and corrosion of the electrodes may usually be avoided by proper design and material.

Construction of Spark Plugs. — Spark plugs are built in a very grea variety of forms, most of which show very little improvement over the simpl and conventional type (Fig. 4). Numerous tests have shown that gas-tight ness is a matter of workmanship rather than of design The insulator and the shell are usually held together either by a threaded bushing, as indicated, or by crimping the edge of the metal shell over the shoulder of the insulator The latter construction is rather cheaper, but prevents the removal of the insulator for cleaning, and also, unless carefully done, is liable to set up undue strains in the porcelain Either construction can be made satisfactorily tight. The inner end of the shell is frequently nearly closed, leaving a small annular spark gap around the electrode. Such "closed end" plugs are suitable for "oily" engines. Steel is usually preferable to brass for the shell, as the latter conducts more heat to the outer part of the insulator.

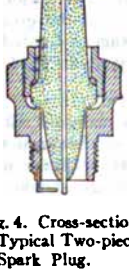


Fig. 4. Cross-section Typical Two-piece Spark Plug.

Mica and various ceramic bodies (steatite, lava, glass, quartz, etc.) are used as insulators. The former has the advantage of freedom from cracking, but gives a surface which is somewhat more liable to collect carbon.

The electrodes are usually of nickel or nickel-manganese alloy, but occasionally copper or silver is used in very hot engines. They are made in a great variety of shapes, although this has no observable effect on the character of the spark except as it affects the breakdown voltage of the gap. This voltage depends on the length of the gap, the shape of the electrodes, the density of the gas, the temperature, and possibly the materials of the electrodes, and upon the rate at which the voltage is applied. The voltage increases nearly linearly with the density of the gas, whether the density results from increased pressure or lowered temperature. For the usual gap length (0.020 inch) the sparking voltage is between 2000 and 6000 volts, depending on the compression ratio of the engine. When the electrodes are at a higher temperature than the gas, the sparking voltage is very considerably decreased below the value to be expected from the density.

Auxiliary Gaps. — If a well-insulated spark gap of proper length is connected in series with a spark plug which is so heavily shunted by carbon that it normally does not fire, the plug will often be found to spark satisfactorily. The beneficial effect of this simple device is due to the fact that it prevents a flow of secondary current during Period 2 (see *Cycle of Operation* above), until the volt-

erminals is high enough to break down the external
full voltage is suddenly applied to the spark plug
if its break down voltage is less than that of the
and, in cases where failure to fire is caused by insuffi-
ling on the plug electrodes, the introduction of a
ment. Devices of this type are widely advertised
'Energizers" and extravagant claims are made as
and economy, which, however, are justified only in
rious misfiring previous to their installation.

ipal overall test of an ignition system is its ability
k gaps satisfactorily, as many gaps being provided
s. The most generally used (but far from satis-
oint" gap shown in Fig. 5. "The third or teaser
gap is left insulated
it but when properly
spark which provides
k gap. Such a spark
tween the main elec-
e of about 8000 volts,
n its operation when
mpulse from a spark
two-point gap.
a set of these gaps
ssive arcing at the
hat at which it will
os are also tested for
h they will just fire
limit should for most
r.p.m. Similar tests
shunted with 100,000
ons of carbon fouling.
ble be tested by long
in the type of engine

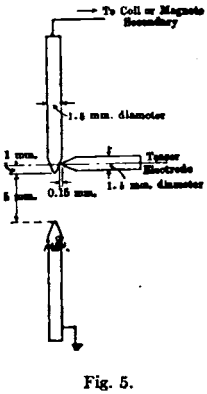


Fig. 5.

sed, since conditions of oil, temperature, etc., vary
in the laboratory should show less than 1 cc. per
pressure of 15 kg. per square centimeter (225 pounds
ow no cracks when the insulators are quenched in
150° C.; and should withstand 25,000 volts a-c.
de and the outer surface of the insulator when
e Report No. 51-III, National Advisory Committee

COSTS. — The standard dimensions adopted by
Engineers for magnetos for 4 and 6 cylinder engines

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DIMENSIONS OF MAGNETOS, S.A.E. STANDARD

	Dimension, millimeters	Dimension, inches
Height of shaft for 4 or 6 cylinder magnetos	45	1.771
Distance from center of front base plate holes to large end of shaft taper	53	2.086
Distance from center of front base plate holes to center of rear base plate holes	50	1.968
Distance between centers of base plate holes left to right	50	1.968
Large diameter of taper	15	0.590
Small diameter of taper	12	0.472
Length of taper	15	0.590
Taper 1 : 5 (included angle) 11° 30′.		
Thread on end of magneto shaft	⅝ in., 16 threads per inch, U. S. Std.	
Woodruff key No. 3.		
Base plate holes for bolts	⅜ in., 16 threads per inch, U. S. Std.	

Three forms of spark-plug threads are in general use in the United States ıe dimensions standardized by the Society of Automotive Engineers being a ollows:

SPARK-PLUG THREADS

	⅞ in.–18 Size		Metric Size		½ in. Size
	Max. inches	Min. inches	Max. mm.	Min. mm.	
Outside diameter	0.875	0.872	17.97	17.85	.....
Pitch diameter	0.839	0.836	17.00	16.88	.7584 at small end
Root diameter	0.803	0.800	15.86	15.74	.....
Pitch	18 per inch		1.5 millimeters		14 per inch
Depth of thread	.....		.....		0.571 inch
Taper	None		None		1 in 16 on diam
Angle of thread	60°		60°		60°

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ng are approximate costs as of 1922:

.....	$35 – $45
ade.....	55 – 80
.....	100 – 185
grade.....	120 – 200
e	95 – 260
.....	20 – 40
.....	6 – 10
or.....	8 – 16
.....	50 approx.
.....	40 approx.
.....	0.35– 2.00

Young, A. P., *Automobile Engineer*, 7, p. 191 et seq., nd Weaver, *Gas Engine Ignition;* Taylor–Jones, E., 8; Campbell, N. R., *Phil. Mag.*, 37, p. 284, 372, 1919; *s of Electric Spark Ignition in Internal Combustion y Committee for Aeronautics* (U. S.) Reports Nos. 51, ldt, P. M., *The Gasoline Automobile*, Vol. III.

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ILLUMINATION, INTERIOR. — (*See also Illumination, Illumination, Street; Vision, Laws of.*) The chief problems in interio tion are: (1) to render visible certain objects or surfaces so as to av and injury of the eyes, and to enhance in effectiveness all operations on good vision; (2) to reveal in their true values the architecture a tion of interiors; and (3) to produce intrinsic artistic effects throug trol of the color, intensity and direction of light. Engineering p been developed mainly with reference to the first of these problems, other two are often of chief importance and must at all times be For a discussion of the hygienic aspects of illumination, see *Vision,*

Advantages of Good Light. — The advantages of good light ar ent that a list of its principal effects may seem commonplace. Th are of such great importance, however, particularly in their relation work, that they should receive careful attention. The main adv good light, including the effects of bright and cheerful surroundings buildings, include the following:

1. A tendency to reduce accidents.
2. Promotes greater accuracy in workmanship.
3. Contributes to increased production for the same labor cost.
4. Tends to reduce eye strain.
5. Helps to improve working and living conditions.
6. Affords greater contentment among the employees.
7. Order and neatness around the shop are encouraged.
8. Supervision of the men is made easier.

It is rather interesting to note that items 4, 5, 6, 7 and 8 all hav bearing on accident prevention in factory work.

Reference Surfaces. — Illumination problems are usually work reference to one or more planes or surfaces whose illumination can b an index to the meeting of the general requirements. Unless specia ations dictate otherwise the plane selected is usually horizontal and of from 2½ to 3 feet above the floor, corresponding with that of desks, counters, work benches, etc. In many cases other surfaces, a walls, faces of shelving, stacks of books, etc., are more significant th trarily chosen horizontal plane. The proper reference surface for th tion of show windows is usually a surface inclined or curving upwar base of the window. In many art galleries and on the stage of a t proper reference planes are vertical. The most significant reference any problem should be selected by a study of the special requiremen

Coefficient of Utilization. — The ratio of the luminous flux rec reference plane to that produced by the light sources used for its il is known as the coefficient of utilization of the system. The light r a reference plane is often termed useful flux to distinguish it from flux output of illuminants. The above terms may be very mislead indiscriminately, for the flux received by other surfaces than a refer is usually essential to the effectiveness of a system of illumination.

DIRECT, INDIRECT AND SEMI-INDIRECT ILLUMINA Methods of illumination may be classified according to the manne light is delivered to the working surfaces. Direct light is that receiv from lamps and their accessory shades and reflectors. Indirect li received by reflection from some extended diffusing surface, as a ceili Systems of illumination are either direct, indirect or semi-indirect. In system the illuminants, including their reflectors and shades, are e

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of their light in the direction of the reference areas.
ls and ceilings is received as an auxiliary component.
wer surfaces of a room have the highest illumination.
nadows, the sharpness of which vary inversely with
lished or glazed surfaces may produce an annoying
on, due to the specular reflection of the exposed light
are a source of great annoyance and fatigue. The
intensify and in some cases exaggerate relief effects,
as aids to vision where color differences are slight.
ighting conceals all primary sources and distributes
urfaces, usually white ceilings and upper walls. The
have the highest illumination. Shadows are elimi-
intensity. Glare from visible light sources is avoided
of glazed surfaces is generally inappreciable. The
on the lower surfaces of a room is very great. The
the indirect system is frequently stated to closely
is not strictly true, however, for daylight though
es a diminishing gradation of illumination from the
the room. The faintness of shadows with indirect
ief effects.

ediates between the two extremes. The light sources
sion by inverted bowl reflectors of translucent glass,
a moderate amount of direct light and reflect the
There is an absence of agreement as to the most
indirect light. It is desirable that the brightness of
l equal or slightly exceed that of the ceiling. The
be adequate to create a normal relief effect and to
f working surfaces to a value above that of the back-
of T. W. Rolph (*Trans. Ill. Eng. Soc., Vol. 7, pp. 234*
y satisfactory results are secured with a direct com-
t.

ich has proved very satisfactory in certain cases is
us bowl fixture system, in which the component of
der bowl may be controlled by the choice of density
By this means it is possible to keep the brightness of
e down to practically any degree that may be thought
of particular value where Mazda C lamps, with their
yed within the bowl of the fixture.

is systems outlined a large allowance must be made
gical effect. Critics of indirect lighting assert that
shadows and the reversal of the customary gradation
oying, distract attention, distort the sense of distance
hers find the same aspects advantageous and hold
are by specular reflection outweighs other considera-
qualities of direct lighting avoided by the indirect
s due to unshaded and poorly-located lamps rather
eral investigators have studied the relative illumina-
or equally effective vision by the different systems.
are inconsistent and are probably due to incidental
l contrast between working surfaces and backgrounds
sible light sources. It is agreed that with equal skill
anks first, semi-indirect lighting second and indirect
of utilization.

Direction of Illumination. — There is no well-de-
illumination. Daylight white is desirable for exact

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color matching and for color printing, but is not essential for other The Moore carbon-dioxide tube reproduces daylight white with gre and also closely approaches daylight in diffusion. True white ma obtained from arc and incandescent lamps by the aid of color screer out the hues present to excess. Magnetite arcs and nitrogen-filled lamps are best adapted to this process. Of the illuminants in comm white flame arc and the intensified carbon arc give the nearest ap white. The nitrogen-filled tungsten lamp surpasses other incandesc in whiteness. The ordinary tungsten lamp and the best grade of mantles are somewhat unlike in tone, but differ about equally fr Light having a predominant hue, as that of the mercury arc, is super revelation of fine detail. Light of amber tint is regarded as softer a than light of bluish or greenish tint. The tint of indirect light is m the color of the reflecting walls and ceilings.

In determining the direction of light the avoidance of glare and s the visual field is most important. In the display of art objects an tural details the dominant direction should be carefully chosen to correct sense of relief. An inversion of light and shade by artifici compared with daylight is especially to be avoided. Head and han are especially to be avoided in reading and in mechanical operat old rule of light from above the left shoulder is an excellent one. I found advantageous in schoolrooms, offices and drafting rooms to k and tables with the windows to the left of those at work and to d artificial light sources from symmetrical positions toward the windo to give a directive effect similar to daylight.

QUANTITY OF LIGHT AND NUMBER OF ILLUMINA DIRECT LIGHTING. — The intensities of illumination required purposes are given in the article on *Vision, Laws of*. The simplest il problems are those in which a uniform illumination of E foot candle on a horizontal plane of A square feet. The useful flux required is th E. If a factor of utilization K is known or assumed for the condit room the total flux F, in lumens, to be produced by the illuminants i

$$F = \frac{AE}{K}.$$

The total watts of electric power or the cubic feet per hour of gas co to produce the required flux is found by dividing the required flux by per watt or per cubic foot per hour given by the type of light source sideration.

LUMENS ON REFERENCE PLANE PER WATT, ELECTRIC

(Lamps and glassware are assumed to be clean and at a height above th plane not exceeding 15 feet.)

Lamp	Reflector or globe	Ceiling	Walls
Tungsten	Silvered reflector	Light	Light
Tungsten	Prismatic reflector	Light	Light
Tungsten	Prismatic reflector	Light	Dark
Tungsten	Enamelled reflector	Light	Light
Tungsten	Enamelled reflector	Light	Dark
Gem	Prismatic reflector	Light	Light
Gem	Prismatic reflector	Light	Dark
5-amp. d-c. arc	Opal inner globe	Light	Medium
Mercury arc	Enamelled reflector	Medium	Medium

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RENCE PLANE PER CUBIC FOOT OF GAS PER HOUR

umed to be clean; new mantles; height above reference gas, 700 B.t.u. per cu. ft.)

Reflector or globe	Ceiling	Walls	Effective lumens per cu. ft. per hour
l globe	Light	Light	49
l globe	Light	Dark	27
l reflector	Light	Light	85
l reflector	Light	Dark	50
matic reflector	Light	Light	140
matic reflector	Light	Dark	128
ghed ball	Light	Light	101
ghed ball	Light	Dark	75
baster globe	Light	Light	66
baster globe	Light	Dark	48
baster globe	Light	Light	87
baster globe	Light	Dark	65

he lumens per watt or per unit of gas consumption nts, see *Lamps, Incandescent; Lamps, Arc* and *Gas*

e Flux. — The preliminary estimates for most prob- on can be made with fair accuracy from the preced- irical values based on laboratory and service tests. *Vol. 3, p. 518, and Vol. 4, pp. 321, 849, 885.*)

s. — Having found the total wattage or rate of gas ed the next step is to select a proper number and is seldom possible to produce a uniform illumination a radial distance greater than the height of the lamp ractically impossible to avoid shadows from a single cal and uniform spacing of several lamps is necessary y direct lighting. The use of many small units with iformity and reduces shadows. The use of few large otes economy. In many cases a compromise must plans. The various spacing schemes in vogue are ypes, viz.: (*a*) a long and narrow room with a single r line, the spacing about equal to the width of the oom divided into squares with lamps located at the of each square preferably not greater than twice the lamps above the reference plane; (*c*) lamps at corners d spaced at not more than twice suspension height lf the spacing from lamp to lamp. Plans of these 1.

cing of lamps very careful attention should be given of ceiling space. Each bay or division may properly ng as this will greatly reduce the shadows cast by possible to secure a very uniform direct illumination ymmetrical distribution if a certain critical ratio of ded. The value of this critical ratio depends on the

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form of light distribution, as shown by the prototype curves of Fig. 10 in t article on *Illumination, Laws of*. These critical ratios, while of interest, a scarcely ever so exact as to warrant the placing of too much dependence upon definite numerical figures, and it should also be remembered that where uniform illumination is necessary, direction of light and shadows are usually of importance as well as uniformity. According to Harrison, it is difficult to obtain illumination results which are satisfactory in all of these respects with a spacing ratio greater than 1.67.

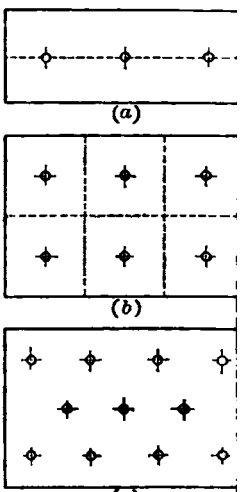


Fig. 1. Spacing Schemes f Direct Lighting

Keeping in mind that there are numerous types of reflectors such as those of metal, opal glass, and the like, the following notes on Holophane and on X-ray units are included merely to illustrate the meaning of the critical ratio mentioned in the preceding paragraph.

Holophane reflectors for tungsten lamps are made in three types, viz., extensive, for wide spacing, the critical ratio of height to spacing being 0.5; intensive, for medium spacing, the critical ratio being 0.67; focussing, for high suspension and close spacing, the critical ratio being 1.33. A spacing chart for Holophane and for X-ray reflectors is shown in Fig. 2. With a ratio of height to spacing below the critical value the light is spotted. With a higher ratio the illumination remains uniform, but with some loss of utilization efficiency, due to the increased absorption of light by the walls. The efficiency does not follo an inverse square relation to the height in any case and is but slightly affecte

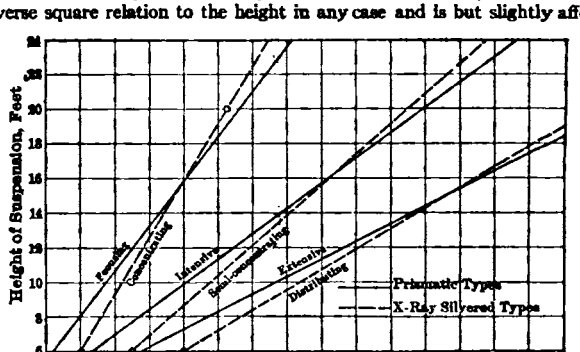


Fig. 2. Maximum Spacing of Reflectors for Uniform Illumination

when the walls are of light color and the reflectors give a strong downward dis tribution. In very large rooms the effect of suspension height on utilizatio efficiency is trifling. The suspension height should if possible be sufficient t remove the light sources from direct lines of vision.

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Single-lamp Units vs. Clusters. — A single-lamp electric unit is les

of several lamps having the same total candle-power. The cross-absorption of light in clusters may be as high as 10 per cent. Gas clusters of the so-called "arc" type have an advantage over single-mantle lamps in heat conservation and facility of remote control. In fact, single-mantle lamps offer a small range of candle-power.

Point-by-point Calculations of Illumination. — Such calculations are very useful in checking up the distribution of illumination. The method of calculating is described in the article on *Illumination, Laws of*.

METHODS OF INDIRECT LIGHTING. — The process of determining the power required to produce a given illumination of any area by indirect means is the same as that outlined above for direct lighting, a suitable value of the efficiency of illumination being used. There are two types of indirect lighting, the bowl and the cove. Indirect lighting from suspended bowls affords greater flexibility in light distribution than cove lighting and is capable of producing more uniform and efficient effects. The efficiencies of utilization obtainable with indirect bowl lighting are given by the National X-ray Reflector Co. as ranging from 0.20 to 0.32 with dark walls and from 0.24 to 0.34 with light walls for ratios of minimum floor dimension to ceiling height of from 1.0 to 3.5; the ceilings are assumed to be painted white and an allowance of 20 per cent for loss of light by dust and lamp aging is included in these values. The proper suspension height for indirect bowl units is approximately three-quarters the height of the room. In spacing the units a symmetrical arrangement at the centers of ceiling squares is highly desirable. The maximum dimension of such a spacing square or rectangle should not exceed a certain ratio to the ceiling height for the best results, viz., for ceiling heights below 12 feet, the maximum ratio is 1.5; for ceiling heights from 12 to 17 feet, the maximum ratio is 1.75; above 17 feet, 2.0.

In the cove type of indirect lighting the lamps are placed in the trough of the cove with axes horizontal, and are backed with a trough reflector of high efficiency. Light is thus thrown to the upper surface of the cove and from it reflected into the room. Cove lighting about the base of a flat-domed ceiling is somewhat more effective than with a flat ceiling. Dust tends to collect on lamps and reflecting surfaces and seriously reduces the average efficiency of the system.

MAINTENANCE OF EFFICIENCY. — Loss of efficiency in lighting systems may be due to the aging of lamps, failure to maintain proper lamp voltage, and the collection of dirt on lamps, reflectors, shades and the reflecting surfaces of the room. Systematic inspection and cleaning are essential if the most economical results are to be secured from large systems. Lamps should be replaced when the bulbs become badly blackened. Globes and reflectors should be cleaned at least once a month for most effective service. C. E. Clewell, *Factory Lighting*, p. 48, reports that a depreciation test of an office installation of tungsten lamps in glass reflectors showed a gradual loss of efficiency which reached a steady value of 19 per cent in 30 days. A similar test in a factory showed a gradual reduction of efficiency which reached a steady value of 48 per cent in 24 days.

In the table on page 804 are given the approximate losses expressed as percentages of the initial illumination on the working plane are taken from *Lighting Data* of the Edison Lamp Works by A. L. Powell for April, 1920.

Arc lamps depreciate in efficiency between trimmings and cleaning from 15 to 30 per cent due to the collection of ash on the inner globes. Arcs are relatively little affected by outside dirt and are quite generally preferred to incandescent

	4 weeks	8 weeks	12 weeks	16 weeks	20 weeks
RLM standard dome..	5	8	10	12	14
Dense opal bowl direct lighting.....	7	10	13	16	19
Prismatic bowl direct lighting.....	9	13	16	19	22
Light density opal bowl direct lighting.....	12	18	24	28	30
Semi-indirect.....	14	22	29	35	40
Totally indirect.....	20	29	37	44	50

to the ceilings of rooms with indirect lighting to prevent the accumulation of dust and the loss of whiteness.

SPECIAL LIGHTING PROBLEMS. — In art galleries for the exhibition of paintings a moderate general illumination should be provided from sources giving good diffusion. Paintings should be illuminated by direct light received from concealed sources several feet in front of, and slightly above, the level of the paintings. The direction of this light should be carefully studied to avoid specular reflection from glass or glossy portions of paint. For good color effects the light should approach as near as possible the color of daylight. Sculpture is effectively lighted by indirect or semi-indirect methods, but the illuminants may properly be suspended along the side of the room containing the windows to obtain directed illumination sufficient to reproduce the relief effects of daylight.

In ritualistic churches it is important to produce a brilliant illumination of the sanctuary with a large vertical component by means of concealed lamps. The distribution of lamps in the nave should be chosen to reveal the architectural effects of the structure. Large and low-hanging pendant fixtures in the axis of the room are generally undesirable. Bracket clusters, groups of small incandescent lamps worked into the capitals of pillars, and small pendant fixtures in the arcades can he used with excellent effect. In non-ritualistic churches adequate reading light is desired at all pews. Brilliant light sources in the field of vision are especially to be avoided. If a balcony is used the light sources should be hung high and thoroughly diffused. The platform should be brightly lighted, but by light sources not visible to the auditors.

Stages and platforms in theatres and public halls should have high illumination, especially in vertical planes, but the light sources should be entirely concealed.

Office desks should be lighted with a view to preventing head and hand shadows and glare from glossy surfaces. Well-diffused general lighting with a dominant component from above the left shoulder is perhaps the best solution of the problem. When local lighting is required a pendant lamp in a deep conical reflector of green flashed opal glass suspended at a height above the desk of 2 to 2.5 feet and near the left edge of the desk will fulfill all requirements.

Show windows should be lighted by entirely concealed light sources placed at or above the upper edge of the window. Illumination should be designed for a surface which is inclined or concave upward from the lower edge of the window. On brilliantly lighted business streets a very high illumination of 20 foot-candles or more is necessary to attract attention. On less brilliantly-lighted streets the illumination may be reduced in proportion. The lamps should be backed by highly efficient reflectors. The form of light distribution

mension of the window, the degree of concentration f the height to the depth of the window space. Tests r (*Ill. Eng. Soc., Vol. 8, p. 555*) show that the coeffi- trim surface depend on the ratio of height to depth of results cited range from 58 per cent for a height to ent for a ratio of 2. Show cases in the aisles of stores how-window lighting. In brightly-lighted rooms the r of the case must be very high to gain attention. are required and these may properly be placed in n the upper dihedral angles of the case. Tublar and ate, due to their space economy.

Bell, Louis, *Art of Illumination;* Steinmetz, C. P., *ination;* Cravath, J. R., and Lansingh, V., *Practical* W. E., *Illumination and Photometry;* Barrows, W. E., *umination;* Trotter, A. P., *Illumination, Its Distri-* Bloch, L., *The Science of Illumination; Lectures on* Johns Hopkins University, Vol. 2; Franklin, W. S., ., *Electrical Photometry and Illumination; Trans. Ill.* E.; *Trans. Am. Gas Inst.; Proc. Nat. El. Lt. Assoc.;* .E.S.; Croft, Terrell, *Practical Electric Illumination; uing; Illuminating Engineering Practice,* University ating Engineering Society Lectures, 1917; Ferguson, rrison, Ward, *Electric Lighting.*

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ILLUMINATION, LAWS OF. — (*See also Angles; Photometric Quantities; Vision, Laws of.*) Light may come from either a point source or a finite source. Serious errors may result from the application of the laws of point sources to the illumination from finite areas, due to the non-parallel rays. These errors are negligible, however, when the distance separating the light source and the illuminated surface exceeds ten times the greatest projected dimension of either in a plane normal to the mean direction of light. For definitions of quantities see *Photometric Quantities.*

LIGHT FROM A POINT SOURCE. — When the light comes from a point source the "inverse square" and the "cosine" laws apply:

Inverse Square Law. — The illumination from a point source varies inversely as the square of the distance from the source. This law rests on the geometrical fact that the spherical area intercepting light flux varies as the square of its radius.

Cosine Law. — The illumination received by an element of surface varies as the cosine of the angle of incidence. The basis of this law is also geometrical. These two laws may be stated thus:

$$E = \frac{I \cos \alpha}{l^2},$$

where E = intensity of illumination in foot-candles; I = intensity of the light source in candle-power; α = angle of incidence of light on the illuminated area and l = distance in feet from the light source to the point illuminated.

Calculation of Light Flux and Mean Intensities from Point Sources — Let I_θ be the mean intensity of a light source at an angle θ from the axis about which the light distribution is symmetrical, usually the vertical axis. The flux within an elementary zone at this angle of inclination is then

$$dF = I_\theta \, d\omega = 2\pi I_\theta \sin \theta \, d\theta.$$

The flux within any finite zone about the axis of distribution may be found by integration when the law of distribution is known. In general, however, it is necessary to employ graphical means of integration for this purpose. The mean intensity within any finite zone cannot be found by direct average, since each beam bears a weight proportional to $\sin \theta$. The graphical methods described below are the most serviceable.

Protractor Methods. — This method is adapted to quick approximations of mean zonal, mean hemispherical and mean spherical intensities. The method assumes a sphere of light distribution divided into zones of equal solid angular content, i.e., of equal altitude. A direct average of the mean intensities of the several zones gives the general mean for all the zones included, since each component zone bears equal weight. For convenience it may be assumed generally that the mean intensity in any zone agrees closely with that at the angle which bisects the area of the zone. Fig. 1 shows a convenient subdivision of the sphere based on this assumption. To obtain the mean spherical candle-power the intensities at all the angles indicated by radial lines are averaged. This result multiplied by 4π gives the total flux from the source. Similarly the average of the intensities at the angles indicated in either hemisphere gives the mean hemispherical candle-power, which may be multiplied by 2π to obtain the hemispherical light flux. The average taken at the three lowest positions gives the mean intensity

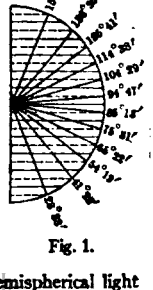
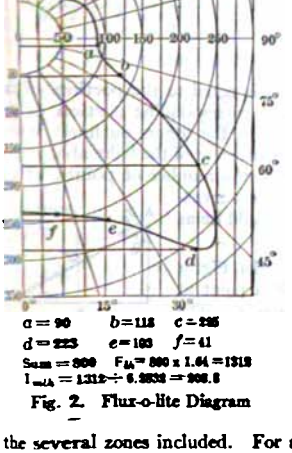


Fig. 1.

from 60° and this value, multiplied by π, gives the flux within the 0° – 60° zone. For convenience in practice a transparent protractor may be prepared with the reference angles shown by black lines. This protractor may be placed over the polar distribution curve and the values for averaging read off directly. The accuracy of the method depends on the regularity of the distribution curve.

Flux-o-lite Diagram. — (Fig. 2.) This diagram is constructed from the polar distribution curve by drawing vertical reference lines tangent to the candle-power circles, with uniform intermediate divisions as desired. To find the flux within any zone the horizontal projection of the mid-zone intensity is measured on the scale created by the vertical reference lines. Multiply this value by the constant which corresponds to the arc of the zone in the accompanying table.



$a = 90$ $b = 118$ $c = 225$
$d = 223$ $e = 163$ $f = 41$
Sum = 860 F_M = 860 x 1.64 = 1312
I_{mh} = 1312 ÷ 6.2832 = 208.8

Fig. 2. Flux-o-lite Diagram

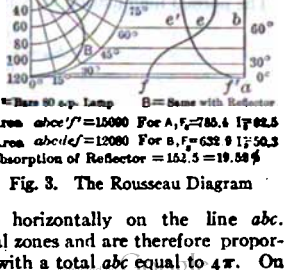
The flux within any angular limits is found by summing the components from the several zones included. For accuracy a large number of small component zones should be taken. For proof, it is readily shown that the solid angular content of any zone is equal to

Arc of zone, degrees	Constant
5	0.548
10	1.098
15	1.64
20	2.18
25	2.72
30	3.25

$$4\pi \sin\theta \sin\frac{\alpha}{2},$$

where α is the arc of the zone in degrees and θ the bisecting angle measured from the vertical axis. The above constants in each case equal $4\pi \sin \alpha/2$ and the horizontal projections read from the diagram are in each case equal to the assumed mean intensity of the zone times the sine of the bisecting angle.

Rousseau Diagram. — (Fig. 3.) The Rousseau diagram admits of considerable accuracy, but involves the measurement of area. The arcs of the several zones of distribution are projected horizontally on the line *abc*. The intercepts equal the altitudes of the several zones and are therefore proportional to their several solid angular contents, with a total *abc* equal to 4π. On each projection line is laid off from *abc* a length equal to the radius of the polar



A = Bare 80 c.p. Lamp B = Same with Reflector
Area *abcef* = 15090 For A, F_s = 785.4 I_{mh} = 192.5
Area *abcdef* = 12080 For B, F_s = 632 9 I_{mh} = 50.3
Absorption of Reflector = 152.5 = 19.5%

Fig. 3. The Rousseau Diagram

curve at the corresponding angle. The terminal points are then connected by the smooth curve *def*. The area *abcdef* so inclosed represents the total flux since

$$\text{Area } abcdef = \int_0^{4\pi} I \, d\omega = 4\pi I_s.$$

The total flux is

$$F_s = \frac{4\pi \times \text{area } abcdef}{\text{length } ac}.$$

The flux in any zone, e.g., between 0° and 60°, is

$$F_z = \frac{4\pi \times \text{area } abef}{\text{length } ac}.$$

The mean intensity between any angular limits is equal to the portion of the area *abcdef* between those limits divided by the corresponding portion of the base line *abc*. This method is to be preferred to the others outlined where accuracy of a high order is desired, as in the measurement of the light absorption of reflectors, globes, shades, etc. In such cases the number of points of the photometric distribution curve determined by direct measure and referred by projection to the line *def* should be as large as practicable.

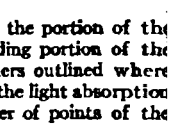


Fig. 4.

Calculation of Illumination at Points. — In Fig. 4 let A be the location of an illuminant and P a point at which the illumination from A is to be determined. The three most important cases of this problem refer respectively to the illumination of elements of surface at P located in horizontal and vertical planes and in a plane normal to the light path AP. From the laws of inverse squares and of cosines (*see above*) the horizontal illumination at P is

$$E_h = \frac{I_\theta \cos\theta}{d^2} = \frac{I_\theta \cos^3\theta}{v^2}.$$

The vertical illumination at P is

$$E_v = \frac{I_\theta \sin\theta}{d^2} = \frac{I_\theta \sin^2\theta}{h^2}.$$

The normal illumination at P is

$$E_n = \frac{I_\theta}{d^2} = \frac{I_\theta \cos^2\theta}{v^2} = \frac{I_\theta \sin^2\theta}{h^2}.$$

Calculations of this type are facilitated by a chart (Fig. 5) showing the value of θ for various values of v and h, and by tables giving the values of the illumination constants $\cos^3\theta/v^2$, $\sin^3\theta/h^2$, and $\cos^2\theta/v^2$ for various values of v and h. Such tables are given below.

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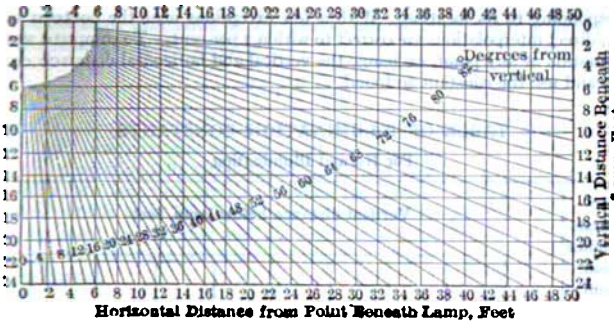


Fig. 5. Angle of Effective Beams for Point-by-point Calculations

TABLE OF ILLUMINATION CONSTANTS

For Horizontal and Vertical Illumination

Horizontal distance from point beneath lamp, feet	Vertical distance below lamp, feet									
	6	7	8	9	10	12	14	16	18	20
0	0.0278	0.0204	0.0156	0.0127	0.0100	0.00695	0.00510	0.00391	0.00309	0.00250
1	0.0266	0.0198	0.0152	0.0122	0.0099	0.00687	0.00505	0.00388	0.00307	0.00249
2	0.0236	0.0182	0.0143	0.0115	0.0094	0.00665	0.00491	0.00382	0.00303	0.00246
3	0.0200	0.0158	0.0129	0.0106	0.0088	0.00635	0.00476	0.00371	0.00296	0.00241
4	0.0160	0.0134	0.0112	0.0094	0.0080	0.00592	0.00453	0.00357	0.00288	0.00235
5	0.0126	0.0111	0.0094	0.0082	0.0072	0.00547	0.00426	0.00340	0.00278	0.00228
6	0.0098	0.0089	0.0080	0.0071	0.0063	0.00496	0.00397	0.00320	0.00264	0.00220
8	0.0060	0.0058	0.0055	0.00515	0.00476	0.00400	0.00333	0.00279	0.00235	0.00200
10	0.0038	0.00385	0.00382	0.00369	0.00353	0.00312	0.00274	0.00238	0.00211	0.00179
12	0.0025	0.00261	0.00266	0.00268	0.00263	0.00245	0.00222	0.00200	0.00178	0.00158
14	0.0017	0.00182	0.00191	0.00195	0.00196	0.00190	0.00180	0.00167	0.00152	0.00138
16	0.0012	0.00131	0.00140	0.00146	0.00149	0.00151	0.00145	0.00138	0.00129	0.00119
18	0.00088	0.00097	0.00105	0.00110	0.00114	0.00118	0.00118	0.00114	0.00109	0.00103
20	0.00066	0.00074	0.00080	0.00085	0.00089	0.00095	0.00097	0.00095	0.00093	0.00088
24	0.00038	0.00044	0.00050	0.00053	0.00057	0.00062	0.00065	0.00067	0.00067	0.00066
28	.....	0.00028	0.00032	0.00036	0.00039	0.00043	0.00046	0.00048	0.00049	0.00049
32	.....	.....	0.00022	0.00024	0.00027	0.00030	0.00033	0.00035	0.00036	0.00037
36	.....	.....	.....	0.00017	0.00019	0.00022	0.00024	0.00026	0.00028	0.00029
40	.....	.....	.....	.....	0.00014	0.00017	0.00019	0.00020	0.00021	0.00022
45	.....	.....	.....	.....	.....	0.00012	0.00014	0.00015	0.00016	0.00017
50	.....	.....	.....	.....	.....	.....	0.00010	0.00011	0.00012	0.00013

The horizontal illumination at any point equals the intensity of the light source in its direction (see Fig. 5) multiplied by the constant in the above table

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corresponding to its location. With a few exceptions near the bottom of the table, direct interpolations are correct to within 2 per cent. To compute vertical illumination at any point, exchange the vertical and horizontal distance components and use the constant so found.

TABLE OF ILLUMINATION CONSTANTS

For Normal Illumination

Horizontal distance from point beneath lamp, feet	Vertical distance below lamp, feet									
	6	7	8	9	10	12	14	16	18	20
0	0.0278	0.0204	0.0156	0.0127	0.0100	0.00695	0.00510	0.00391	0.00309	0.00250
1	0.0270	0.0200	0.0154	0.0122	0.00990	0.00690	0.00507	0.00389	0.00308	0.00249
2	0.0250	0.0189	0.0147	0.0118	0.00962	0.00675	0.00500	0.00384	0.00304	0.00247
3	0.0222	0.0172	0.0137	0.0111	0.00917	0.00653	0.00487	0.00377	0.00300	0.00244
4	0.0200	0.0154	0.0125	0.0103	0.00842	0.00625	0.00472	0.00367	0.00294	0.00240
5	0.0164	0.0135	0.0112	0.00943	0.00800	0.00592	0.00452	0.00356	0.00286	0.00235
6	0.0139	0.01175	0.01000	0.00855	0.00735	0.00555	0.00431	0.00342	0.00278	0.00229
8	0.0100	0.00885	0.00780	0.00689	0.00610	0.00480	0.00385	0.00312	0.00258	0.00215
10	0.00735	0.00672	0.00610	0.00552	0.00500	0.00410	0.00338	0.00281	0.00235	0.00200
12	0.00556	0.00518	0.00480	0.00444	0.00410	0.00347	0.00294	0.00250	0.00214	0.00184
14	0.00431	0.00408	0.00385	0.00361	0.00338	0.00294	0.00255	0.00221	0.00192	0.00168
16	0.00342	0.00327	0.00312	0.00297	0.00281	0.00250	0.00221	0.00195	0.00172	0.00152
18	0.00278	0.00268	0.00258	0.00247	0.00235	0.00214	0.00192	0.00172	0.00154	0.00138
20	0.00229	0.00222	0.00215	0.00208	0.00200	0.00184	0.00168	0.00152	0.00138	0.00125
24	0.00163	0.00160	0.00156	0.00152	0.00148	0.00139	0.00129	0.00120	0.00111	0.00102
28	0.00122	0.00120	0.00118	0.00115	0.00113	0.00108	0.00102	0.00096	0.00090	0.00084
32	0.00094	0.00093	0.00092	0.00090	0.00089	0.00086	0.00082	0.00078	0.00074	0.00070
36	0.00075	0.00074	0.00074	0.00073	0.00072	0.00069	0.00067	0.00064	0.00062	0.00059
40	0.00061	0.00061	0.00060	0.00059	0.00058	0.00057	0.00056	0.00054	0.00052	0.00050
45	0.00049	0.00048	0.00048	0.00047	0.00047	0.00046	0.00045	0.00044	0.00043	0.00041
50	0.00039	0.00039	0.00039	0.00039	0.00038	0.00038	0.00037	0.00036	0.00035	0.00034

The normal illumination at any point equals the intensity of the light source in its direction (see Fig. 5) multiplied by the constant in the above table corresponding to its location.

Calculation of Solid Angle Subtended by Illuminated Area. — In many cases it is desired to compute the total flux of light which falls upon a plane area from an approximate point source. This problem resolves itself into two elements, (1) to determine the mean intensity acting toward the illuminated plane, to which the methods previously described apply, and (2) to determine the solid angle subtended by the area illuminated at the source of light. The following theorems apply to the latter problem.

The solid angle subtended by a circle with the light source in its axis (Fig. 6) is

$$\omega = 2\pi (1 - \cos \alpha).$$

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ded by a rectangle, one corner of which is directly be-
Fig. 7), is

$$\omega = \tan^{-1}\frac{ac}{hd}.$$

f S falls on one edge of the area, the latter may be
es to meet the above theorem.
within the area, the area may
sections. When the projec-
ig. 7, the surface may be ex-
em and the solid angle sub-
substracted from that of the



Fig. 6.



Fig. 7.

S OF LIGHT DISTRIBUTION FOR UNIFORM

he most important phase of this problem, viz., the
horizontal plane by one and by many illuminants,
rm of light distribution required to obtain uniform
om a single lamp is found by reversing the expression
,

$$\frac{I_\theta \cos^3\theta}{v^2} \quad \text{to} \quad I_\theta = \frac{E_h v^2}{\cos^3\theta},$$

ants. The resulting form of polar curve for various
orizontal
n in Fig.
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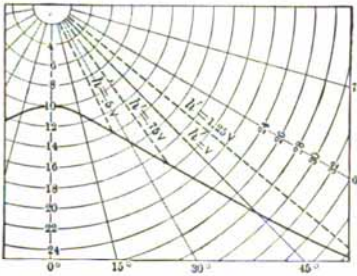


Fig. 8. Light Distribution Required to Obtain Uniform Horizontal Illumination from One Source

ratios of horizontal spacing s to vertical distance to
light distribution shown in Fig. 10 are required.

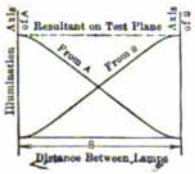


Fig. 9.

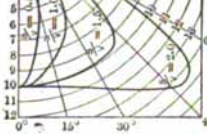


Fig. 10. Curves of Light Distribution for Uniform Illumination from many Sources

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sity of illumination, except in that portion of the room lying outside the ou
row of lamps. By aid of well-designed reflectors it is possible to closely appr
mate the typical distribution curves for certain ratios of spacing to height
this ratio is important as a criterion in the selection of reflecting devices.

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p. 601 and p. 1367, and numerous other articles in recent volumes. See a
Bibliography in article on *Illumination, Interior.*

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ILLUMINATION, STREET. — (*See also Illumination, Interior; Illumination, Laws of; Lamps, Arc; Lamps, Incandescent; Lighting Plants.*) Street lighting is intended to promote public safety, facilitate travel and business, and reveal architectural effects during hours of natural darkness. Experience shows that good street lighting attracts traffic and stimulates retail trade. The most important factors affecting the degree of street illumination required are the density of traffic, prevalence of retail business, degree of police supervision needed and the architectural importance of the thoroughfare. In moderate and dim light vision depends primarily on differences of brightness and is but slightly assisted by color distinctions. Objects may be seen directly and in fine detail against a darker background, but are seen in mass or silhouette against a brighter background.

Requirements of Street Lighting. — The most important streets require sufficient illumination for direct and detail vision to clearly reveal vehicles, persons, obstructions, irregularities of the pavement, and to permit the easy reading of timepieces and addresses, which calls for an average of about 0.5 foot-candle and a minimum of about 0.2 foot-candle on the most important, working surface. Uniform illumination without deep shadows, which may be obtained by well-diffused light sources with fairly close spacing, is highly desirable on important streets.

Secondary streets with moderate evening traffic and orderly conditions require greater illumination at intersections than at intermediate points. The silhouette aspect of vision is very important in such streets and emphasizes the need of fairly bright and even roadway illumination without spots of deep shade from foliage. An average illumination of about 0.1 foot-candle and a minimum of about 0.06 foot-candle meet the reasonable requirements of such streets. In this range of intensities the eye is highly susceptible to glare. Brilliant light sources without diffusing globes and suspended at a low level often largely defeat their purpose under these conditions.

Minor streets with scattered buildings and infrequent travel require mainly beacon lighting, equivalent in intensity to moderate moonlight, or normal illumination varying from a minimum of about 0.02 foot-candle to an average of about 0.03 foot-candle. At such low intensities the need of good diffusion at light sources is most acute, but is quite generally neglected for reasons of supposed economy.

Reference Planes. — Street illumination in America is usually referred to normal reference planes (i.e., perpendicular to the light rays), and to horizontal planes in Europe. There is wide diversity in the elevation of reference planes, the most common levels being that of the pavement and that of a plane four feet above the pavement. The use of normal planes of reference takes satisfactory account of the light from but one source, while it is possible to sum up the light received from all directions on horizontal planes. It is evident from the cosine law of incidence that the horizontal illumination from low and distant lamps is less in magnitude and more difficult of exact measurement than the normal component. Normal illumination is a more useful index to the visibility of upright objects. Small objects as cards and timepieces are instinctively held normal to the rays of the nearest lamp. The vertical component of street illumination should have due consideration for its importance in revealing the architecture of buildings and assisting in the recognition of persons.

TYPES OF ILLUMINANTS. — The illuminants most extensively used in street lighting are as follows: (*For detailed descriptions and data see Lamps, Arc, Lamps, Incandescent; and Gas Lighting.*)

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Electric Arc Lamps on Series Circuits, including (*a*) carbon arcs open d-c., enclosed d-c. and enclosed a-c. types, with standard currents of 6.6 7.5 and 9.6 amperes; (*b*) flame carbon arcs of open d-c., enclosed d-c. and enclosed a-c. types, with standard currents of 6.6, 7.5 and 9.6 amperes; and (*c* metallic or luminous arcs of open d-c. type with standard currents 4.0, 5.5 and 6.6 amperes, arranged for suspension and pedestal mounting.

Electric Arc Lamps on Multiple Circuits at or near 110 volts, including (*a*) carbon arcs of open d-c., enclosed d-c. and enclosed a-c. types; (*b*) flame carbon of open d-c., enclosed d-c. and enclosed a-c. types; and (*c*) quartz tube mercury arcs.

Electric Incandescent Lamps, Series Type, are made only in the gas filled design with standard currents of 5.5, 6.6, 7.5, 15 and 20 amperes, and a range of candle-power of from 60 to 1000.

Electric Incandescent Lamps, Multiple Type at or near 110 volts of from 10 to 1000 watts.

High-pressure Gas Lamps of upright and inverted types, including (*a*) compressed gas, (*b*) compressed air and (*c*) compressed gas and air types.

Low-pressure Gas Lamps of upright and inverted types, including (*a*) single mantle lamps and (*b*) clusters of 3, 4 and 5 mantles.

Naphtha Vapor Mantle Lamps of self-contained, upright type with nominal candle-power of from 45 to 60.

Relative Advantages of Various Street Illuminants. — The advantages of electric lighting over gas lighting are (1) superior flexibility in sizes and possible locations, (2) greater ease of maintenance, (3) availability of white color, and (4) ease of control from central points with series circuits. The advantages of gas over electricity are (1) lower probability of interruption by accident, (2) steadiness of light and (3) the low intrinsic brilliancy of mantles.

Both electric and gas lamps suffer fluctuations due to unsteady pressure, but these conditions are more easily regulated in electric systems. Skillful maintenance is necessary to insure the proper efficiency of all street lamps, but affords a simpler problem in the case of electric lamps. High-pressure gas lamps require maintenance of an exceptionally high order.

Gas lamps are usually lighted by hand or by local automatic clock devices, though a few methods of central control have been devised. Naphtha vapor lamps are difficult to maintain in good efficiency and require costly attention, as each lamp must be filled by hand and heated by a blast torch before lighting. Such lamps should be used only where electric or gas lighting from central systems is not available.

Series electric lamps tend to economy in power distribution and to simplicity of central control. Separate mains must be used for all circuits requiring central control. Lamps operated in multiple from regular mains are lighted and extinguished by hand or by special clock switches. The high voltage of series circuits involves elements of danger and liabilities to interruption by accidents not found in parallel systems. Parallel systems can employ metal poles and grounded supports with greater safety. Incandescent electric lamps provide a very wide range of candle-power and involve smaller expense for maintenance and renewals than arc or gas lamps. On well-regulated circuits incandescent lamps surpass all other street illuminants in steadiness. The effectiveness of incandescent lamps as commonly installed without diffusing shades is often badly impaired by glare.

The color of light is relatively less important in street lighting than in interiors. White is generally preferred, as satisfying a sense of naturalness. Yellow and green have superior penetrating power in fog and smoke.

Small vs. Large Units. — Large units are generally more efficient than

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small units and involve relatively less expense for installation, maintenance and operation per unit of light production. With proper spacing the light of small units can be more completely utilized on roadways and produces a more uniform illumination. Small units lend themselves more readily to decorative schemes and to the lighting of shady streets and curving roadways. The effect of numerous small units at low levels, especially when unshaded, is distinctly more obtrusive and glaring than a small number of high power sources hung relatively high and well diffused.

Ratings of Street Lamps. — Street lamps are variously rated in candle-power, watts and rate of gas consumption. Much confusion is caused by loose usage of the term candle-power, which in different cases refers to mean horizontal, maximum, mean spherical, mean lower hemispherical and merely nominal values. Horizontal and maximum candle-power or that at any specified angle are significant only when comparing lamps having a definite form of light distribution in common. Mean spherical candle-power gives the gross light output of a lamp without any index to the effectiveness with which it may be utilized. It is an appropriate rating for a bare luminous element without accessories. The mean lower hemispherical candle-power is perhaps the best single index to the available light output of a lamp, but it cannot be conveniently measured in service. Candle-power ratings are sometimes of a purely nominal nature, e.g., the 1200 and 2000 candle-power ratings applied to carbon arc lamps denote lamps consuming 330 and 480 watts respectively.

The rated candle-power of gas and gasoline mantle lamps usually represents the maximum intensity which a given type of lamp can produce commercially. This rating almost invariably exceeds the average results in service by a wide margin due to imperfect maintenance, and can serve only as an index to the type of lamp referred to.

Incandescent electric lamps are rated in nominal horizontal candle-power, on the arbitrary bases of 1 candle-power for each 10 lumens of the actual initial performance. Such a nominal rating corresponds approximately to the old actual horizontal candle-power rating.

The candle-power rating of incandescent lamps installed on streets with reflectors is often taken to imply the actual average intensity at some angle between 15° and 25° below horizontal. A test of 130 incandescent lamps with flat enameled metal reflectors in service, which was made by the writer in 1913, showed the average candle-power of such units at 25° below horizontal to be 111.6 per cent of the rated horizontal candle-power of the lamps.

It should be noted that with the development of the Mazda C lamp a dome reflector has superseded to some extent the older flat radial reflector.

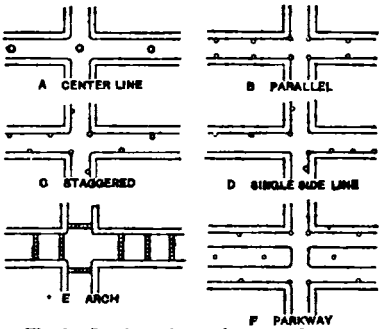


Fig. 1. Spacing Schemes for Street Lamps

Indefinite candle-power specifications in lighting contracts have caused much litigation. Arc lamps of all types are preferably rated in watts, as affording the only accurately measurable index to their performance. The specification that a reasonable average of candle-power as indicated by a prescribed photometric test shall be maintained is recognized as a valuable check on the quality of maintenence and service.

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SPACING OF LAMPS. — The plans of lamp spacing most w include: (1) center suspension at street intersections only; (2) cent sion at street intersections with one intermediate center suspension; suspension at street intersections and one intermediate curb unit; units, located opposite each other; (5) curb units, staggered; and park-way with a line of posts down its center. Several examples diagrammatically in Fig. 1. Plan A, or single center line spacing i effective method of using high-power units. Lamps may be hung wires between poles or buildings or from mast arms projecting over In some cases lamps are mounted directly on poles or standards in a ce way or series of safety isles. Center suspension is especially desirable one lamp is placed at an intersection. Plan B, or parallel spacing, a or staggered spacing, are best adapted to the brilliant lighting of main fares with high-power units and the lighting of ordinary streets with s The staggered arrangement favors the meeting of a definite minimu ment of roadway illumination with the smallest number of lamps Plan D, or single side line spacing, sacrifices symmetry and uniform convenience of running electric circuits or gas piping on but one s street. Plan E, or arch lighting, is adapted only to incandescen lamps; it tends to give a street a festive appearance, but is not a method of illumination. Plan F, or parkway lighting, is of obvious v the roadway is divided as shown.

Side vs. Center Mounting. — Fig. 2 shows the effect of center mounting on the per cent of the total light which falls within the limits

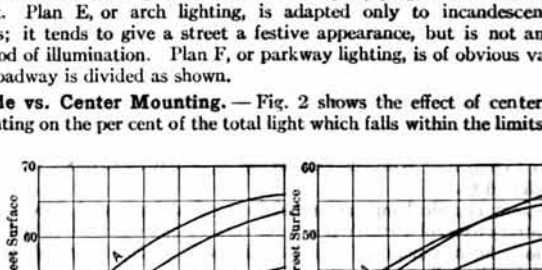


Fig. 2. Per Cent of Light from Arc Lamps which falls within Limits of th

A. 9.6 amp. Open Carbon Arc, Clear Globe
B. 4 amp. Magnetite Arc, Clear Globe
C. 6.6 amp. Magnetite Arc,
D. 6.6 amp. Enclosed Carbo Globe

of various widths. These curves all refer to a mounting height of 20 f street level. The lamps with side mounting are assumed to be over a which is distant from the nearer street line by an amount equal to on total width of the street. The higher efficiency of center mounting is (*Data by P. S. Millar, Trans. Ill. Eng. Soc., Vol. 5, p. 658.*)

It is obvious that mounting the lamp at the street intersection p light to shine up and down both streets and hence utilizes a much larg of the light than when the lamp is not mounted at the street intersect

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this reason, street intersection units, usually on suspension mounting, are likely to continue in use for a considerable time in the future.

Various attempts have been made to increase the percentage of light thrown on the street by reflectors of special design which deflect lengthwise of the street light which would otherwise be thrown to the sides. These have had a very limited acceptance.

Excellent use of large units at intersections and small units at intermediate points may be made on secondary streets, especially where foliage interferes with the distribution of light at distances. On curved roadways it is preferable to locate the lamps on the outer sides of the curves, as they are then visible at greater distances.

Height of Suspension. — The spacing of lamps should be laid out with due regard to the height of suspension of the lamps and the degree of minimum illumination to be provided. In many cities a standard height of mounting is employed with each type of lamp. When such is the case, spacing problems are readily solved by the aid of diagrams such as shown in Fig. 3. Taking account of the suspension height and the light distribution curve of each lamp in its normal service condition, the horizontal distances from the axis of the lamp at

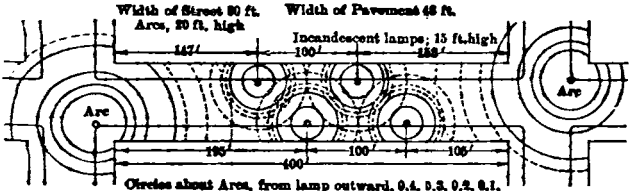


Fig. 3. Spacing and Illumination Plan for a Minimum Normal Illumination of 0.04 Foot-candle

which various normal intensities of illumination are produced at an appropriate level, as that of the street or at a height four feet above the street, are computed by the point-by-point method. Using these distances as radii, circles are drawn to scale about a center representing the axis of the lamp and are marked with the corresponding intensity of illumination. These diagrams are preferably made on translucent tracing cloth and several of each type should be prepared. A plan of the space to be lighted is drawn to the same scale on a separate paper and the circle diagrams are used as templates for various trial spacings until the desired result is obtained. The circles then furnish points for the plotting of illumination profiles or contours at the center line and curb lines, from which the approximate average illumination is readily computed. The illustration shows an appropriate location for 4-ampere magnetite arcs, with globes at street intersections, and 60-candle-power series incandescent lamps with flat enameled metal reflectors at intermediate points, to produce a minimum normal illumination of 0.04 f.c. on a section of street 80 feet wide and 480 feet long lying between centers of intersecting streets.

Selection of Height of Suspension. — The most appropriate suspension height for a street lamp depends on its light output, form of distribution and intrinsic brilliancy, and upon the degree of minimum illumination required. It is practically impossible to realize uniform illumination from large arcs and high-pressure gas lamps without higher suspension than that commonly employed. The usual result is a bright spot immediately about the lamp and low

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illumination at mid-points. The contrast so produced reduces the effi of the light.

A high ratio of suspension height to horizontal spacing tends to im uniformity of light distribution and to increase the distance over whic lamp can provide illumination above a specified minimum value. A l of height to distance is especially desirable when the maximum light of the lamp is more than 30° below the horizontal.

The following example may be taken. In Fig. 4 polar curve (*a*) r 510-watt magnetite arc with clear globe and (*b*) to a 450-watt d-c. flame vertical electrodes and a light opal globe. The illumination curves normal illumination at various distances for various suspension hei case (*a*) the maximum intensity is but 10° below the horizontal and litt distant points is obtained by employing a suspension height exceedin In case (*b*), however, the maximum intensity is much lower on the po and a much higher suspension could advantageously be employed. Fig the effect of height of suspension of these two lamps on the normal illu at various distances.

The actual suspension height is often determined by the exigencies ming, by the length of wooden poles available, and by the necessity of distributing light below the foliage of trees. It must be recognized that a lamp with high mounting throws a smaller total percentage of its light

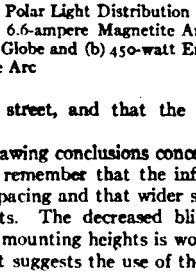
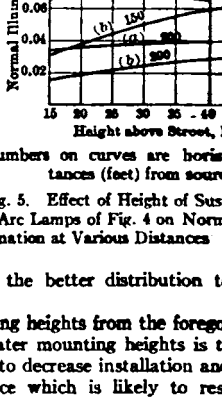


Fig. 4. Polar Light Distribution Curves of (a) 6.6-ampere Magnetite Arc with Clear Globe and (b) 450-watt Enclosed Flame Arc



Numbers on curves are horiz tances (feet) from sour

Fig. 5. Effect of Height of Sus Arc Lamps of Fig. 4 on Norm nation at Various Distances

on the street, and that the gain is from the better distribution t points.

In drawing conclusions concerning mounting heights from the foregc well to remember that the influence of greater mounting heights is t wider spacing and that wider spacing tends to decrease installation an ing costs. The decreased blinding influence which is likely to res greater mounting heights is worthy of careful consideration.

Sweet suggests the use of the letter "M" for the ratio of spacing di mounting height and the approximate relation between various values and uniformity of illumination on the street surface according to Sweet in the table on the top of page 819.

LIGHTING SCHEDULES. — All-night schedules provide for total of from 3830 to 4000 hours of operation. The former total res lighting 30 minutes after sunset and extinguishing an hour before sunri latter involves one half-hour longer burning each night. The "Phil moonlight schedule" allows lamps to remain unlighted on nights when t

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e ratio of maximum to minimum illumination on the street surface	
other than e refractor	Holophane refractor
to 1	33 to 1
to 1	14 to 1
to 1	5 to 1
to 1	2 to 1

other nights the lamps are lighted one hour before one hour after moonrise. This schedule calls for an of operation. The "Frund system" ignores the moon ch the provision of the moonlight schedule apply, 3000 hours. As a large portion of the cost of street ges the saving of reduced schedules as compared with uch less in proportion than the reduction of hours. *orld* issues a detailed set of lighting schedules for the es being furnished for northern, middle and southern tes.

IGHTING (Pre-war figures). — The cost of street n an annual price per lamp or fixture for a specified g. This cost may properly include all fixed charges essories as well as a due proportion of the charges on nd other appliances assignable to the service, all costs ls involved in the service, and a reasonable charge for se costs naturally vary with the character of the dis- poles, rate of depreciation of lamps and the cost of y. Depreciation rates on street lamps and special ng them are apt to reach or exceed 10 per cent, due to average prices charged per year for various types of ll-night schedules in a representative group of cities

OR ELECTRIC STREET LAMPS; ALL-NIGHT SCHEDULE

	Cities averaged	Average rate	Maximum rate	Minimum rate
.....	27	$63.00	$80.00	$45.00
.....	40	87.00	100.00	74.00
rc....	16	70.00	85.00	60.00
.....	6	29.50	39.00	18.50
.....	16	23.25	28.00	15.00
.....	4	20.00	28.00	18.50
.....	16	18.00	22.50	12.50

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The increasing use of large Mazda C lamps makes the cost of such units interest. The following rates are taken from one of the large Public Utilit and may be taken as representative.

Number of lamps	400 C. P.	600 C. P.	1000 C. P
1 to 250 lamps	$66.00	$80.00	$104.00
251 to 750 lamps	61.88	75.00	97.50
751 to 1250 lamps	57.75	70.00	91.00
1251 to 1750 lamps	53.63	65.00	84.50
Over 1750 lamps	49.50	60.00	78.00

Single-mantle gas lamps are usually furnished on an all-night schedule f prices ranging from $20 to $25 per annum. In many of the smaller cities speci display systems of incandescent electric lamps are operated on main busine streets, the expense being assumed jointly by the city and the occupants abutting property. The lamps are usually arranged in arches, festoons or clusters on pedestals, and are often operated from constant-potential mains permit the turning off of part of the lamps after midnight. These systems a usually maintained by the operating company and charged for on a flat ra basis.

BIBLIOGRAPHY. — Bell, Louis, *Art of Illumination; Lectures on Illumi nating Engineering;* Johns Hopkins Univ., 1911, Vol. 2, Chap. 14; Barrows, W. E *Light, Photometry and Illumination;* Trotter, A. P., *Illumination, Its Distribu tion and Measurement;* Bloch, L., *The Science of Illumination*, London; *Trans Ill. Eng. Soc.; Trans. A.I.E.E.; Proc. Nat. El. L. Assoc.* See also *Bibliograph* in article on *Illumination, Interior*.

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INDETERMINATE FORMS. — (*See also Derivatives.*) Let $f(x)$ and $F(x)$ be any two functions of x and let $y = \frac{f(x)}{F(x)}$. For certain values of x, both $f(x)$ and $F(x)$ may be zero, making y equal to $\frac{0}{0}$, an expression which, considered alone, may be anything between 0 and ∞. Its true value may, however, be determined from the nature of the functions $f(x)$ and $F(x)$ by the following process, which involves finding the derivatives of the two functions. If $y_1 = \frac{0}{0}$ when $x = x_1$, then

$$y_1 = \left.\frac{\frac{d}{dx} f(x)}{\frac{d}{dx} F(x)}\right|_{x=x_1}$$

which expression may have a perfectly determinate value. For example if

$$y = \frac{x^3 - 4}{x^3 - 8}$$

and $x = 2$, then

$$y_1 = \frac{0}{0} = \left.\frac{2x}{3x^2}\right|_{x_1=2} = \frac{4}{12} = \frac{1}{3}.$$

If the ratio of the derivatives is still indeterminate, differentiate numerator and denominator again and, if necessary, repeat the process until a determinate form is obtained.

When $y = \frac{f(x)}{F(x)}$ reduces to the indeterminate form $\frac{\infty}{\infty}$ for any particular value x_1 of x, the corresponding value of y is

$$y_1 = \left.\frac{\frac{d}{dx}\left(\frac{1}{F(x)}\right)}{\frac{d}{dx}\left(\frac{1}{f(x)}\right)}\right|_{x=x_1}$$

When $y = f(x) \times F(x)$ reduces to the indeterminate form $0 \times \infty$ for any particular value x_1 of x, the corresponding value of y is

$$y_1 = \left.\frac{\frac{d}{dx} f(x)}{\frac{d}{dx}\left(\frac{1}{F(x)}\right)}\right|_{x=x_1}$$

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INDUCTANCE AND INDUCTIVE REACTANCE.—(*See also Alternating Currents; Electricity and Magnetism, Principles of; Skin Effect; Transmission Lines.*) The phenomena of self and mutual inductance are described in the article on *Electricity and Magnetism, Principles of.* In general when the current i_1 in a circuit, No. 1 say, is varying at the rate $\frac{di_1}{dt}$, a potential drop, in the direction of the current (or *back* e.m.f.) is induced in the circuit, which may be written

$$v_{11} = L_1 \frac{di_1}{dt},$$

where L_1 is called the coefficient of self induction, or self inductance, or simply the inductance, of the circuit. Similarly, when a second circuit, No. 2 say, is in the vicinity of No. 1 and the current i_2 in No. 2,* is varying at the rate $\frac{di_2}{dt}$, an additional potential drop is induced in circuit No. 1 equal to

$$v_{12} = M_{12} \frac{di_2}{dt},$$

where M_{12} is called the coefficient of mutual induction, or simply the mutual inductance, of one circuit with respect to the other.

When the currents in both instances are sine-wave currents of effective values I_1 and I_2 respectively and of frequency f, the effective values of these potential drops are

$$V_{11} = x_1 I_1 \qquad \text{and} \qquad V_{12} = x_{12} I_2 \tag{1}$$

and V_{11} leads I_1 by 90 degrees, and V_{12} leads i_2 by 90 degrees, and

$$x_1 = 2\pi f L_1 \qquad \text{and} \qquad x_{12} = 2\pi f M_{12}. \tag{1a}$$

x_1 is called the inductive self-reactance, or simply the inductive reactance of circuit No. 1. (*see Alternating Currents*), and x_{12} is called the inductive mutual reactance of one circuit with respect to the other. The mutual inductance, and therefore the mutual reactance, between any two circuits is the same for No. 1 with respect to No. 2 as for No. 2 with respect to No. 1, i.e., $M_{12} = M_{21}$ and $x_{12} = x_{21}$.

The total inductive† drop in any circuit due to the *variation of the current* in this and in any number of neighboring circuits is

$$v_1 = L_1 \frac{di_1}{dt} + M_{12} \frac{di_2}{dt} + M_{13} \frac{di_3}{dt} + \text{etc.} \tag{2}$$

For sine-wave currents of frequency f the total inductive* drop is, in *vector notation* (*see Alternating Currents*),

$$V_1 = j\,(x_1 I_1 + x_{12} I_2 + x_{13} I_3 + \ldots). \tag{2a}$$

Units of Inductance and Reactance. — The practical unit of inductance is the henry, the c.g.s. electromagnetic unit the abhenry (also called a "centimeter"), and the c.g.s. electrostatic unit the stathenry. Inductances are fre-

* i_2 is to be considered positive with respect to i_1 when the flux lines threading No 1 due to the current in No. 2 thread through No. 1 in the same direction as the flux lines due to the current in No. 1.

† In addition to these drops there are also the resistance drop and such other back e.m.f.'s as may be present. See *Alternating Currents.*

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ently expressed in thousandths of a henry, i.e., in millihenrys. The units of ductance are the same as the units of resistance (q.v.) See *Units and Conversion tables* for the interrelations of the various units.

Total Inductance of Two or More Circuits in Series. — When several circuits, having the coefficients L_1, L_2, L_3, etc., and M_{12}, M_{13}, M_{23}, etc., are connected in series the currents $i_1 = i_2 = i_3 = \text{etc.} = i$, say, and the total induced e.m.f. is $v = v_1 + v_2 + v_3$, etc., or

$$v = \left[(L_1 + L_2 + L_3 + \text{etc.}) + 2 (M_{12} + M_{13} + M_{23} + \text{etc.}) \right] \frac{di}{dt},$$

hence the resultant or total inductance is

$$L = (L_1 + L_2 + L_3 + \text{etc}) + 2 (M_{12} + M_{13} + M_{23} + \text{etc.}). \qquad (3)$$

This relation makes possible the accurate calculation of the self inductance of a coil of a number of turns when the self inductance of each turn and the mutual inductance of each pair of turns are known.

RELATION BETWEEN FLUX, CURRENT AND INDUCTANCE. — When the permeability of the conductors and of the medium between and surrounding them is constant (e.g., when the conductors and medium are non-magnetic substances), the self and mutual inductances are constants, independent of the values of the currents, for any given arrangement, shape and size of the circuits. Under these conditions the total number of linkages (*see Electricity and Magnetism, Principles of*) between the flux lines linking any particular circuit, No. 1, and the turns forming that circuit may be expressed by the relation

$$\lambda_1 = L_1 i_1 + M_{12} i_2 + M_{13} i_3 + \text{etc.}, \qquad (4)$$

where

$L_1 i_1 = \lambda_{11}$ = the linkages between the flux lines due to the current i_1 in circuit No. 1 and the turns of circuit No. 1,

$M_{12} i_2 = \lambda_{12}$ = the linkages between the flux lines due to the current i_2 in circuit No. 2 and the turns of circuit No. 1, etc.

Hence the common definition of inductance as "linkages per unit current." In certain simple cases the linkages per unit current may be calculated from the configuration of the circuit or circuits, starting from the fundamental relations given by equations (35), (36) and (29) in the article on *Electricity and Magnetism, Principles of*.

Internal Flux, Internal Inductance and Internal Reactance. — In the case of a wire of finite cross-section the various "filaments" of which the wire may be considered as made up are not all linked by the same number of flux lines, and consequently the back e.m.f.'s induced in the various filaments are different, tending to produce a non-uniform distribution of current. This variation in the induced e.m.f. from filament to filament is due only to that portion of the total flux which actually cuts the wire in question; it may therefore be called the "internal flux," and that portion of the inductance or reactance corresponding to this internal flux may be designated as the "internal inductance" and "internal reactance" respectively. Although the internal flux tends to produce a non-uniformity in the distribution of current, this effect is counteracted by the resistance of the wire and for ordinary non-magnetic wires at frequencies under 60 cycles per second the current remains practically uniformly distributed over the cross-section of the wire. See article on *Skin Effect*.

FORMULAS FOR SELF INDUCTANCE.—The following formulas, unless otherwise noted, are taken from a very comprehensive paper on the calculation

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of inductance by Rosa and Grover in the *Bull. Bur. Stand.*, Vol. 8, No. 1, p. 1912, in which the accuracy of the various formulas is thoroughly discussed an many others given, as well as tables to minimize the labor of calculation. Se also Dwight, H. B., *New Formulas for Reactance Coils*, Proc. A.I.E.E., Sept., 191

Unless otherwise stated *all formulas are in c.g.s. electromagnetic units;* th conversion factors are given in the article on *Units and Conversion Factors*.

Self Inductance of a Single Circular Turn formed by a Wire of Circula Cross-Section. — Let a = mean radius of the turn, in centimeters, r = radiu of the wire, in centimeters; then the self inductance is

$$L = 4\pi a\left[\left(1+\frac{r^2}{8a^2}\right)\log_e\frac{8a}{r}+\frac{r^2}{24a^2}-1.75\right]. \qquad (5$$

This formula is derived from an infinite series in $\frac{r}{a}$, hence for $\frac{r}{a}$ large it is ap proximate only; however, for $\frac{r}{a}$ less than 0.1 which covers all ordinary cases the error is less than 1 part in 100,000.

Mutual Inductance of Two Co-axial Circles. — Dimensions as in Fig. 1, all in centimeters. Put

$$k=\sqrt{1-\left(\frac{m_2}{m_1}\right)^2}, \qquad h_1=\frac{m_1-m_2}{m_1+m_2}.$$

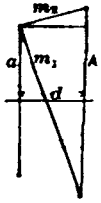


Fig. 1.

For $k < 0.2$ use the formula

$$M=\frac{\pi^2k^2}{4}\sqrt{Aa}\left[1+\frac{3}{4}k^2+\frac{75}{128}k^4+\frac{245}{512}k^6+\ldots\right], \qquad (6)$$

the general term in the brackets being

$$\left(\frac{3\cdot5\cdot7\ldots(2n+1)}{4\cdot6\cdot8\ldots(2n+2)}\right)^2\frac{(2n+2)}{(2n-1)}k^{2n}.$$

For $k > 0.2$ use the formula

$$M=2\pi^2h_1^{3/2}\sqrt{Aa}\left[1+\frac{3}{8}h_1^2+\frac{15}{64}h_1^4+\frac{175}{1024}h_1^6+\ldots\right], \qquad (6a)$$

the general term in the brackets being

$$\left(\frac{n+1}{2n+1}\right)\left[\frac{3\cdot5\cdot7\ldots(2n+1)}{4\cdot6\cdot8\ldots(2n+2)}\right]^2h_1^{2n}.$$

Self Inductance of a Long Solenoid* of Circular Cross-Section. — Let

l = axial length of solenoid in centimeters,
m_1 = number of turns per centimeter length, i.e., total number of turns = $m_1 l$,
a = mean radius of the solenoid in centimeters

Then for $\frac{a}{l}$ small, the self inductance is, to a first approximation,

$$L = 4\pi^2 m_1^2 a^2 l. \qquad (7)$$

There is a considerable error in this formula, due to the end effect, but the variations in L due to changes in l are almost exactly proportional to the changes in

* By a solenoid is meant a coil in which the wire forms a uniform, straight cylindrical helix.

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l and hence this formula may be used for calculating the corresponding variations in L as long as $\frac{a}{l}$ remains small.

Self Inductance of a Single-layer Short Solenoid of Circular Cross-Section. — For such a solenoid (see Fig. 2) the summation formula, equation (3), becomes when there are n turns,

$$L = nL_1 + 2(n-1)M_{12} + 2(n-2)M_{13} + 2(n-3)M_{14} + \ldots + 2M_{1n}, \qquad (8)$$

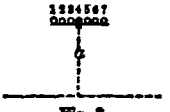


Fig. 2.

where L_1 is the self inductance of a single turn, M_{12} is the mutual inductance of the first and second turns or any two adjacent turns, M_{13} is the mutual inductance of the first and third or of any two turns separated by one, etc., and M_{1n} is the mutual inductance of the first and last turns. L_1 may be calculated from equation (5) and the M's from equation (6) or (6a). The general equation (3) may also be used to calculate the self inductance of a coil of any number of layers, but the calculation becomes tedious.

Self Inductance of Circular Coil of Rectangular Section (Fig. 3). — Dimensions as in Fig. 3, all in centimeters, also

N = total number of turns,
$R = 0.2235\,(b+c)$.

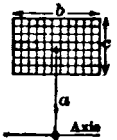


Fig. 3.

Then to a degree of approximation sufficient for most practical purposes

$$L = 4\pi a N^2 \left\{ \log_e \frac{8a}{R} \left(1 + \frac{3R^2}{16a^2} \right) - \left(2 + \frac{R^2}{16a^2} \right) \right\}. \qquad (9)$$

See also Doggett, L. A., *Elec. W., 63, p. 259, Jan. 31, 1914.*

Mutual Inductance of Two Concentric Co-axial Solenoids.* — All dimensions being in centimeters, let

l = one-half the length of the *shorter* coil,
x = one-half the length of the *longer* coil,
A = radius of *outer* coil (which may be either the shorter or longer coil),
a = radius of the *inner* coil,

$$d = x\sqrt{1 + \left(\frac{A}{x}\right)^2},$$

N_1 and N_2 = the *total* number of turns in the first and second coils respectively.

Then as a first approximation, for $\frac{A}{x}$ small, the mutual inductance between the two coils is

$$M = \frac{2\pi^2 a^2 N_1 N_2}{d}. \qquad (10)$$

By calculating a sufficient number of terms the mutual inductance may be obtained exactly from the formula

$$M = \frac{2\pi^2 a^2 N_1 N_2}{d}\left[1 - \frac{A^2}{2d^4}\cdot\frac{4l^2 - 3a^2}{4} - \frac{A^2(4x^2 - 3A^2)}{8d^8}\cdot\frac{8l^4 - 20l^2a^2 + 5a^4}{8} - \frac{A^2(8x^4 - 20x^2A^2 + 5A^4)}{16d^{12}}\cdot\frac{(64l^6 - 336l^4a^2 + 280l^2a^4 - 35a^6)}{64} - \ldots \right]. \qquad (10a)$$

* One solenoid inside the other with their centers coinciding.

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Mutual Induction of Two Co-axial Circular Coils Each of Rectangular Section (Fig. 4). — Dimensions as in Fig. 4, all in centimeters. N_1 and N_2 represent the total number of turns on the two coils respectively. The following formula, known as the "formula of quadratures," is sufficiently exact for most practical cases:

$$M = \frac{N_1 N_2}{6}(M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 - 2M_0), \qquad (11)$$

where M_0 is the mutual inductance of the two central turns o_1 and o_2 in Fig. 4. M_1 is the mutual inductance of the circle through o_2 and the circle through 1, M_8 is the mutual inductance of the circle through o_1 and the circle through 5, etc. These mutual inductances M_0, M_1 . . . M_8 may be calculated from equation (6) or (6a). When the sections of the two coils are small compared with their distance apart, $M_0 = M_1 = \ldots M_8$ and equation (11) becomes

$$M = N_1 N_2 M_0. \qquad (11a)$$

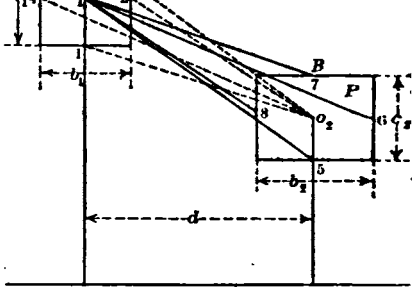


Fig. 4.

INDUCTANCE OF STRAIGHT CONDUCTORS. — The inductance of a circuit formed by straight conductors, such as the wires of a transmission line, may be considered from two points of view, viz., (1) each conductor may be looked upon as having a certain *self* inductance independent of the position of the other conductors forming the circuit or circuits and a *mutual* inductance with each of these conductors or (2) when the conductors are symmetrically arranged and the currents in them bear a fixed relation to one another, as in a two-wire single-phase or symmetrical three-wire three-phase transmission line, each conductor may be looked upon as having a *total* inductance which takes into account both its self inductance and its mutual inductance with respect to the other wires. In the case of a 2-wire line the total inductance of the loop formed by the two conductors is twice the total inductance of *each* conductor; in the case of more than two wires the "loop inductance" has no simple physical meaning.

In the following paragraphs are given the formulas for *self*, *mutual* and *total* inductance *per conductor* for straight conductors of various sections and for various arrangements of such conductors. *The formulas are all in c.g.s. electromagnetic units* unless otherwise specified; see *Units and Conversion Factors*.

Self Inductance of a Single Straight Round Wire, Return Neglected. — Let

l = length of wire, in centimeters,
d = diameter of round wire, in centimeters,
$r = \frac{d}{2}$ = radius of round wire, in centimeters.

Then for a round wire the self inductance is

$$L' = 2\left[l \log_e \frac{l + \sqrt{l^2 + r^2}}{r} - \sqrt{l^2 + r^2} + \frac{l}{4} + r\right] \qquad (12)$$

$$= 2l\left[\log_e \frac{2l}{r} - \frac{3}{4}\right] \text{ approximately.} \qquad (12a)$$

Where the permeability of the wire is μ, and that of the medium outside is unity and the frequency low (12a) appears in the form

$$L' = 2l\left[\log_e \frac{2l}{r} - 1 + \frac{\mu}{4}\right]. \qquad (12b)$$

The last formula is of theoretical interest only, as the value to assign to μ is doubtful and when such wires are used even for currents of moderate frequencies the skin effect is appreciable; see article on *Skin Effect*.

External and Internal Self Inductance of a Round Wire. — The self inductance of a round wire may be considered as made up of two parts, viz. the inductance due to the flux *external* to the wire and that due to the flux within the wire. The first or "external" inductance is

$$L_e = 2l\left[\log_e \frac{2l}{r} - 1\right], \qquad (13)$$

and the "internal" self inductance is

$$L_i = l\frac{\mu}{2}. \qquad (13a)$$

Self Inductance of a Hollow Tube of Circular Section, Return Neglected. — The *external* inductance is the same as for a solid wire, i.e., equation (13), taking for r the external radius of the tube. The *internal* inductance of the tube, putting r_2 = external radius and r_1 = internal radius, is

$$L_i = 2\mu l\left[\frac{r_1^4}{(r_2^2 - r_1^2)^2}\log_e \frac{r_2}{r_1} - \frac{1}{4}\frac{3r_1^2 - r_2^2}{r_2^2 - r_1^2}\right]. \qquad (14)$$

The term in the square brackets is always less than ¼, i.e., the internal inductance of a hollow tube is always less than the internal inductance of a solid wire; see equation (13a). In the limit, where $r_1 = r_2$ (tube with infinitely thin walls), the *internal* inductance is zero.

Self Inductance of a Straight Bar or Strip, Return Neglected. — For a straight bar of a non-magnetic substance and of rectangular cross-section the self inductance, neglecting the return circuit, is

$$L' = 2l\left[\log_e \frac{2l}{a+b} + \frac{1}{2} + \frac{0.2235\,(a+b)}{l}\right], \qquad (15)$$

where a and b are the lengths of the two edges, in centimeters.

This formula is not applicable to thin strips at close spacing; see H. B. Dwight, *El. Rev. and West. Elec. 70, p. 1087, June 30, 1917.*

Mutual Inductance of Two Parallel Straight Wires or Bars. — See Fig. 5. Same notation as above and in addition let

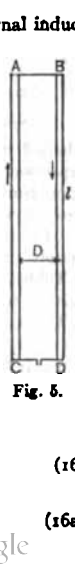


Fig. 5.

D = distance between centers of the two wires, in centimeters.

Then the mutual inductance between the two is

$$M = 2\left[l\log_e \frac{l + \sqrt{l^2 + D^2}}{D} - \sqrt{l^2 + D^2} + D\right] \qquad (16)$$

$$= 2l\left[\log_e \frac{2l}{D} - 1 + \frac{D}{l}\right] \text{approximately,} \qquad (16a)$$

when the length l is great in comparison with D.

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Equation (16), which is an exact expression when the wires have no appreciab cross-section, is not an exact expression for the mutual inductance of two parall cylindrical wires, but is not appreciably in error even when the section is larg and D is small if l is great compared with D.

Equation (16) is also applicable, with a practically negligible error to bars rectangular section and in fact to the mutual inductance between any two pa allel conductors of any section and external to each other, e.g., between an ove head wire and a rail, the distance D being the distance* between the center gravity of the two sections.

Mutual Inductance Between a Tube and an Interior Wire. — Us ing the same notation as for equation (14) above the mutual inductance this case is

$$M = 2l\left[\log_e \frac{2l}{r_2} - \frac{r_2^2 \log_e r_2 - r_1^2 \log_e r_1}{r_2^2 - r_1^2} - \frac{1}{2}\right]. \qquad (16b$$

Total Inductance of a Two-wire Transmission Line. — Let the tw wires (Fig. 5) be designated as No. 1 and No. 2 and the currents as i_1 and i Since $i_2 = -i_1$, from equation (2) the total inductive drop in each wire is

$$v_1 = (L_1 - M_{12})\frac{di_1}{dt}.$$

The total inductance of each wire is then $L = L_1 - M_{12}$, where L_1 is given by equation (12) or (14) and M_{12} by equation (16). For a length so great that d and D are negligible compared with l, this total inductance per wire for equa round wires becomes

$$L = 2l\left[\log_e \frac{2D}{d} + \frac{\mu}{4}\right],$$

where d is the diameter of each wire. The total inductance of the line per unit length of *wire*† is

$$\left.\begin{aligned} L &= \frac{\mu}{2} + 2\log_e \frac{2D}{d} && \text{abhenries per centimeter} \\ &= 0.01524\mu + 0.14037 \log_{10} 2D/d && \text{millihenries per 1000 feet} \\ &= 0.08047\mu + 0.74113 \log_{10} 2D/d && \text{millihenries per mile,} \end{aligned}\right\} \qquad (17)$$

where D and d may be expressed in any units of length provided they are both expressed in the *same* units. The formulas given in equation (17) also apply approximately to stranded wires, provided d is taken as the diameter of the *solid* wire having a cross-section equal to that of the copper in the stranded wire. i.e., the inductance of a No. 0000 stranded wire on a given spacing is approximately the same as that of a No. 9000 solid wire on the same spacing.

Tables of L and the corresponding reactances for 25 and 60 cycles for various sizes of wires and various spacings are given below.

The above formula is not applicable to conductors at close spacing when the frequency is high; see F. B. Silsbie, *Elec. W.*, *68*, *p. 125*, *July 15*, *1916*.

Total Inductance of a Rectangle. — Let L_a = self-inductance of long side, L_b = self-inductance of short side (calculated from the proper formulas, 12 to 15) and let M_a = mutual inductance between the two long sides and M_b = the mutual inductance between the two short sides (calculated from formula 16); then the total inductance of the rectangle is

$$L = 2(L_a - M_a) + 2(L_b - M_b)$$

*Accurately, the geometrical mean distance between the two areas; see *Bull. Bur. Stand.*, 1912, Vol. 8, pp. 125 and 126. For round wires, solid or tubular, the geometrical mean distance between them is exactly the distance between their centers.

†To obtain the total inductance of both wires multiply by *twice* the length of the line.

SELF INDUCTANCE OF SOLID NON-MAGNETIC WIRES*

Millihenries per 1000 *FEET* of each wire of a single-phase or of a symmetrical three-phase line

Size of wire, cir. mils. or A.W.G.	Diam. of wire, inches	Inches between wires, center to center							
		1	3	6	9	12	18	24	30
1,000,000	1.0000	0.05750	0.1245	0.1667	0.1915	0.2090	0.2337	0.2512	0.2648
750,000	0.8660	0.06627	0.1332	0.1755	0.2002	0.2178	0.2425	0.2600	0.2736
500,000	0.7071	0.07863	0.1456	0.1879	0.2126	0.2301	0.2548	0.2724	0.2860
350,000	0.5916	0.08950	0.1565	0.1987	0.2235	0.2410	0.2657	0.2832	0.2968
250,000	0.5000	0.09976	0.1667	0.2090	0.2337	0.2512	0.2760	0.2935	0.3071
0000	0.4600	0.1048	0.1718	0.2141	0.2388	0.2563	0.2810	0.2986	0.3122
000	0.4096	0.1119	0.1789	0.2211	0.2459	0.2634	0.2881	0.3057	0.3193
00	0.3648	0.1190	0.1860	0.2282	0.2529	0.2705	0.2952	0.3127	0.3263
0	0.3249	0.1260	0.1930	0.2353	0.2600	0.2775	0.3022	0.3198	0.3334
1	0.2893	0.1331	0.2001	0.2423	0.2671	0.2846	0.3093	0.3269	0.3405
2	0.2576	0.1402	0.2072	0.2494	0.2741	0.2917	0.3164	0.3339	0.3475
4	0.2043	0.1543	0.2213	0.2635	0.2883	0.3058	0.3305	0.3481	0.3617
6	0.1620	0.1685	0.2354	0.2777	0.3024	0.3199	0.3447	0.3622	0.3758
8	0.1285	0.1826	0.2496	0.2918	0.3165	0.3341	0.3588	0.3763	0.3899
10	0.1019	0.1967	0.2637	0.3060	0.3307	0.3482	0.3729	0.3905	0.4041
12	0.0808	0.2109	0.2778	0.3201	0.3448	0.3623	0.3871	0.4046	0.4182
14	0.0640	0.2250	0.2920	0.3342	0.3590	0.3765	0.4012	0.4187	0.4323
16	0.0508	0.2391	0.3061	0.3484	0.3731	0.3906	0.4153	0.4329	0.4465

Size of wire, cir. mils. or A.W.G.	Feet between wires, center to center								
	3	4	5	6	8	10	15	20	25
1,000,000	0.2760	0.2935	0.3071	0.3182	0.3358	0.3494	0.3741	0.3916	0.4052
750,000	0.2847	0.3023	0.3159	0.3270	0.3445	0.3581	0.3828	0.4004	0.4140
500,000	0.2971	0.3146	0.3282	0.3393	0.3569	0.3705	0.3952	0.4127	0.4263
350,000	0.3080	0.3255	0.3391	0.3502	0.3678	0.3814	0.4061	0.4236	0.4372
250,000	0.3182	0.3358	0.3494	0.3605	0.3780	0.3916	0.4163	0.4339	0.4475
0000	0.3233	0.3408	0.3544	0.3656	0.3831	0.3967	0.4214	0.4390	0.4526
000	0.3304	0.3479	0.3615	0.3726	0.3902	0.4038	0.4285	0.4460	0.4596
00	0.3374	0.3550	0.3686	0.3797	0.3972	0.4108	0.4356	0.4531	0.4667
0	0.3445	0.3620	0.3756	0.3867	0.4043	0.4179	0.4426	0.4601	0.4737
1	0.3516	0.3691	0.3827	0.3938	0.4114	0.4250	0.4497	0.4672	0.4808
2	0.3586	0.3762	0.3898	0.4009	0.4184	0.4320	0.4568	0.4743	0.4879
4	0.3728	0.3903	0.4039	0.4150	0.4326	0.4462	0.4709	0.4884	0.5020
6	0.3869	0.4045	0.4181	0.4292	0.4467	0.4603	0.4850	0.5026	0.5162
8	0.4011	0.4186	0.4322	0.4433	0.4608	0.4744	0.4992	0.5167	0.5303
10	0.4152	0.4327	0.4463	0.4574	0.4750	0.4886	0.5133	0.5308	0.5444
12	0.4293	0.4469	0.4605	0.4716	0.4891	0.5027	0.5274	0.5450	0.5586
14	0.4435	0.4610	0.4746	0.4857	0.5033	0.5169	0.5416	0.5591	0.5727
16	0.4576	0.4751	0.4887	0.4998	0.5174	0.5310	0.5557	0.5732	0.5868

*The inductances given in this table also apply, with a practically negligible error (about 1 per cent) to ordinary stranded wires of the *same cross-section*.

SELF INDUCTANCE OF SOLID NON-MAGNETIC WIR

Millihenries per MILE of each wire of a single-phase or of a sy three-phase line

Size of wire, cir. mils. or A.W.G.	Diam. of wire, inches	Inches between wires, center to cente						
		1	3	6	9	12	18	2
1,000,000	1 0000	0.3036	0.6572	0.8803	1.011	1.103	1.234	1.3
750,000	0.8660	0.3499	0.7035	0.9266	1.057	1.150	1.280	1.3
500,000	0.7071	0.4152	0.7688	0.9919	1.122	1.215	1.346	1.4
350,000	0 5916	0.4726	0.8262	1.049	1.180	1.272	1.403	1.4
250,000	0.5000	0.5267	0.8803	1.103	1.234	1.327	1.457	1.5
0000	0.4600	0.5536	0.9072	1.130	1.261	1.353	1.484	1.5
000	0.4096	0.5909	0.9445	1.168	1.298	1.391	1.521	1.6
00	0.3648	0.6282	0.9818	1.205	1.335	1.428	1.559	1.6
0	0.3249	0.6654	1.019	1.242	1.373	1.465	1.596	1.6
1	0.2893	0.7029	1.057	1.280	1.410	1.503	1.633	1.7
2	0.2576	0.7402	1.094	1.317	1.447	1.540	1.671	1.7
4	0.2043	0.8148	1.168	1.392	1.522	1.615	1.745	1.8
6	0.1620	0.8894	1.243	1.466	1.597	1.689	1.820	1.9
8	0.1285	0.9641	1.318	1.541	1.671	1.764	1.894	1.9
10	0.1019	1.039	1.392	1.615	1.746	1.839	1.969	2.0
12	0.08081	1.113	1.467	1.690	1.821	1.913	2.044	2.1
14	0.06408	1.188	1.542	1.765	1.895	1.988	2.118	2.2
16	0.05082	1.263	1.616	1.839	1.970	2.062	2.193	2.2

Size of wire, cir. mils. or A.W.G.	Feet between wires, center to center							
	3	4	5	6	8	10	15	2
1,000,000	1.457	1.550	1.622	1.680	1.773	1.845	1.975	2.0
750,000	1.503	1.596	1.668	1.726	1.819	1.891	2.021	2.1
500,000	1.569	1.661	1.733	1.792	1.884	1.956	2.087	2.1
350,000	1.626	1.719	1.791	1.849	1.942	2.014	2.144	2.2
250,000	1.680	1.773	1.845	1.903	1.996	2.068	2.198	2.2
0000	1.707	1.800	1.872	1.930	2.023	2.095	2.225	2.3
000	1.744	1.837	1.909	1.967	2.060	2.132	2.262	2.3
00	1.782	1.874	1.946	2.005	2.097	2.169	2.300	2.3
0	1.819	1.911	1.983	2.042	2.135	2.206	2.337	2.4
1	1.856	1.949	2.021	2.079	2.172	2.244	2.374	2.4
2	1.894	1.986	2.058	2.117	2.209	2.281	2.412	2.5
4	1.968	2.061	2.133	2.191	2.284	2.356	2.486	2.5
6	2.043	2.135	2.207	2.266	2.359	2.430	2.561	2.6
8	2.118	2.210	2.282	2.341	2.433	2.505	2.636	2.7
10	2.192	2.285	2.357	2.415	2.508	2.580	2.710	2.8
12	2.267	2.359	2.431	2.490	2.582	2.654	2.785	2.8
14	2.341	2.434	2.506	2.565	2.657	2.729	2.860	2.9
16	2.416	2.509	2.581	2.639	2.732	2.804	2.934	3.0

*The inductances given in this table also apply, with a practically negli (about 1 per cent) to ordinary stranded wires of the *same cross-section*.

ANCE OF SOLID NON-MAGNETIC WIRES*

each wire of a single-phase or of a symmetrical three-phase line

Inches between wires, center to center

	3	6	9	12	18	24	30
770	0.1032	0.1383	0.1588	0.1733	0.1939	0.2085	0.2196
697	0.1105	0.1456	0.1661	0.1807	0.2011	0.2157	0.2270
623	0.1208	0.1558	0.1763	0.1909	0.2115	0.2259	0.2372
425	0.1298	0.1648	0.1854	0.1998	0.2204	0.2350	0.2462
274	0.1383	0.1733	0.1939	0.2085	0.2289	0.2435	0.2548
997	0.1425	0.1775	0.1981	0.2126	0.2331	0.2477	0.2589
883	0.1484	0.1835	0.2039	0.2185	0.2389	0.2536	0.2649
869	0.1542	0.1893	0.2097	0.2243	0.2449	0.2594	0.2707
815	0.1601	0.1951	0.2157	0.2302	0.2507	0.2652	0.2765
701	0.1661	0.2011	0.2215	0.2361	0.2565	0.2712	0.2825
663	0.1719	0.2069	0.2273	0.2419	0.2625	0.2770	0.2883
610	0.1835	0.2187	0.2391	0.2537	0.2741	0.2887	0.3001
597	0.1953	0.2303	0.2509	0.2653	0.2859	0.3004	0.3117
575	0.2071	0.2421	0.2625	0.2771	0.2975	0.3122	0.3235
542	0.2187	0.2537	0.2743	0.2889	0.3093	0.3239	0.3353
519	0.2305	0.2655	0.2861	0.3005	0.3211	0.3356	0.3469
556	0.2422	0.2773	0.2977	0.3123	0.3327	0.3473	0.3587
534	0.2539	0.2889	0.3095	0.3239	0.3445	0.3591	0.3703

Feet between wires, center to center

	5	6	8	10	15	20	25
1335	0.2548	0.2639	0.2785	0.2898	0.3103	0.3249	0.3362
1507	0.2620	0.2712	0.2858	0.2971	0.3175	0.3321	0.3434
1609	0.2723	0.2815	0.2960	0.3073	0.3279	0.3423	0.3536
1701	0.2814	0.2905	0.3051	0.3164	0.3368	0.3514	0.3627
1785	0.2898	0.2990	0.3136	0.3249	0.3453	0.3599	0.3712
1828	0.2941	0.3032	0.3178	0.3291	0.3495	0.3642	0.3755
1886	0.2999	0.3090	0.3236	0.3349	0.3554	0.3700	0.3813
1944	0.3057	0.3150	0.3294	0.3407	0.3613	0.3758	0.3871
2002	0.3115	0.3208	0.3354	0.3466	0.3671	0.3818	0.3929
2062	0.3175	0.3266	0.3412	0.3525	0.3730	0.3876	0.3989
2120	0.3233	0.3326	0.3470	0.3583	0.3789	0.3934	0.4047
2238	0.3351	0.3442	0.3588	0.3701	0.3906	0.4052	0.4165
2354	0.3467	0.3560	0.3706	0.3818	0.4023	0.4169	0.4281
2472	0.3585	0.3678	0.3822	0.3935	0.4141	0.4286	0.4399
2590	0.3703	0.3794	0.3940	0.4053	0.4257	0.4404	0.4517
2706	0.3819	0.3912	0.4056	0.4169	0.4375	0.4520	0.4633
2824	0.3937	0.4030	0.4174	0.4287	0.4493	0.4638	0.4751
2942	0.4055	0.4146	0.4292	0.4405	0.4609	0.4755	0.4869

n this table also apply, with a practically negligible error ry stranded wires of the *same cross-section*.

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60-CYCLE REACTANCE OF SOLID NON-MAGNETIC W

Ohms per MILE of each wire of a single-phase or of a symm three-phase line

Size of wire, cir. mils. or A.W.G.	Diam. of wire, inches	Inches between wires, center to cente						
		1	3	6	9	12	18	2
1,000,000	1.0000	0.1145	0.2478	0.3319	0.3811	0.4158	0.4652	0.5
750,000	0.8660	0.1319	0.2652	0.3493	0.3985	0.4336	0.4826	0.5
500,000	0.7071	0.1565	0.2898	0.3739	0.4230	0.4581	0.5074	0.5
350,000	0.5916	0.1782	0.3115	0.3955	0.4449	0.4795	0.5289	0.5
250,000	0.5000	0.1986	0.3319	0.4153	0.4651	0.5003	0.5493	0.5
0000	0.4600	0.2087	0.3420	0.4260	0.4754	0.5101	0.5595	0.5
000	0.4096	0.2228	0.3561	0.4403	0.4893	0.5244	0.5734	0.6
00	0.3648	0.2368	0.3701	0.4543	0.5033	0.5384	0.5877	0.6
0	0.3249	0.2509	0.3842	0.4682	0.5176	0.5523	0.6017	0.6
1	0.2893	0.2650	0.3985	0.4826	0.5316	0.5666	0.6156	0.6
2	0.2576	0.2791	0.4124	0.4965	0.5455	0.5806	0.6300	0.6
4	0.2043	0.3072	0.4403	0.5248	0.5738	0.6089	0.6579	0.6
6	0.1620	0.3353	0.4686	0.5527	0.6021	0.6368	0.6861	0.7
8	0.1285	0.3635	0.4969	0.5810	0.6300	0.6650	0.7140	0.7
10	0.1019	0.3917	0.5248	0.6089	0.6582	0.6933	0.7423	0.7
12	0.08081	0.4196	0.5531	0.6371	0.6865	0.7212	0.7706	0.8
14	0.06408	0.4479	0.5813	0.6654	0.7144	0.7495	0.7985	0.8
16	0.05082	0.4762	0.6092	0.6933	0.7427	0.7774	0.8268	0.8

Size of wire, cir. mils. or A.W.G.	Feet between wires, center to center							
	3	4	5	6	8	10	15	2
1,000,000	0.5493	0.5844	0.6115	0.6334	0.6684	0.6956	0.7446	0.7
750,000	0.5666	0.6017	0.6288	0.6507	0.6858	0.7129	0.7619	0.7
500,000	0.5915	0.6262	0.6533	0.6756	0.7103	0.7374	0.7868	0.8
350,000	0.6130	0.6481	0.6752	0.6971	0.7321	0.7593	0.8083	0.8
250,000	0.6334	0.6684	0.6956	0.7174	0.7525	0.7796	0.8286	0.8
0000	0.6435	0.6786	0.7057	0.7276	0.7627	0.7898	0.8388	0.8
000	0.6575	0.6925	0.7196	0.7416	0.7766	0.8038	0.8528	0.8
00	0.6718	0.7065	0.7336	0.7559	0.7906	0.8177	0.8671	0.9
0	0.6858	0.7204	0.7476	0.7698	0.8049	0.8317	0.8810	0.9
1	0.6997	0.7348	0.7619	0.7838	0.8188	0.8460	0.8950	0.9
2	0.7140	0.7487	0.7759	0.7981	0.8328	0.8599	0.9093	0.9
4	0.7419	0.7770	0.8041	0.8260	0.8611	0.8882	0.9372	0.9
6	0.7702	0.8049	0.8320	0.8543	0.8893	0.9161	0.9655	1.0
8	0.7985	0.8332	0.8603	0.8826	0.9172	0.9444	0.9938	1.0
10	0.8264	0.8614	0.8886	0.9105	0.9455	0.9727	1.022	1.0
12	0.8547	0.8893	0.9165	0.9387	0.9734	1.001	1.050	1.0
14	0.8826	0.9176	0.9448	0.9670	1.002	1.029	1.078	1.1
16	0.9108	0.9459	0.9730	0.9949	1.030	1.057	1.106	1.1

*The reactances given in this table also apply, with a practically neg (about 1 per cent) to ordinary stranded wires of the *same cross-section*.

f a Concentric Cable.—In a similar manner the ncentric main may be found from equations (3), (13), ve for the total inductance per unit length of *cable*

$$\frac{}{d_2^2)^2} \log_e \frac{d_2}{d_1} - \frac{d_2^2}{2\,(d_2^2 - d_1^2)}\Bigg] \text{ abhenries per centimter,}$$

ternal conductor, assumed solid, d_1 = internal diameter d_2 = external diameter of outer conductor.

Three-wire Transmission Line. — Let the wires be and 3; and the three currents in the direction away , i_2 and i_3. From equation (1) the inductive drop in

$$\left.\begin{aligned} v_1 &= L_1 \frac{di_1}{dt} + M_{12}\frac{di_2}{dt} + M_{13}\frac{di_3}{dt},\\ v_2 &= M_{12}\frac{di_1}{dt} + L_2 \frac{di_2}{dt} + M_{23}\frac{di_3}{dt},\\ v_3 &= M_{13}\frac{di_1}{dt} + M_{23}\frac{di_2}{dt} + L_3\frac{di_3}{dt}. \end{aligned}\right\} \qquad (18)$$

nd M's in terms of the radii and distances apart of the equations (12) or (14) and (16).

ngle Arrangement. — For ordinary three-phase work l current, the sum of the three line currents at any in- hence

$-i_1$, $(i_1 + i_3) = -i_2$, and $(i_1 + i_2) = -i_3$.

re all of the same size and are arranged so that they an equilateral prism, a common arrangement, $L_1 = L_2 =$, and the inductive drops per unit length in the three

$$= L\frac{di_1}{dt},\quad v_2 = L\frac{di_2}{dt},\quad v_3 = L\frac{di_3}{dt}, \qquad (19)$$

ne value as in equation (17), numerical values of which anying tables.

ent of effective value I and frequency f, the inductive it length of line has the effective value

$$V = 2\pi fLI \qquad (19a)$$

this particular wire by 90 degrees, irrespective of whether not, the only condition being that no current returns to ny other conductor than the three line wires.

Wires in the Same Plane. — Let the three wires of have equal diameters d, and let No. 2 be the middle nd 3 be at equal distances (D between centers) from ides of No. 2. Under these conditions, considering unit

as in (17), taking D as the distance between either outer dle wire,

.3863 abhenries per centimeter
millihenries per 1000 feet
millihenries per mile.

otation $\frac{di}{dt} = j\,2\pi fI$ where f is the frequency, I the current

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Then equations (18) for the inductive drops in the three wires become, provi
only that $i_1 + i_2 + i_3 = 0$,

$$\left.\begin{aligned} v_1 &= L\frac{di_1}{dt} - M\frac{di_2}{dt}, \\ v_2 &= L\frac{di_2}{dt}, \\ v_3 &= L\frac{di_3}{dt} - M\frac{di_1}{dt}. \end{aligned}\right\}$$

Such an arrangement, therefore, causes an unbalancing of the system, when the wires are far apart, so that L is large compared with M, the effec slight. It can be avoided by transposing the wires at intervals.

Inductance of Overhead Wires With Earth Return. — This case is susceptible of a definite solution, since the inductance depends upon the tribution of the return current in the earth. When the current returns thro one or more rails immediately below the wire, the leakage current to the ea may be neglected and the wire and rails* treated as linear conductors, apply the formulas given above. When there is no metallic return circuit, an appr imate solution may be obtained by considering the earth as equivalent to "images" of the overhead wires in the plane of the earth's surface, i.e., c sidering the return circuit as consisting of the same number of wires as th are overhead, these fictitious return wires being the same distance below earth as the actual wires are above it. The value of the inductances as t calculated can never be greater than the actual inductances but will usually slightly less than the actual values.

EFFECT OF FREQUENCY ON INDUCTANCE. — See article *Skin Effect.*

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* The *external* self-inductance of a rail is practically the same as that of a round wir taking for r the perimeter of the rail divided by 2π; see equation (13). The *interna* self-inductance depends upon the permeability μ and the frequency of the current. Th internal inductance, however, is small compared with the external inductance and fo approximate calculations may be neglected. See *Rails, Track and Third; Trolley System Overhead.*

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INDUCTION COILS. — (*See also Electricity and Magnetism, Principles of; Electromagnet Windings; Ignition, Electric.*) An induction coil is a device which transforms a low direct e.m.f. to a high alternating e.m.f. of unsymmetrical form. The single-winding coil, called a primary coil, is used extensively in gas-engine ignition and in automatic gas lighting, and the double-winding coil, called a secondary coil, is used for the excitation of X-ray tubes, gas-engine ignition, automatic gas lighting, electrotherapeutics and wireless telegraphy.

PRIMARY INDUCTION COIL. — The primary induction coil consists of a single coil wound upon an iron core made up of a compact bundle of soft-iron wires. To obtain a spark from such a coil it is connected in series with a battery and some kind of "make-and-break" contact. When the circuit is closed, the current increases gradually according to the expression,

$$i_t = \frac{E}{R}\left(1 - \epsilon^{-\frac{Rt}{L}}\right),$$

where i_t equals the current at any time t seconds after the circuit is closed, E equals the e.m.f. of the battery, R equals the resistance in ohms and L equals the inductance in henries of the entire circuit, and ϵ the base of the natural system of logarithms. The shape of the current curve at "make" is shown in the curve AB (Fig. 1),* which is an oscillograph record taken when an e.m.f. of 4 volts is impressed upon a primary coil of 1 ohm resistance and 0.01 henry inductance.

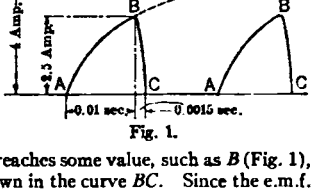


Fig. 1.

If the circuit is opened when the current reaches some value, such as B (Fig. 1), the current decreases rapidly to zero as shown in the curve BC. Since the e.m.f. induced in such a coil at any instant equals $L\frac{di}{dt}$ when the current falls from B to C, the e.m.f. induced in the coil will be many times that of the battery e.m.f. and a spark will be established between the open contacts at "break." For use in connection with gas engines the "make and break" contacts are located within the cylinder. Reliable ignition is obtained when about 0.02 joule is dissipated in the spark at "break." Since the energy dissipated as heat in the spark is converted from the electromagnetic energy stored up in the coil, it follows that the coil must have an inductance and carry a current at "break" such that the energy stored up, i.e., $\frac{1}{2}LI^2$, will exceed the required value of 0.02 joule. In practice it is customary to design the coil and time of contact so that $\frac{1}{2}LI^2$ equals about 0.04 joule, such coils having an efficiency of about 50 per cent. One-half of the energy put into the coil is then used up in heating the conductors and metallic parts by I^2R and hysteresis losses.

SECONDARY INDUCTION COIL. — The secondary coil has two separate windings wound about an iron core, one of few turns called the primary winding and the other of many turns called the secondary winding. The primary winding is connected in series with a battery and an interrupter (described below). The spark is produced between the terminals of the secondary winding. In most cases a condenser is shunted across the interrupter to prevent sparking at

*This and the following oscillograph records are due to Bailey, B. F., *Elec. W. 1910*, *Vol. LV.*, *p. 943.*

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that point. Since the e.m.f. induced in each turn linked by the magnetic flux is the same, the e.m.f. induced in the secondary winding, neglecting leakage, will equal $\frac{N_s}{N_p}$ times that induced in the primary winding, where N_s and N_p equal the respective number of turns on the secondary and primary windings. Secondary coils which give sparks as long as 5 feet have been constructed in this manner.

Effect of Shunting Interrupter with Capacity.— (*See also Ignition, Electric.*) When the interrupter is shunted by a capacity the e.m.f. induced in the secondary winding becomes oscillatory. This effect of the capacity is well shown in the oscillograph records given in Figs. 2 and 3. In each case a high non-inductive

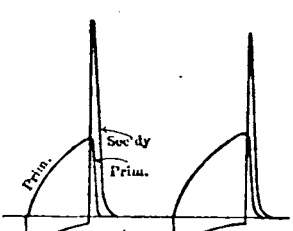


Fig. 2.

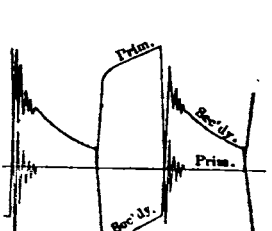


Fig. 3.

resistance is connected across the secondary terminals, and the curves indicate the variation of the primary current and the secondary e.m.f. In Fig. 2 the interrupter is unshunted by a condenser, and as a result the secondary e.m.f. increases at "break" and decreases to zero without oscillation. In Fig. 3 the interrupter is shunted by a condenser and the secondary e.m.f. becomes oscillatory. The form of the e.m.f. curve in any actual case is not shown accurately by Fig. 3 except at the time of "break," since the resistance between the terminals of a spark gap decreases rapidly after the spark is established. In Fig. 4 a low resistance is connected across the secondary terminals and shows the general form of the e.m.f. curve after the spark is established.

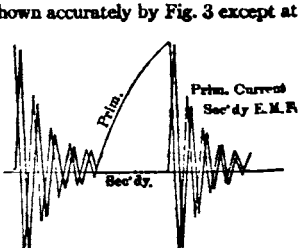


Fig. 4.

Although not shown by the curves owing to difference in scale, the capacity shunted around the interrupter also increases the secondary e.m.f. above the value obtained without the capacity. Assuming that no spark is formed at the interrupter, it may be shown that the e.m.f. of the secondary equals $\frac{N_s}{N_p}\sqrt{\frac{L}{C}}I_b$, where L equals the inductance of the primary in henries, C equals the capacity of the condenser in farads and I_b equals the primary current at "break" in amperes. If C is made so low that a spark appears at the interrupter, the above formula no longer holds and the secondary e.m.f. will be greatly reduced. C should then be made as small as possible but of sufficient size to suppress the spark at the interrupter.

Insulation. — The conductors in the secondary winding must be heavily insulated to withstand the very high e.m.f. induced in that winding. In most

ses a double-covered silk insulation impregnated with some insulating compound is used. In large induction coils the secondary winding is built up of several flat coils insulated from each other by ebonite or fiber disks. The coils are so wound that the electrical connections are made alternately at the top and at the bottom of the respective coils.

Dimensions of Three-inch Coil. — The general dimensions of parts of a 3-inch induction coil, as reported by S. R. Bottone, *Radiography* (*London*, *1898*), are given following: Iron, bundle of No. 20 (B. & S. G.) annealed iron wire, 1¼ in. diameter, 13 in. long. Primary winding, four layers of No. 12 double silk-covered copper wire, about 4¼ lb. Ebonite tube over primary, 12 in. long, 2 in. inside diameter, 2½ in. outside. Two ebonite heads, 5 in. square, ½ in. thick. Seven vulcanized fiber circlets (for sections), 4½ in. diameter, ⅞ in. thick, 2½ in. central aperture. Secondary winding, 4 lb. No. 36 double-silk-covered wire. Platinum-tip contact breaker, height from base to center of iron hammer, 2½ in., size of iron head of hammer ⅝ in. diameter, ⅝ in. long. Base (fitted with false bottom to contain condenser), 18 in. long by 9 in. wide by 2¾ in. deep. Condenser, 144 sheets of tinfoil, size 6 by 12 in., interleaved with 144 sheets of paraffined paper 8 by 13 in.

Dimensions of Six-inch Coil.—Similar dimensions for a 6-inch induction coil, as reported by Bottone, are given following: Iron, bundle of No. 16 (B. & S. G.) annealed iron wire, 1½ in. diameter, 15 in. long. Primary winding, four layer of No. 12 double silk-covered copper wire, about 5 lb. Ebonite tube over primary 14 in. long, 2¼ in. inside diameter, 2¾ in. outside. Ebonite heads 6 in. square, ⅝ in. thick. Seven vulcanized fiber circlets 5¼ in. diameter, ⅛ in. thick, with 2¾ in. central hole. Secondary winding, 7 lb. No. 38 double-silk-covered copper wire. Platinum-tip contact breaker, height from base to center of hammer, 3 in. size of hammer head, 1 in. diameter, 1 in. long. Base (fitted with false bottom to contain condenser), 20 in. long by 10 in. wide by 3½ in. deep. Condenser, 144 sheets of tinfoil, size 6 by 12 in., interleaved with 144 sheets of paraffined paper, 8 by 13 in.

Interrupters. — An interrupter should be so designed that it will close the circuit for a definite time by easy adjustment and will open the circuit at the end of that time as quickly as possible. Two distinct types, the mechanical and the electrolytic interrupter, are in common use. Mechanical interrupters may be divided into the following forms: hammer, atonic, commutator and mercury interrupters. Of the electrolytic interrupters the Wehnelt type is the most popular.

Hammer Interrupter. — In the hammer interrupter, shown in Fig. 5, the circuit is opened at *A* when the core *B* attracts the iron mass *C* mounted at the free end of the spring blade *D*. Since the core attracts the iron mass only when the circuit is closed and loses its attraction when the circuit is opened, the spring blade is set in vibration and opens and closes the circuit in rapid succession. This type is used extensively in connection with small coils. The contacts at *A* are usually tipped with platinum to withstand the intense heat developed by sparking. The rapidity of the "break" is not great enough for large coils, and when a large current must be broken, trouble is experienced in keeping the contact points in good condition.

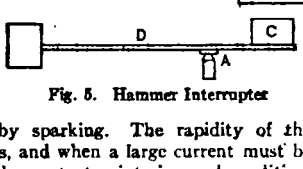


Fig. 5. Hammer Interrupter

Atonic Interrupter. — In the atonic interrupter, shown in Fig. 6, the free end of the iron strip *P* is attracted as in the hammer interrupter and is

returned to its original position by the spring *R*. The circuit is opened at th contacts *ab* when the free end of *P* strikes the blade *L*. Interrupters constructe in this manner open the circuit quicker than do the hammer type since the attracted member is moving faster at the instant of "break." The period of the atonic interrupter may be varied within wide limits by regulating the tension on the spring *R* by means of the thumb-screw *M*.

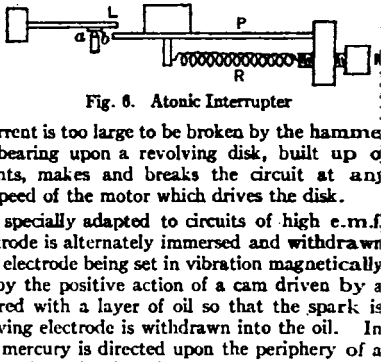


Fig. 6. Atonic Interrupter

Commutator Interrupters are often used when the primary current is too large to be broken by the hamme or atonic interrupters. A brush bearing upon a revolving disk, built up o conducting and insulating segments, makes and breaks the circuit at an desired rate, depending upon the speed of the motor which drives the disk.

Mercury Interrupters are specially adapted to circuits of high e.m.f. In the *plunger* type a pointed electrode is alternately immersed and withdrawn from a cup of mercury, the moving electrode being set in vibration magnetically as in the hammer interrupter, or by the positive action of a cam driven by a motor. The mercury cup is covered with a layer of oil so that the spark is quickly extinguished when the moving electrode is withdrawn into the oil. In the *turbine* type a small stream of mercury is directed upon the periphery of a revolving toothed wheel. The circuit is made when the mercury stream strikes a tooth and is broken when the mercury stream passes through a slot between the teeth. The toothed wheel is rotated at high speed by a motor which also drives a small mercury pump.

Wehnelt Interrupter. — The Wehnelt interrupter has two fixed electrodes which are immersed in dilute sulphuric acid. The anode consists of a small platinum wire insulated by glass except at its tip end. The cathode usually consists of a sheet of lead. If the electrolyte is well circulated, an interrupter of this kind will give about 450 interruptions per second with 24 volts impressed upon the primary circuit. When used with large coils the electrolyte heats up quickly, and a cooling coil is sometimes immersed in the electrolyte to control the temperature.

Tesla Coil. — In some cases, as in wireless telegraphy, electro-therapeutics, etc., where a unidirectional e.m.f. is not required, but an e.m.f. of high frequency is desired, a Tesla coil may be used in place of an induction coil. The construction of a simple Tesla coil is shown in Fig. 7. In the primary circuit a primary winding of few turns and a small spark gap are shunted by a condenser. Secondary and primary windings are wound together upon an air core. If an alternating e.m.f. of from 5,000 to 10,000 volts is impressed upon the primary the condenser is charged until the voltage across the primary gap breaks it down. The condenser then discharges through the gap, producing an oscillating current in the primary winding. The oscillating current in the primary induces a high-frequency e.m.f. in the secondary, which is sufficient to break down the long secondary spark gap.

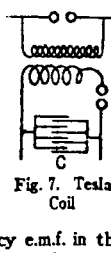


Fig. 7. Tesla Coil

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INSULATING MATERIALS, MISCELLANEOUS. — (*See also Cambric, Varnished; Electricity and Magnetism, Principles of; Gutta Percha; Insulating Materials, Testing of; Paper, Impregnated; Rubber; Wires and Cables, Insulated.*) Materials used in the insulation of electrical apparatus may be classified as follows (*see also Standardisation Rules of A.I.E.E.*):

1. Vitreous, including glass, enamel, etc., 2. Stony, such as slate, marble, mica, asbestos, porcelain, etc., 3. Osseus, such as bone and ivory, 4. Resinous, including shellac, resins, copal and other gum, 5. Bituminous, as bitumen, asphaltum, pitch, etc., 6. Waxy, including bees-wax, paraffin, etc., 7. Elastic, such as india-rubber, ebonite, gutta-percha, etc., 8. Oily, including various oils and fats of animal and vegetable origin as mineral petroleum, 9. Cellulose, including dry wood and paper, cotton, celluloid, etc., 10. Silk and allied animal tissue such as catgut, 11. Sulphur, 12. Amber, 13. Molded insulations.

SELECTION OF INSULATING MATERIAL. — In selecting an insulating material for any special purpose and in predetermining accurately the behavior of such a material under working conditions, it is desirable that the following electrical, physical and chemical properties of the material should be known as far as they apply to the use in question.

Electric.—

- Dielectric strength (kilovolts per mm. at puncture).
- Dielectric loss.
- Specific inductive capacity; Direct-current; Alternating-current.
- Conductivity or resistivity. Surface leakage.
- Temperature coefficient of resistance.

Physical.—

- Specific gravity and specific weight.
- Hardness.
- Toughness.
- Brittleness.
- Ductility.
- Workability.
- Flexibility (with reference to varnished cloths, etc.).
- Strength (tensile, compressive and shearing).
- Fracture (fibrous, crystalline or amorphous).
- Ability to take polish.
- Melting point.
- Shrinkage.
- Adhesiveness.
- Effect of high temperature (electric arc).
- Effect of low temperature.
- Artificial aging test.
- Porosity.
- Viscosity.
- Flash and fire test.
- Film-making power.
- Rate of drying.
- Penetration.
- Absorption of moisture.
- Amount of volatile matter given off at prescribed temperatures.

Chemical.—

- Proximate composition.
- Solubility in water, oil, etc.
- Effect of moisture and moist air.
- Weathering qualities.
- Chemical effect upon metals in contact.
- Presence of acid.

DIELECTRIC STRENGTH. — According to best authorities, an insulating material should be homogeneous and free from moisture in order to have high dielectric strength. In addition, some authorities claim it should also have a low specific inductive capacity (permittivity). These claims are based on experiments made on some of the more important insulations. Whether they apply to all insulations in general is a question which requires more extensive experiments before it can be answered definitely. However, enough experi-

ments have been made to warrant that these claims be given consid
choosing insulating material for uses in which very high dielectric
required.

The breakdown voltage is influenced by the size and shape of elec
frequency and wave shape of the applied voltage, time of voltage a
and the temperature of the insulation. The literature on the sub
always clear on these points nor is there a standard practice adopted.

The Continental Fiber Company has adopted the practice of u
needle points on test specimens over 0.125 inch thick and disc electr
in diameter for test specimens 0.125 inch thick or less, and raising the
the rate of 5000 volts per second from zero to puncture voltage.

Table I illustrates the effect of the thickness of the test specimen
dielectric strength of porcelain. The effect may be greater or less
insulating materials. It is obvious, however, that a standard thickn
test specimen should be adopted in order to obtain comparable value
tric strength of the various insulations.

TABLE I.—DIELECTRIC STRENGTH OF PORCELAIN
DIFFERENT THICKNESSES OF TEST SPECIMEN

(Peek: Dielectric Phenomena in High Voltage Engineering)

Total thickness, mm.	Kv./mm.
0.5	16.0
1.0	14.5
2.0	12.2
5.0	11.0
10.0	9.6
15.0	9.2

Table II illustrates the effect of the time of application of voltag
shows the effect of temperature on the dielectric strength. The

TABLE II.—VARIATION OF DIELECTRIC STRENGTH WI
TIME OF APPLIED VOLTAGE

(Peek: Dielectric Phenomena in High Voltage Engineering)

Material	Thickness, mm.	Time to puncture, min.	25° C. kv/mm.	
Oil-impregnated paper, 30 layers, 60-cycle, 10 cm. diameter discs, round edges.	1.90	"Inst."	39.4	
		1	33.1	
		2	31.0	
		4	29.2	
		6	28.2	
		10	26.8	
		20	25.5	
		40	23.6	
		60	22.7	
		80	22.1	
		100	21.6	

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was thoroughly dried prior to impregnation with oil. If moisture the effect of temperature may be opposite from paper (see article on *Fibre*). It follows, therefore, that ferably be tested at a definite relative humidity at a defi- the time of application of voltage should be standardized nparable results.

dielectric strength of various insulating materials. The all obtained under the same test conditions. The litera- values were obtained seldom stated the test conditions. annot be used to compare absolutely the dielectric strength s but will serve only as a guide in choosing materials of a ric strength.

AGE is due to a film of moisture on the surface of the isture may contain soluble salts and condensed gases, d carbon dioxide from the air. This film may indeed be le, on cleaned quartz glass, it has been found to be from Waxy materials have no surface film because the moisture face tends to draw into drops instead of spreading over esistivity according to Curtis is independent of voltage and relative humidity being constant. The temperature range was 25° to 30° C. with relative humidity at 25 per cent. of most insulating materials decreases upon exposure to t light. The results obtained by Curtis indicate that a to ultra-violet light will produce the same or sometimes would be produced in years by sunlight.

s defined as the resistance between two opposite edges of imeter square. The values in Table III are those obtained ures from 25° to 29° C. and are given for 30 and 90 per cent be test voltage was 200 volts.

apparent surface leakage should be distinguished from . The surface moisture film under high voltage is soon generated with the leakage current. Then a new leakage e oxidation of the insulation with ozone generated at the formed by local ionization of the surrounding air. If the on is covered with an oil such as blown linseed oil prior to voltage the oxidized film can be greatly reduced, and the voltage will be increased. Even though all the actual removed, the flash-over voltage would still be limited ent surface leakage, which, for a given leakage distance, tion and shape of the electrodes, relative specific inductive he insulation and the shape of the insulation (contour of urface leakage at all existed the flash-over voltage would n voltage of the air between the electrodes. (Adapted *Phenomena in High Voltage Engineering*).

are available on the flash-over voltage of insulations, this ed in Table III.

TIVITY of insulating materials in general follows Ohm's tion of any consequence is a few vegetable oils, as for which the resistance decreases with increase in the applied e resistivity varies with the amount of moisture present ature. In Shrader's work on the effect of moisture, he n insulating material, which is generally considered non- olume resistivity of 26×10^{10} ohm-cm. ordinarily, but vacuum, had a resistivity of 8×10^{14} ohm-cm., or 3000

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TABLE III.—ELECTRICAL PROPERTIES OF INSULATING MATERIALS

Material	Dielectric strength			Resistivity				S.I.C.	
	Specimen thickness, mm.	Kv. per mm. (*a*)	Authority	Volume ohm-cm.	Authority	Surface (*b*)		Air unity	Authority (p. 856)
						Ohms, 30 %	Ohms, 90 %		
Amberite	.....	.....	...	5×10^{16}	26	2×10^{15}	4×10^{12}	.....	...
Ambroin	0.84	6.0	2	1.7×10^{13}	2	.....	.....	.....	...
Asbestos paper	1.2	4.2	3	1.6×10^{11}	24	.....	.....	.....	...
Asphalt (Byerlyte)	3.6	14.0	4	.....	...	.....	.....	2.7	25
Bakelite, C–1	.....	up to 27.5	5	over 2×10^{14}	5	.....	.....	5.2 to 9.9	5
Bakelite, wood molding mixture	.....	17.7 to 21.6	5	1×10^{12}	5	.....	.....	4.5 to 5.5	5
Bakelite, asbestos molding mixture	.....	up to 9.8	5	4×10^{11}	5	.....	.....	.....	...
Bakelite, Continental	3.2	15.7	7	.....	...	.....	.....	.....	...
Bakelite, Micarta-213	.....	up to 31.4	6	5×10^{11}	5	.....	.....	5	6
Bakelite, Micarta-21D	.....	5.9	6	.....	...	.....	.....	5	6
Bakelite, Micarta-21H	.....	15.7	6	.....	...	.....	.....	5	6
Bakelite-Dilecto-X	3.2	25.6	7	1×10^{12}	7	.....	.....	5	7
Bakelite-Dilecto-XX	3.2	25.6	7	1×10^{12}	7	.....	.....	5	7
Celluloid (clear)	0.25	12 to 28	1	2×10^{10}	26	8×10^{10}	2×10^{9}	.....	...
Celluloid (colored)	0.25	10.2 to 18.9	1	.....	...	.....	.....	.....	...
Ceresin	.....	.....	...	over 5×10^{16}	26	8×10^{16}	8×10^{16}	.....	...
Condensite (molded)	5.7	19.7	8	4×10^{13}	26	7×10^{11}	6×10^{9}		

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Electrose (black)	.....	.....	...	1×10^{14}	26	3×10^{19}	8×10^{9}	.....	...
Electrose (yellow)	.....	.....	...	5×10^{13}	26	1×10^{15}	5×10^{8}	.....	...
Empire cloth, canvas	.41	28.9	9	.....	...	.....	.....	.....	...
Empire cloth, linen	.15	54.0	9	.....	...	.....	.....	.....	...
Empire cloth, muslin	.38	48.0	9	.....	...	.....	.....	.....	...
Empire cloth, silk	.15	48.0	9	.....	...	.....	.....	.....	...
Faturan	3	10	10	.....	...	.....	.....	.....	...
Fiber, vulcanized, including hard fiber, all colors	0.79	8.9 to 16.7	12	5 to 20×10^{9}	26	3×10^{10}	1×10^{7}	5	...
	3.2	4.9 to 10.8	12	5 to 20×10^{9}	26	3×10^{10}	1×10^{7}	5	...
	6.4	3.9 to 8.9	12	5 to 20×10^{9}	26	3×10^{10}	1×10^{7}	5	...
	12.7	3 to 5.9	12	5 to 20×10^{9}	26	3×10^{10}	1×10^{7}	5	...
Galalith (white)	.....	6 to 8.5	13	1×10^{10}	26	6×10^{10}	6×10^{8}	.....	...
Glass (ordinary)	.....	8 to 9	13	9×10^{13}	27	.....	.....	5.5 to 9.1	25
Glass (plate)	.....	.....	...	2×10^{13}	26	3×10^{13}	2×10^{7}	5.5 to 9.1	25
Gummon	.....	.....	...	3×10^{13}	26	5×10^{12}	3×10^{8}	.....	...
Hermit	.....	2 to 3	23	1×10^{10}	26	3×10^{13}	5×10^{8}	.....	...
Jute (impregnated)	6	1.2	14	.....	...	.....	.....	3 to 4	28
Lava	.....	3 to 10	15	2×10^{10}	26	6×10^{11}	1×10^{8}	.....	...
Litholite	4.5	4.5	16	.....	...	.....	.....	.....	...
Marble	.....	6.5	13	1 to 100×10^{9}	26	8×10^{10}	2×10^{7}	8.3	29
Mica	.6	21 to 28	13	.04 to 200×10^{11}	26	2×10^{13}	3×10^{9}	5 to 7	40
Micabond, plate	1.6	37.5	17	.....	...	.....	.....	.....	...
Micabond, flexible	1.6	23.1	17	.....	...	.....	.....	.....	...
Micanite, plate	1.6	37.5	18	.....	...	.....	.....	.....	...
Micanite, flexible	1.6	23.1	18	.....	...	.....	.....	.....	...
Minerallac	.....	39.4	19	5×10^{9}	8	.....	.....	2.1	8
Paper	0.13	8.7	40	5×10^{6}	...	.....	.....	2.6	40
Paraffin (parowax)	.....	11.5	13	1×10^{16}	26	1.5×10^{19}	5×10^{11}	2.1	31

TABLE III.—ELECTRICAL PROPERTIES OF INSULATING MATERIALS—Continued

Material	Dielectric strength			Resistivity				S.I.C.	
						Surface (*b*)			
	Specimen thickness, mm.	K.V. per mm. (*a*)	Authority	Volume ohm-cm.	Authority	Ohms, 30%	Ohms, 90%	Air unity	Authority (p. 856)
Paraffin (special)	.....	.....	...	over 5×10^{18}	26	over 1×10^{18}	over 1×10^{18}	.....	...
Porcelain	20	8.0	21	3×10^{14}	26	4×10^{13}	5×10^{8}	4.4	21
Pressboard (oiled)	0.25	39.3	40	.....	...	.....	.....	5.0	32
Pressboard (oiled)	1.58	29.2	40	.....	...	.....	.....	5.0	32
Pressboard (oiled)	3.17	21.1	40	.....	...	.....	.....	5.0	32
Pressboard (varnished)	0.25	26.3	40	.....	...	.....	.....	3	32
Pressboard (varnished)	1.58	15.5	40	.....	...	.....	.....	3	32
Pressboard (varnished)	3.17	9.5	40	.....	...	.....	.....	3	32
Presspahn	.....	5.2 to 9.3	33	1×10^{10}	34	.....	.....	.....	...
Redmanol (molded)	5.1	11.8 to 18.5	8	2.5 to 25×10^{10}	8	.....	.....	.....	...
Redmanol (laminated)	0.8	41 to 51	8	2.2×10^{11}	8	.....	.....	.....	...
Rosin	.....	.....	...	$.5\times10^{16}$	26	8×10^{14}	2×10^{14}	2.5	38
Rubber (hard)	0.5	70	37	1×10^{18}	26	6×10^{15}	1×10^{9}	2.0 to 3.5	30
Shellac	.....	.....	...	1×10^{16}	26	2×10^{14}	6×10^{9}	3.0 to 3.7	39
Slate	10.3	1.3	22	1×10^{18}	26	2×10^{8}	1×10^{7}	6.6 to 7.4	35
Stabalite	.....	.....	...	3×10^{13}	26	6×10^{13}	4×10^{7}	.....	...
Sulphur	.....	.....	...	1×10^{17}	26	1×10^{16}	1×10^{14}	2.9 to 3.2	39
Tegit	.....	.....	...	2×10^{12}	26	2×10^{12}	5×10^{7}	.....	...

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times as great. As to the effect of temperature, Curtis found that in 53 of the insulations which he investigated, the ratio of the resistivity at 20° C. to that at 30° C. varied from 1 to 5.3.

The values given in Table III are for room temperature at ordinary atmospheric humidity. The unit used is the resistance to the current flowing through the material between two opposite faces of a centimeter cube, no surface leakage being present.

DIELECTRIC LOSS is due to the following causes:

With either d-c. or a-c.

1. Ionization of occluded gases.
2. I^2R losses due to leakage current.

With a-c. only.

3. Oscillatory movement of particles of higher or lower specific capacity than the surrounding medium, due to the charges induced on them being alternately attracted and repelled by the electrodes.
4. I^2R losses due to displacement current.

Generally, dielectric loss varies as the square of the voltage up to a certain dielectric stress at which the loss begins to increase faster than the square of the voltage. The increase occurs when the occluded gases or other particles of low specific inductive capacity begin to ionize. This has the effect of greatly increasing the dielectric stress on the particles of high specific capacity which soon rupture. Dielectric loss therefore has a bearing upon the dielectric strength of insulations especially when the voltage is applied indefinitely.

Table IV gives dielectric loss of varnished cloth and oil treated paper. No data are available on insulations in general.

The power-factor of insulation is the ratio of the power dissipated in it (i.e., the dielectric loss) to the apparent power delivered to it.

As the charging current and therefore the apparent power increases, with the specific capacity, it is obvious that low power factor may result either from low dielectric loss or high specific capacity. The power factor is therefore not a good indication of the quality of insulation.

THE PHYSICAL PROPERTIES of insulating materials are given in Table V. The degree of hardness is not listed because it has been determined for only a very limited number of materials. Furthermore, there seems to be no agreement in the unit chosen to express the degree of hardness. Transverse strength is not given because no standard method for making this test has been adopted. Very few values can be found in the literature for shearing strength and so this property is also omitted.

Souder and Hidnert found that the expansion of insulating materials is a function of the temperature, medium in which the material is heated (air or oil), time, rapidity of heating or cooling. Of these factors the medium is the most important for materials which absorb moisture in considerable quantities. The values given for the linear temperature coefficient of expansion are those obtained in an air medium with the exception of Continental-Bakelite which, when heated in air, has an irregular expansion.

MOLDED INSULATIONS may be classified as Hot Molded Insulations and Cold Molded Insulations.

Hot Molded Insulations are subjected to heat and pressure simultaneously in the mold. Three classes of binders are used.

1. Gums, such as shellac and copal which become soft and plastic when heated and hard when cold. These gums are mixed with short asbestos fiber, cotton fiber, ground mica, infusorial earth, barytes or any of a great variety of materials.

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Authorities for Table III: (1) Hobart and Turner. (2) Physicalis
nische Reichsanstalt. (3) Steinmetz. (4) Byerly & Sons, Manu
(5) General Bakelite Co. (6) Westinghouse. (7) Continental F
(8) Electrical Testing Laboratory. (9) Mica Insulator Co. (10) B
(11) Formica Insulation Co. (12) William Eves, 3d. (13) Wa
Baur. (15) American Lava Corporation. (16) Symons. (17) Chic
Co. (18) Mica Insulation Co. (19) Minerallac Electric Co. (20
& Robinson. (21) The Locke Insulator Mfg. Co. (22) Massachus
tute of Technology. (23) Electrician. (24) Whittaker's Pocket Bo
Pirani. (26) Curtis. (27) Table of French Physical Society. (28)
Howe. (29) Schmidt. (30) Various. (31) Zietkowsky. (32) Hend
Kinzbrunner. (34) Stadt Lab., Munich. (35) Schulze. (36) E.
(37) C. C. Paterson, E. H. Raynor, A. Kinnes. (38) Boltzmann. (
ner. (40) Peek.

TABLE IV.—DIELECTRIC LOSSES

(Peek: Dielectric Phenomena in High Voltage Engineering)

(Effective Sine Wave 60 Cycles)

Total thickness mm.	Insulation	No. of layers	Temp. °C.	Volts per mm.
4.0	Varnished cloth	15	25	4,000 6,000 8,000 10,000 12,000
4.0	Varnished cloth	15	90	4,000 6,000 8,000 10,000 12,000
2.5	Oil-treated paper	30	25	10,000 14,000
2.5	Oil-treated paper	30	60	10,000 14,000
2.5	Oil-treated paper	30	90	10,000 14,000
2.5	Oil-treated paper	30	120	10,000 14,000

These losses may be lower or very much higher, depending upon the
of the insulation.

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TABLE V.—PHYSICAL PROPERTIES OF INSULATING MATERIALS

Material	Specific gravity	Tensile strength pounds per square inch	Compressive strength, pounds per square inch	Linear temperature, coefficient per °C.
Ambroin, Grade A. F.	.....	2,140 up to	2,680 up to	
Bakelite, C–1	1.27	11,000	32,000	.00011
Wood molding mixture	1.34	4,000	36,000	.00003
Asbestos molding mixture	1.89	4,200	36,000	.00002
Micarta, 213	1.36	15,000	*22,000	.00002
Micarta, 21D	1.36	10,000	*21,000	.00002
Micarta, 21H	1.36	10,000	*20,000	.00020
Dielecto-X	1.32	12,000	*20,000	.000052
Dielecto-XX	to 1.38	.....	†43,000	.....
Continental Bakelite Grade CBL	1.36	8,500	*23,000 †41,000	‡.00003
Condensite (molded)	.....	5,000	30,000	.00002 to .00004
Condensite, celoron	.....	13,000	40,000	.....
Fiber	1.2 to 1.5	9,000 to 14,000	25,000 to 43,000	.000027 .....
Formica, Grade P	1.25	20,000	50,000	.00001 to .00003
Lava	2.50 to 2.70	....	20,000 to 30,000	....
Marble	2.50 to 2.80	....	9,000 to 22,000	.00001 to .00002
Porcelain	2.30 to 2.50	3,000	20,000	.000002 to .00002
Redmanol (moulded)	1.32	3,500 to 7,200	43,000 to 55,000	....
Redmanol (laminated)	1.30 to 1.40	13,000 to 31,000	*26,000 to 40,000†	....
Slate	2.65	.....	11,000 to 30,000	....
Wood, Maple	.....	8,000 to 12,000	6,000 to 8,000	....
Wood, Walnut	.....	8,000 to 14,000	4,000 to 8,000	....

* parallel to lamination.
† perpendicular to laminations.
‡ measured in an oil bath.

A proper combination of gums and fillers is selected to obtain the desired result These materials are mixed by the use of a grinder, hot rollers or a solvent whi is afterwards driven off. The mixed material is heated to fuse the binders a then placed in a heated mold. The charged mold while hot is pressed in a co

press to produce the desired form and then allowed to cool and harden un pressure. Insulations molded thus are generally mechanically weak, ha high dielectric strength, soften and distort at about 40 to 60° C. and low in co

2. Synthetic Resin such as that produced by the mixture of phenol and for aldehyde in the presence of ammonia. These chemicals combine to form a liqu varnish which has the remarkable property of hardening upon heating with hc softening upon subsequent heating even when heated to carbonization. variety of other chemicals can be used. In this pure form the insulation translucent with a beautiful variety of colors and takes a high polish and known as synthetic amber. Examples of this product are on the marke bakelite, condensite, and redmanol. A molding mixture consists of this resi wood flour, asbestos fiber or other materials, molded in a hot press and allow to set. The resin in solution may be spread on paper or fabric which is th pressed together and heated to drive off the solvent. An example of such product is micarta. Insulations of this group have great mechanical strengt high dielectric strength and in most cases, resist temperatures up to 150° C.

3. Vulcanizing Agent. Hard rubber or vulcanite is an example of this grou Crude rubber is mixed with fillers and a vulcanizing agent, such as sulphu and then vulcanized in molds under heat and pressure. These insulations ha high resistivity, fair mechanical strength, and distort under slight loads even a room temperature.

Cold Molded Insulations are made by the use of two classes of binders.

1. Binder dissolved to mix with a filler, the solvent of which is expelled aft the mold is completed. The binder may be (*a*) a pitch dissolved in benzine c naphtha, (*b*) phenolic resin dissolved in alcohol or benzol, heat being continue after the solvent is driven off the mixture to polymerize or harden the resi and (*c*) silicate of soda dissolved in water, the water being expelled from th mixture in a drying oven. The filler used with these binders is generally asbes tos. The characteristics of each are: (*a*) soften at 60° C., fair in mechanica and in dielectric strength, and low cost; (*b*) does not soften up to 150° C., and not as strong mechanically, nor as good electrically as the hot molded insulations; (*c*) weak mechanically and electrically, resists high temperatures, but hygroscopic.

2. Set by chemical action: Examples of this group are: (*a*) Portland cement with asbestos fiber, the excess water being driven off by heating; and (*b*) lime and silica mixed with water properly treated and used with a filler of asbestos or magnesia. The properties of each are (*a*) not weakened by moisture, fair electrically up to 400° C., mechanically fair, porous in structure, but can be made weatherproof with a coating which will limit the temperature in use: (*b*) mechanically weak and resists very high temperature.

MISCELLANEOUS INSULATIONS. — Insulating materials are often described in general terms without specific data. A material is said to be "heat proof" which may mean that it will not deteriorate when used continuously at some temperature within the range of 30° and 250° C. Dielectric strength is sometimes quoted without reference to the thickness of the test specimen. If the test has been made on a very thin specimen, the dielectric strength obtained will be misleading to those who are not aware of the law of the increase of dielectric strength with the decrease of the thickness of the test specimen. Claims may be made that an insulating material is insoluble in certain solvents and is weatherproof. Such claims are not absolute. They are only general and refer to ordinary conditions found in the use of insulations. If the working conditions are unusual and severe, specific information should be obtained on the appropriateness of the insulation under consideration.

The more important types of insulation are described in alphabetical order in the following pages.

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ivity and specific inductive capacity, and a dielectric
ost purposes except very high voltage apparatus and
ticles on *Corona* and *Spark Gap*.

is made by compressing scrap amber. It is now in
as surface leakage is concerned is the equal of native
urface should be well cleaned to avoid surface leakage
deliquescent salts in handling it with the fingers.

aking in a vacuum silicate of sodium, asbestos, fossil
alcohol. It is moulded in heated moulds, under high
of Ambroin will resist very high temperatures and are
ields. Ambroin is only slightly hygroscopic as com-
ors of the same nature. (Adapted from Hobart and

l consisting chiefly of silica, magnesia, lime, alumina
The structure is of innumerable fibers the ultimate
to be a single row of the molecular structure of the
exceedingly smooth and glossy and have very little
ether when they are spun into a yarn, this resulting in
This difficulty, however, has been partly overcome so
ade which have fair tensile strength but not equal to
rtant varieties of asbestos are amianthus and amphi-
orm of asbestos paper, cardboard, yarn, cloth and as a
s.

l particles of iron oxide or grit which cannot be entirely
slight degree its insulating qualities. It is hygroscopic
be used on high voltage, in general not over 3300 volts.
ids and alkalies and withstands very high temperatures.
nsulating qualities break down at 1000° C., but recover
1000° C. it loses its mechanical strength and melts at
n extensive use as a heat insulator.

e trade names of asbestos impregnated with pitches,
cellon and phenolic rosin are eshallite, ambroin, tena-
d festonite.

pitch found in geological formation in various parts of
sed (1) in the manufacture of insulating varnishes and
pregnation of hygroscopic non-waterproof insulating
insulating covering for cables. The various grades of
al work are called Trinidad, Bitumen, Elaterite, Gil-
anjak. Asphalt insulators possess a high insulation
ength, flexibility and mechanical toughness, are very
l by moisture.

umen) softens at from 90° to 100° C. and is not recom-
ersion in hot oils, or where it would be subjected to
ain grades of Byerlyte melt at temperatures ranging
hile the melting point of Gilsonite varies from 230° to
that the dielectric strength of pure asphalt is 30,000
on sheet 1/16th inch thick).

organic substance resulting from the chemical conden-
rmaldehyde (General Bakelite Co., N. Y.). It may be
as a solid. The liquid Bakelite is useful for the impreg-
ls, for enameling under heat and pressure and as a bind-
ompounds. The solid Bakelite is unaffected by water,
ll chemicals. It does not melt or soften at ordinary

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machine temperatures; it is destroyed only at temperatures in the vicinity o 300° C. It is easily and accurately moulded and may be made to take any color. It compares favorably with rubber and gutta-percha in every way except that it is not as flexible as those substances. The moulded insulation will withstand a temperature of 90° to 450° C., depending on the filler used.

Bakelite-Dilecto is made by hot pressing paper which has been saturated with raw bakelite. It is furnished in five different grades in the form of sheets tubes and rods. If immersed in water for eight days, it will absorb from 1 to 6 per cent of its weight of water, depending upon the grade. In general, it is considered non-hygroscopic and resists ozone indefinitely. It withstands a temperature of 105° C. continuously and 150° C. for short periods of time without deterioration. Its chemical inertness is similar to that of Bakelite. It can be worked with any machine shop tool and takes a splendid polish.

Bakelite Micarta is primarily an insulating material but can be used for many other purposes as for example, pinions and gears, the wearing properties of which are better than rawhide. It is furnished in the form of sheets, rods, and tubes and can be machined accurately and takes a good polish. For short periods of time, it will withstand a temperature of 140° C. Its chemical inertness is similar to that of Bakelite.

Bitumen. — See section on *Asphalt.*

Byerlyte. — See section on *Asphalt.*

Cambric, Varnished. — See separate article on *Cambric, Varnished.*

Cellon is obtained by heating cellulose in a closed glass vessel with acetic anhydride to 180° C. or 110° C. if hydrocellulose is used. When sulphuric acid is used as a catalyser, the reaction occurs at about 55° C. The resulting mass is thinned by adding acetic acid. The cellon is precipitated by adding water, benzine or ether and afterwards washed thoroughly with water. It is then dried at a temperature not exceeding 100° C. The finished product is furnished in either a hard or flexible form in any desired color. Its specific gravity is 1.35 and its dielectric strength is 30 kv. per mm. It can be shaped with any tool, polished and becomes elastic in boiling water and can then be pressed into moulds.

Celluloid (xylonite) is a dried solution of gun-cotton (pyrolin) and oil. It may be machined or moulded into any form by softening in boiling water. Its dielectric strength is very much reduced at high temperatures, and it is very combustible. It is only slightly hygroscopic.

Coal-tar Pitch is the residue remaining after the fractional distillation of coal tar. It flows at low temperature and when cold is quite brittle. Symons gives its dielectric strength as 1000 volts per millimeter.

Condensite is a hard infusible substance, the chief constituent of which is a resinous gum, made by the reaction between phenol and formaldehyde. Condensite is produced by combining this gum under heat and pressure with a hardening agent. It is supplied in three grades; for plastic moulding, for impregnating and as a cement. It can, in general, be moulded to an accuracy of .002 in. plus or minus, with all kinds of metal inserts.

It is non-inflammable, non-corrosive, and infusible, insoluble in oils, most acids and other solvents and shrinks but one-fifth of one per cent in moulding. The impregnating material is used in connection with metal, wood, paper, cardboard, rubber, leather, etc. The plastic cement is used for fastening together the parts of porcelain insulators, for sealing terminals in porcelain bases, etc.

The value given for dielectric strength in Table I was obtained between blunt needle points, normal temperature, oil immersion, 60 cycles, and the voltage applied for about 10 seconds. Flash-over voltage as tested by the Bureau of

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Standards at radio frequency was 25 kv. between skirted stubs ⅝ in. apart on a specimen 4 inches by 4 inches by ⅛ inch thick.

The carbonization point is 287° C. Condensite will withstand temperatures of 148° to 215° C. continuously, depending upon the filler used. The shearing strength is 5000 pounds per square inch.

Condensite-Cellulac is claimed to be non-hygroscopic and impervious to gas or acids. It has no corrosive effects at ordinary temperatures and can be used in the weather. It is furnished in sheets, rods, tubes and in plastic uncured state for filling irregular spaces in which it will afterwards harden.

Condensite Celoron is a new insulating material on the market. The composition of this material has not as yet been published. It has a high dielectric strength and has excellent physical properties.

Conduline is made especially for insulating cable joints and end bells. Aside from having good insulating qualities, it has very desirable physical properties. It does not become brittle at low temperatures but remains plastic. The upper temperature limit of plasticity is 95° C. when it suddenly changes over to a very mobile liquid state completed at 110° C. When this filling compound is used in connection with a cable cell, known on the market as "Conducell," cable joints are obtained which are claimed to be uniform in quality and construction.

Continental Bakelite is made by hot pressing canvas or cloth which has been saturated with raw Bakelite. It is furnished in two grades, CB and CBL, in the form of sheets, rods and tubes. It is non-hygroscopic. It absorbs only 2 per cent of its weight of water when immersed for eight days. It withstands 105° C., continuously and 150° C. periodically without deterioration. It can be machined and takes a good polish. Its chemical inertness is equal to that of Bakelite.

Copal is a resinous substance, which makes a colorless varnish when dissolved in alcohol, oil of turpentine or linseed oil. Copal is easily fused, is very inflammable and is quite brittle when cold.

Cornimit is made from fish offals by a Danish process. It is not as hygroscopic as galalith and has higher electrical resistance. The cost of it is very low compared with other insulations.

Dorrite can be moulded or stamped into any commercial size or shape. It is said to be fire-proof, acid-proof and water-proof. A specimen 3.2 mm. thick, and 7.6 cm. square, after being immersed in water for 70 hours is reported to withstand 40 kv. without signs of leakage or change.

Ebonestos is an English product made of asbestos fiber impregnated and mixed with various gums and is moulded accurately under heat and pressure. It is furnished in four grades: (*a*) Bright and natural finish, hard and short grained, and low softening point. (*b*) Dull black finish, hard and short grained, softening point 100° C. (*c*) Tough fibrous material with varnish finish and softening point of 80° C. (*d*) Coarse fibrous fire-proof material. A specimen of grade "A" after being immersed for 48 hours in brine had an electrical resistance of 5×10^{12} ohm-cm.

Ebonite. — See section on *Rubber, Hard.*

Elaterite. — See section on *Asphalt.*

Electrobestos is an English product and is an asbestos compound which will withstand temperatures up to 900° C. at 500 volts. It is used in heating and cooking devices and arc lamps.

Electrose has been in use for thirty-two years. It is a composite insulation which does not tarnish metals because no sulphur is used in its vulcanization. Its compressive strength is 10,000 pounds per square inch. Its temperature

coefficient of expansion is very low and it can therefore be used for mountin electrical parts accurately such as the diaphragm and magnet in telephon cases. It possesses hardness and toughness without brittleness, takes a smoot polished surface and is moisture, water and oil proof. It does not shrink o warp under ordinary conditions. A piece 12 inches by 12 inches and ⅛ inc thick arcs over at 75,000 volts but does not puncture between brass sphere ⅜ inch in diameter.

It can be moulded into a great variety of shapes. It is used extensively in a types of insulators, bushings and terminals, for railway work, power transmissio radio and telephone transmission over a wide range of frequencies and voltages

Empire Cloth consists of a closely-woven cambric coated with two or mor films of an oxidized oil, prepared by a special process. Canvas, duck, linen, silk and paper are also coated by the same process. (See *Varnished Cambric.*)

Erinoid is an English product made from solids of milk and is similar to Gala lith and resembles horn in appearance. It is furnished in sheets, tubes, and rod in various colors including a striated appearance. Its insulating properties ar good if not used in damp places. It can be shaped with tools and polished by rotating in a barrel with Erinoid shavings and pumice stone.

Eswelite is somewhat similar to Bakelite except that it is brittle and become flexible in boiling water. According to Bütlemann its specific gravity is 1.2 and its dielectric strength is 15 kv. per mm.

Fiber is pure cotton cellulose chemically treated to form a hard bone-like material. It is known by various trade names such as Fiber, Vulcanized Fiber Hard Fiber, Horn Fiber. These fibers are all essentially the same and vary only in quality and uniformity with the skill and experience of the manufacturer. Fiber of best quality has its origin in old rags because the natural oil of the virgin cotton fiber is deleterious and cannot be removed by easy chemical process. This oil is removed in the wearing and washing of the garment. All dirt and grit must be removed from the rags. The quality also depends on the assortment of the rags.

"Vulcanized Fiber sheets are made by passing cotton rag paper through a strong acid or chloride bath and rolling it up on a large drum where each layer of paper sticks to the layer beneath it. When the proper thickness is obtained the acid soaked material is cut from the drum and cut in half forming two sheets of raw fibre. These sheets are put through a soaking process in large wooden tubs, each subsequent tub containing a weaker solution, the last tub containing pure water." (Catalogue of The Continental Fiber Co.)

The soaking process requires from one week to one year depending on the thickness of the sheet. A very small amount of acid will remain in spite of all the soaking. The sheets are air dried and seasoned at a constant temperature. During the drying, they warp and shrink to one-half the original thickness. They are flattened in a steam heated hydraulic press and then calendered to exact thickness.

According to Almy the mechanical and physical properties of fiber varie between wide limits according to the manipulation of the chemical treatment and the varying quality of the original paper or rags. A fiber for a particular use should therefore be selected with great care.

Fiber is not waterproof. It will absorb water but is not injured beyond warping by either hot or cold water because it returns to its original dimensions and properties when dried. Dilute acids and alkalis cause no other effects than water, but concentrated acids cause disintegration. Organic solvents and oils have no effect whatever. At a sustained temperature of 80° to 100° C., it loses its water of condition and becomes brittle and chars in a short period of time at 200° C.

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According to Eves, the dielectric strength is about the same for all colors of a given fiber. The tendency of the iron salts in the coloring matter to lower the dielectric strength is offset by the loading effect of the coloring matter which gives the fiber greater homogeneity. The dielectric strength of thin specimens of fiber increase with increase in temperature whereas it decreases with increase in temperature with thick specimens. The moisture is dispelled from the thin specimens at the higher temperatures but is retained in the thicker specimens. This difference in the retained moisture explains the variations in dielectric strength as the temperature is increased. Fig. 1 gives the average breakdown voltage for different thicknesses of fiber of all colors.

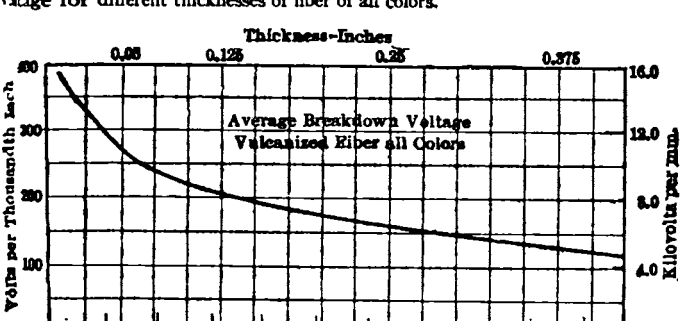


Fig. 1.

Fiber is used very extensively. One of the greatest uses of fiber, either for mechanical or electrical purposes, is for railway signal insulation. The Railway Signal Association's specification requires a specific gravity of 1.3 to 1.5; an absorption when immersed in water at 70° F. for twenty-four hours, not to exceed 45 per cent by weight for 3.18 mm. fiber, 30 per cent for 4.76 mm. and 26 per cent for 6.35 mm. fiber; a tensile strength of 5000 pounds per square inch; a dielectric strength of 1280 volts per millimeter for all thicknesses under an application of voltage for one minute between disc electrodes 2.54 cm. in diameter; withstand bending into a circle of a radius ten times the thickness without cracking or splitting.

Formica is furnished in three grades in the form of sheets, tubes and rods, and can be moulded. Its physical and chemical properties are claimed to be similar to those of redmanol. Its electrical and mechanical properties as given by the manufacturer are: dielectric strength, 39 kv. per mm. Resistivity, 12×10^{12} ohm-cm., tensile and compressive strength, averaging 20,000 pounds per square inch, specific gravity of 1.25 to 1.35 and a linear coefficient of expansion of .00002 per degree centigrade. It will withstand a temperature of 150° C. continuously.

Fuller-Board. — See section on *Pressboard.*

Galalith is a German product made by heating skimmed milk with caustic soda and precipitating the casein with acid. The casein plates after being dried are saturated with formaldehyde and dried again resulting in a translucent sheet of yellow-white color. It is rather hygroscopic but serves as a good insulator in dry places. It can be shaped cold after being softened with hot water. Its specific gravity is 1.32.

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Gilsonite. — See section on *Asphalt.*

Glass is a silicate of soda or potash combined with certain metallic oxides usually lead oxide. Owing to the condensation of moisture upon its surface glass has a very large surface leakage. Rain water roughens its surface and th resulting accumulation of dirt reduces its insulating qualities. According t Gray and Dobbie the specific resistance of potash glass is higher than tha of soda glass. Annealed glass has in general a higher specific resistance tha unannealed glass. As compared with porcelain, glass is inferior in mechanica strength; whereas porcelain is only chipped by a blow, glass is easily cracked o shattered.

G-E Sealing Compounds are divided into two classes:

(1) For the protection of coils from the penetration of moisture and minera oils. These compounds withstand rough handling, and possesses uniform flow point under continued heat, a high degree of fluidity and high penetration at the treating temperature.

(2) For filling cavities to exclude moisture, dust and dirt. The first group in this class includes solid compound which are melted, poured in place and solidified by cooling. Some of the uses are, for filling cable end bells and joints and for filling over screw heads in receptacles, sockets and switches. The second group includes plastic compounds some of which set without the application of heat. They are used to fill in spaces between wires of armatures and of field coils.

The flow point varies from 65° to 250° C., depending upon the compound. The breakdown voltage of No. 227 joint compound is 75 kv. at 65° for a 0.25 inch gap, and of No. 239 filling compound is 40 kv. at 80° C. for a 0.2 inch gap.

Gummon is a coal tar product. It will withstand the flame of a Bunsen burner, remaining perfectly hard. It is not easily sawed or drilled as it takes the temper out of steel. Other insulating materials having similar properties are agalite and australite.

Gutta-Percha. — See article on *Gutta-Percha.*

Hemit is furnished in four grades. Grade A can be moulded accurately with metal inserts and is claimed to be less brittle than porcelain. It withstands a temperature of 318° C. continuously and sudden changes of temperature without cracking. It is non-hygroscopic and not affected by dilute acids. Grade B can be shaped with tools or moulded. It is hygroscopic and does not resist acid. It will withstand a temperature of 300° C. continuously and sudden changes of temperature. Grade C 1 is moulded in sheets and is non-hygroscopic, but does not resist acids. It withstands a continuous temperature of 425° C. and exposures to the electric arc and sudden changes of temperature. Grade C 2 is moulded in sheets and should not be exposed to moisture which reduces its dielectric strength. It is unaffected by the electric arc and withstands a continuous temperature of 1100° C. and sudden changes of temperature.

Jute is a fiber obtained from the inner bark of certain trees growing in India. Commercial jute is usually softened and rendered less brittle by impregnating it with paraffin or some similar mineral oil. It is used extensively as a filler in lead-covered cables and as a constituent of certain kinds of paper and pressboard.

Kalanite is an English product furnished in three grades. (A) in sheets and rods which can be shaped with tools, (B) a moulding mixture and (E) in sheets which are fire resisting and used for arc shields and switch boxes.

Lava is a mineral talc, machined in its natural condition and then baked at a temperature of 1100° C. to a condition of extreme hardness. It is then unaffected by any subsequent temperature short of its baking temperature. It is slowly attacked by hydrochloric acid but is not affected by other acids or alkalies.

ls dimensions are unchanged by absorption of moisture and it has a negligible oefficient of expansion with temperature.

Lavite. — See section on *Lava*.

Leatheroid. — See section on *Fiber*.

Litholite is an insulating material resembling psychiloid in structure. It is made in sheets and is pressed into any form. It is softened by sulphuric acid and distilled water and is reduced to a pulp if immersed in caustic soda. It is tough but inflammable. It is used for commutator rings, bushings, washers, formers, bobbins and for square and round tubing.

Marble is the name given to any limestone which is sufficiently compact to admit of a polish. While pure marble is white, the presence of iron oxide or other impurities give it different colors. It is used principally for switchboard work and should not contain metallic veins, which reduce its insulating qualities. If used on circuits of 1000 volts or more, it should be saturated with an insulating varnish and baked. It shows oil spots and for that reason it is sometimes stained black and given a so-called marine finish.

Mica is an anhydrous silicate of aluminium and potash or sodium. It crystallizes in a laminated mass, some grades of which may be subdivided down to a thickness of 0.0008 millimeter. The ultimate thickness of cleavage layers is unknown and may be finally but one layer of the molecular structure. It is useful as an insulator because of its high insulating qualities and its ability to withstand high temperatures. Owing to its impurity, lack of flexibility and excessive surface leakage in the natural state, the laminæ are separated and sorted into various grades of purity and are then cemented together to form plate or flexible reconstructed mica of any thickness or purity. Moulded mica is used in the manufacture of overhead line material and in the making of moulded pieces as a substitute for hard rubber. It softens at 136° F. Moulded mica is insoluble in water, but is affected by certain oils and all acids and alkalies to some extent. Mica loses its insulating qualities at a temperature of 1000° C., but recovers them after cooling. Andrews showed that the dielectric strength of mica is greatly reduced when immersed in or coated with oil.

Micabond Cloth, Paper and Plate are forms of reconstructed mica. Micabond cloth is India sheet mica faced on one side with muslin and on the other with Japanese insulating paper, bonded together with a special binder. It is furnished in three different grades varying in flexibility and in thicknesses from .005 inch to 0.125 inch. Among its uses is the insulation of field coils and transformer coils. Micabond paper is made in the same way as the cloth except paper of different grades are used on both sides of the mica. It is furnished in the different grades in the form of sheets and tapes and in thickness from 10 to 30 mils. Micabond plate is made of mica sheets bonded with orange shellac. Grades 101 and 111 are furnished in sheets from .01 to 0.125 inch thick and are used for armature slots, spools for magnets and other similar purposes. These grades can be moulded. Grades 102 and 104 are also furnished in sheets which are very carefully milled to exact thickness varying from .01 to 0.125 inch and are intended especially for the insulation of commutator segments. These grades cannot be moulded. Grade 21 is made by a special process and is recommended for use in electric flat iron and ranges. Micabond is also furnished in the form of tubes, washers and commutator rings.

Micanite is also a reconstructed mica. White mica of India and amber mica of Canada are used. The mica films are very carefully inspected for purity and the bonding material is carefully selected to give the best results. It is furnished in the same forms and in the same grades and dimensions as micabond. Its uses are the same as those of micabond.

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Minerallac is furnished in four grades all of which are impervious and show no alkali or acid reactions. Grade No. 1 is an impregnating of the consistency of molasses with a flash point of 230° C. Grade semi-solid compound used in cable end bells and potheads or for imp coils, fiber and wood for use on high voltage. Grades No. 2-A is use of No. 2 in warm climates because of its higher flow point. Grade N semi-solid compound for use on voltages below 2000 volts. Grade N mineral insulating compound for use in high voltage cable joints. Its ture coefficient of expansion is low and its dielectric energy loss is low.

	No. 2	No. 2-A	No. 20	No. 6
Flow point, °C.....	48	59	75	68
Drip point, °C.....	63	85	127	91
Flash point, °C.....	200	243	348	182

Oil. — See article on *Oil, Transformer.*

Paper (*See article on Paper, Impregnated.*) The various kinds used for insulation may be divided into two classes according to the manufacture:

(*a*) Fiber or pulp compressed into paper, examples of which are K and Fuller board. This class of paper may receive a sizing treatment solution to harden the surface.

(*b*) Fiber specially digested or parchmentized to give a close grained texture, an example of which is fish paper. This class of paper mus fully washed out in the manufacturing process to remove all digesting otherwise the product becomes very brittle and disintegrates with age

The following list gives the name, origin and method of manufact well-known papers in use:

Name	Origin	Method of manufa
Linen paper	Linen rags	Compressed and sized
Kraft paper	Wood pulp	Sulphate treatment u
Rope paper	Old rope	Compressed and unsi
Press board	Cotton rags	Compressed and sized
Fuller board	Cotton rags	Compressed and unsi
Fish paper	Cotton rags	Digested with sulphu
Fiber	Cotton rags	Digested with zinc ch
Asbestos paper	Asbestos and cotton	Compressed and unsi

Paper is very hygroscopic and should not be used for insulation u impregnated or sealed. It is used extensively in telephone cables sea lead sheath. Paraffined paper is used as a dielectric in electric c Impregnated with oils, it is used in power cables in which it is also with a lead sheath. Many other uses might be listed but these are important.

Paraffin is a product obtained by the destructive distillation of shale. The dielectric strength of cloth, wood and paper is increased b nation with paraffin and the materials are rendered less hygroscopic.

is acidproof but is very inflammable and has a melting point depending upon the grade. The commercial grades of paraffin have melting points varying from 47° to 52° C. Its insulating properties are excellent. The surface leakage is very low and is practically constant up to 90 per cent relative humidity. A special grade of paraffin has such high electric resistance that it cannot be measured by any methods yet conceived. Its melting point is 58° C.

Paxolin is an English trade name for an insulation which is similar to bakelite micarta.

Pitch is a residue from vegetable oils. Examples are cottonseed pitch and wood pitch. Coal tar residues are often referred to as pitches. Pitch is used mainly as a binder in moulded insulations.

Porcelain (*See article on Insulation for Overhead Lines.*) Porcelain is distinguished from other forms of earthenware by a vitrified and non-porous structure. It is composed of china clay, ball clay, flint and felspar. China clay, sometimes called kaolin, is slightly plastic whereas ball clay is very tough and plastic. By a proper combination of the two the desired plasticity is obtained. Flint is in the form of pure sand or quartz ground so finely as to be entirely free from any gritty feeling. Feldspar is a natural rock and is ground as fine as the flint. These four ingredients are mixed in proper proportions and passed through the manufacturing processes which require very skillful care and experience upon which depends the quality of the product. Such articles as knobs, cleats and lamp sockets are made by a dry process and are not suitable for high voltage because of their porosity. Insulators are made by a wet process and are non-porous which is necessary for high voltage use. The glaze is provided to protect the porcelain from dust and deterioration in the weather and should have the same temperature coefficient of expansion as the porcelain.

In the dry process the great variety of forms of the product is obtained by pressing the material into a steel mold. Articles made with this process shrink $\frac{1}{32}$ inch per inch in firing. The shape of the insulator made by the wet process is obtained by turning it down with machine tools before firing. It shrinks about $\frac{3}{16}$ inch per inch in the firing process. The shrinkage is caused by the material fusing at the high temperature attained and filling the voids between the finely divided particles.

The mechanical strength depends upon the flint content, the heat resistance upon the clay and the dielectric strength upon the feldspar which unfortunately also adds brittleness. In a special type of porcelain for spark plugs, magnesia is used which adds mechanical strength at high temperatures. Porcelain, because of its low tensile strength, should be used under a compressive strain. It is comparatively inexpensive, chemically inert and not sensitive to changes of temperature. The fracture of good porcelain is conchoidal, fine grained, white and bright.

Pressboard is similar to paper in its construction, except that it is thicker and less flexible. It is usually hygroscopic unless impregnated with some moisture repellant. It is pressed into many useful forms, and is used as an insulator, principally in connection with low voltages. See sections on *Fiber*, *Paper*, *etc.*, for other properties.

The dielectric strength of oiled pressboard is not very definite. It depends a great deal upon the time of application of the stress. The dielectric strength of varnished pressboard is low but uniform and depends largely on the varnish film.

Presspahn is a type of pressboard made in Germany. It is strong and can be easily bent. It is usually impregnated and boiled in pure linseed oil, thinned with benzine. Other insulations which are similar to presspahn are pertinax, casta and repelite. These sometimes contain inserts of linen or cotton.

Redmanol is a synthetic resin or amber, made of phenol and anhydrou hexamethylenetetramine. It is chemically inert, non-corrosive and no inflammable. Its physical and chemical properties remain unchanged wit age, but its dielectric strength increases with age. It is manufactured in fo forms: molded, laminated, transparent and paint.

Moulded Redmanol is furnished in a number of different grades and can b moulded very accurately with metal inserts. These grades do not warp an some of them with proper fillers can be used continuously in air at temperatur up to 260° C. and in super-heated steam up to 343° C. The properties var with the different grades.

Laminated Redmanol is tough, strong and flexible and can be shaped with too very accurately and takes a smooth polish. It does not warp or deteriorat with age or upon exposure to heat and weather. It is recommended as an insu lator to withstand the effect of salt sea air. It is available in sheets, tubes an rods in different grades with different properties.

Transparent Redmanol has a refractive index of 1.66 and therefore possesse brilliancy and lustre when polished.

Redmanol paint is used for coating electrolytic baths and vats containin solutions of not over 50 per cent of nitric acid, and as a protective coatin against ammonia and sulphur dioxide fumes. These coatings withstan indefinitely a temperature of 230° C. and are not affected by boiling water o strong salt solutions.

Resin is the oxidized exudation of certain trees or plants and may be of recen origin or exist as a fossil. Some of the common resins which are used for insula ting purposes are mastic, shellac, jalap, colophony, storax, amber, copal, kauri gum, gutta-percha, gum arabic, chicle and dammar. Most resins are insolubl in water but dissolve in alcohol, ether, etc., forming varnishes of high dielectri strength. The resin varnishes are limited in their use by the fact that they become brittle at low temperatures, and will disintegrate if under vibration. Resins are hygroscopic and in general possess undesirable acid properties.

Rubber. — (See article on *Rubber*.) Hard rubber is frequently referred to as ebonite or vulcanite. According to Paterson, Rayner and Kinnes, the best grade of hard rubber is composed of 65 per cent of para rubber and 35 per cent of sulphur. They made up a number of specimens accordingly and also a number with 15 per cent of various adulterants and in addition obtained one specimen in the open market. Their results show that a good grade can generally be identified by the specific gravity and yield point. The specific gravity of the specimens made up without adulterants was 1.2 and that of the open market was 1.5. The yield point of the former was 75° C. and the latter 56° C. Adulterants will usually increase the specific gravity.

The yield point was obtained by supporting a specimen 25 mm. wide and 10 mm. thick as a cantilever beam with a one pound weight fixed at 15 cm. from the support in an oven and observing the yield after two hours heating at each temperature. The temperature at which the specimen yields and takes a permanent set is the yield point. A high grade will yield not more than 20 mm. in two hours at 70°C.

The dielectric strength test should be applied under oil and by imbedding snugly two spheres 51 mm. in diameter in a specimen 10 cm. thick until the spheres are 0.5 mm. apart. The best grade of hard rubber should show a dielectric strength of 110 kv. per mm.

French chalk or steatite as an adulterant will not materially affect the dielectric strength but the product will be spotty and will not take a good polish.

The surface resistivity of rubber decreases upon exposure to light. Curtis

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found that a high surface resistivity could be restored by washing the surface with a dilute solution of ammonia and rinsing it thoroughly with water. The surface should be thoroughly wiped with a cloth until it is dry. The appearance of the surface can be improved by rubbing it, after it is dry, with waste oiled with a light lubricating oil.

Sindanyo is an English product made of asbestos with a special binder. It is manufactured in the form of sheets under pressure and then afterwards impregnated with an insulating compound. The sheets are furnished in two grades and of dimensions 3 feet by 4 feet or 3.5 feet by 8 feet and 0.125 inch to 2 inches thick. The Ebony grade is a substitute for slate and marble. Its dielectric properties are better than marble or slate as it is non-hygroscopic and free of metallic veins. As its mechanical strength is greater than that of either marble or slate it can be used in thinner slabs for the same purpose. It will not swell or warp under severe conditions and withstands temperature up to 200° C.

The plain grade is fire resisting and has good mechanical strength but unstable dielectric properties. It will withstand 900° C. without disintegration, warping or diminution of mechanical strength. It is used for arc deflectors and insulation in heating units.

Slate is any rock having a fissile structure, the common variety being composed principally of silica, alumina, and oxides of iron. It is hygroscopic and should be boiled in paraffin. It is often permeated by metallic veins, making it unfit for use unless the electrical connections are insulated by bushings. It is useful for switchboard and switch-base work owing to its desirable mechanical and fireproof qualities. Its dielectric strength decreases rapidly as the temperature increases, and at a high temperature slate becomes a conductor. When a high voltage is impressed upon a piece of slate for some time, the slate usually is not punctured but, due to the consequent rise in temperature, the slate acts as a short-circuit to the impressed voltage. The breakdown is thus only apparent as the specimens regain their dielectric properties after cooling.

Stanol is an English product made of asbestos and a rubber compound. It is furnished in sheets ⅛ inch thick and 50 inches by 60 inches. It is flexible and is used for lining controller cases and switch boxes. Its dielectric strength is 3.9 kv. per mm.

Varnished Cambric. — See article on *Cambric, Varnished.*

Varnishes, Insulating, are made in two classes: (1) baking varnishes, which harden by oxidation when subjected to artificial heat and (2) air-drying varnishes and similar compounds, which harden or set by evaporation of the solvent. Varnishes and similar compounds are manufactured in a number of grades adapted for use in armature, field and transformer coils, magnet and arc lamp spools, transformer bushings, insulating cloth, paper and fiber, armature and transformer stampings, asbestos and magnesia board, cut-out boxes, switch and panel boards, mica plate, flexible mica, mica cloth and paper, storage batteries, weatherproof wire, iron and metal fittings, moulding, pot-heads, taped connections, etc. Some of the trade designations are P. and B., S. P. C., S. V. W., G. P., H. R., Voltalac, W. P., Glinolac, Benolite, Dolph's, Ohmlac, Mineralac, Nico, M.C., Insullac, Enamelac, Armalac, Chatterton, Linolac, M. I. C., etc.

Vulcabeston is an English product often called "J. P. Bakelite" and is furnished in the form of sheets or special moulded forms. One grade is made of asbestos fiber and rubber as a binder. It is slightly elastic and has a tensile strength of 3600 pounds per square inch. It is claimed to withstand a temperature of 145° C. without physical changes. When immersed in cold water for 48 hours it absorbs 1.75 per cent of its weight of water. Grade No. 201 is

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made of asbestos fiber with a special phenolic gum as a binder. It has a tensile strength of 9000 pounds per square inch and will withstand a temperature of 260° C. without undergoing physical changes. It absorbs 0.6 per cent of its weight of water when immersed in cold water for 48 hours.

Vulcanite. — See article on *Rubber*.

Wood. — Thoroughly dried hard wood, if impregnated with an insulating material, makes a good insulator. The woods commonly used are maple, cherry, ash and yellow pine. For use in transformers, wood is usually impregnated with transformer oil, and when used in air, the wood is impregnated with paraffin or rosin.

Other Insulations which are in very general use but not described in published literature are: Carvanite, Faturan, Kalanite, Pilit, Solidite, Stabelite and Tegit.

Information on the various insulating materials described were obtained from the authorities cited in the bibliography, from the following manufacturers: American Lava Corporation, American Vulcanized Fiber Company, Chicago Mica Company, Condensite Company of America, Continental Fiber Company, Delaware Hard Fiber Company, Diamond State Fiber Company, Formica Insulation Company, General Bakelite Company, General Electric Company, M. Kirchberger & Co., Mica Insulator Company, Minerallac Electric Co., National Fiber and Insulation Company, Redmanol Chemical Products Company, J. Spaulding & Sons Company, D. M. Steward Manufacturing Company, R. Thomas & Sons Company, and Westinghouse Electric and Manufacturing Company.

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INSULATING MATERIALS, TESTING OF. — (*See also Insulating Materials, Properties of.*) The most important electrical properties of an insulating material are its dielectric strength, specific inductive capacity, resistivity, dielectric loss, and power factor. Some of the more common methods of measuring these quantities are described below.

DIELECTRIC STRENGTH. — The dielectric strength of an insulating material is defined as the puncturing voltage per unit thickness, the thickness usually being measured in centimeters. The voltage required is in general higher than can be conveniently obtained with direct-current sources of e.m.f. and alternating e.m.f.'s are therefore used in such tests. The materials to be tested are placed between electrodes connected to the high-tension terminals of a transformer, which receives power from a low-voltage alternator.

Testing Transformers and Alternators. — Transformers for such use are made to deliver voltages up to 500,000 volts. For the purpose of comparison and computation of the maximum e.m.f. from the effective value, it is essential that the alternator should give a sine-wave voltage at all loads. Both transformer and alternator should be large enough to operate with good voltage regulation at all testing loads, so that no distortion of the wave-form will be produced by the charging current. Skinner suggests the following ratings of testing transformers:

Max. test voltage	Cap. of trans. in kw.*	Max. test voltage	Cap. of trans. in kw.
2,000	1	50,000	50
6,000	3	100,000	100
10,000	5	150,000	150
30,000	30	250,000	250

* Testing transformers are usually rated by their four-hour capacity.

The alternator should have a distributed field winding and in order that the combination of alternator and transformer may respond to any instantaneous rise, the impedance of each should be low; that is, the speed of the alternator should be high and the e.m.f. induced per turn in the transformer should be high.

Form of Electrodes. — Many investigators have demonstrated that the form and size of the electrodes used are important factors of the test. If the edges of the electrodes are rounded, the resulting brush discharge heats the specimen so that it breaks down at a low voltage. If the edges of the electrodes are not rounded, the increased flux density at the edges produces an excessive strain on the dielectric under the edges of the electrodes. Most authorities favor the use of flat electrodes with slightly rounded edges. Hendricks suggests flat electrodes with corners rounded to a radius equal to one-tenth of the diameter of the flat face. Kinzbrunner has discussed in detail the effects of various shapes of electrodes.

For testing oils or other liquids two standards composed of definitely shaped terminals supported in a liquid container are commonly used. In one the test-piece terminals consists of brass balls ½ inch in diameter fastened to rods 3/16 inch in diameter and placed vertically in a glass tube. The distance between the balls

is adjustable, a distance of 0.15 inch, however, being considered sta
the other standard the terminals consist of brass disks 1 inch in
mounted on rods ⅜ inch in diameter and placed horizontally in a
made of Bakelite or some other insulating material. The spaci
disks in this case is also adjustable, although 0.1 inch is adopted as a
Average dry oil should not break down in the ball electrode standa
than 60,000 volts and in the disk electrode standard at
30,000 volts.

Time of Electrification. — Materials may be tested by impr
puncturing voltage, 1. instantaneously, 2. in steps of one-minute d
3. in several instantaneous applications of decreasing voltage and
time of electrification. The question of the proper time of electrific
present undecided, although many investigators favor the one-minu
fication. For arguments against this standard, see paper by Kinzbru
erence in Bibliography at end of this article).

Control of Voltage. — The voltage impressed between the test
may be controlled 1. by varying the excitation of the alternator, 2.
ing resistance in series with the low-voltage terminals of the transfor
varying the number of active turns on the low-tension side of the trans
by an induction regulator in series with the transformer primary. A
tion of the first and third methods is very commonly used. In t
method the voltage wave is made more peaked as resistance is intro
the third method, if used alone, the circuit must be broken as conn
made to the tap leads. By varying the field excitation of the alte
changing the tap connections between tests, the shape of the volta
kept constant and the variation of field saturation in the alternator
to a minimum. The last method is probably the most commonly use
entirely satisfactory results.

Measurement of Voltage. — The voltage impressed upon the mat
test may be determined by 1. a variable spark gap shunted across
trodes, 2. by a voltmeter and an extension coil or multiplier connec
the electrodes, 3. by an electrostatic voltmeter connected across the
4. by a voltmeter connected across the low-tension terminals of the tr
the reading of which is to be multiplied by the ratio of transformat
transformer, 5. by a potential transformer and a voltmeter connec
the terminals and 6. by a special voltmeter winding placed in the mi
high-tension winding of the power transformer. The needle spark-ga
while convenient because of its indication of the maximum rather tha
tive value of the voltage, is tedious in use, and its readings are depen
the time of electrification, circulation of air, the condition of the ne
The sphere spark gap is preferable; see *Spark Gap*. The use of the
and extension coil, while flexible and convenient, is not recommende
of the load which is placed upon the transformer and the possibility
in the extension coil. The use of an electrostatic voltmeter is desira
that at high voltages the moving element must be immersed in oil, n
instrument sluggish in action, and may frequently break down. In a
involving the ratio of transformation of the transformer, the results are
able owing to the assumption of a constant ratio of transformation at
The use of the potential transformer and voltmeter is prohibited in
by the cost of the instrument transformer and the excessive disto
introduced by such an arrangement.

A voltmeter winding in the power transformer furnishes as a rule
accurate and efficient method of measurement, the chief source of e
due to leakage flux and impedance drop in the transformer.

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in Results.— The puncturing voltage of an insulating s previous history, precise condition when tested, size, ity of electrostatic field, temperature, time of electrifi- he surrounding medium. The puncturing voltage is ature than any other factor, and since the temperature l greatly under the action of the corona discharge (*see* at corona discharge should be eliminated. To prevent corona, 1. guard rings may be supplied, as described by , 2. the electrodes may be imbedded in the dielectric cein drop" method described by Walter may be used e electrodes and test specimen may be immersed in oil dricks. In the last case materials easily permeated by with a varnish before testing. While the temperature ay range from $-25°$ C. to $+125°$ C., tests between should suffice to indicate average working conditions.

TIVE CAPACITY OR DIELECTRIC CON- *Condensers.*) The specific inductive capacity of any the capacity of a condenser, in which the substance in tween the plates, to the capacity of the same condenser the plates is filled with afr. This ratio, designated mperature of the substance, the time of electrification e frequency, when tested with alternating currents. pacity of most substances decreases as the tempera- the case of a few substances. The specific inductive ases with the time of electrification and decreases as The determination of the specific inductive capacity termination of the capacity of a condenser of known ylindrical condenser is commonly used for solid material r for liquids. Having determined the capacity of any ensions from test, the specific inductive capacity of the ained by substituting the known constants in the con- the article on *Capacity and Charging Current.* asuring capacity are given in the article on *Condensers,*

American Institute of Electrical Engineers recommend surements be made with alternating current. The ty with alternating current, therefore, is of such a detailed description of the method is given below. consideration is a liquid a standard condenser Cs is is first obtained on the container with air as a dielec- e same container with the unknown liquid as a dielec- ty is

$$K = \frac{R_a}{R_x}.$$

with air in the container and R_x is the corresponding n dielectric.

ent Bridge Method.—A Wheatstone bridge as shown a mica or an air condenser, R and R_2 are resistances is a variable inductance and L_2 may be a fixed induct- be either a telephone or a vibration galvanometer, for 60-cycle work. As the capacity to be measured ethod should be used by inserting, first the unknown C and varying R and L until a balance is obtained, and

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then a standard condenser C_s in the same arm and obtaining a balance again by varying R and L, but leaving C_x, L_x and R_x undisturbed. Then

$$C_x = \frac{R_s}{R_x} C_s,$$

where R_x and R_s are corresponding readings obtained on R with C_x and C_s.

The power factor is equal to sin θ_x or tan θ_x when θ_x is small, and may be computed from the following equation:

$$\tan (O_x - O_s) = \pi \left(\frac{L_x}{R_x} - \frac{L_s}{R_s} \right),$$

where O_s is the angle by which the current falls short of being 90° ahead of the e.m.f. impressed on the standard condenser, and is zero for an air condenser and seldom more than 5′ for a good mica condenser. L_x and L_s are readings obtained on L with C_x and C_s respectively.

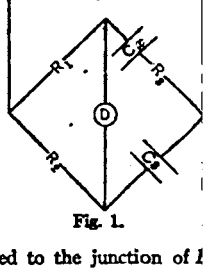


Fig. 1.

If only an approximate value of the specific inductive capacity is desired, the inductances L and L_s may be omitted in Fig. 1. In this case the current in the detector will not be zero when the bridge is balanced but will be a minimum.

Where a telephone detector is used and high degree of accuracy is required, the bridge should be shielded so that the observer will be at the same potential as the telephone. Also a guard ring should be provided in the condenser under test, the ring being on the side nearer the detector and connected to the junction of L and L_s.

INSULATION RESISTANCE. — The method commonly employed is one of substitution. A standard resistance R_s (usually $\frac{1}{10}$ megohm) connected in series with a D'Arsonval galvanometer is connected across a direct-current source of e.m.f. of about 500 volts and the deflection D_s of the galvanometer noted. The galvanometer must have a sensitiveness of about 1×10^9 and the deflection should be directly proportional to the current. If the galvanometer is shunted, an Ayrton universal shunt should be used (*see Shunts*) so that the damping of the galvanometer will be independent of the multiplying power. The deflection D_x is then noted when the unknown resistance R_x is connected in place of the standard resistance. Then

$$R_x = \frac{D_s}{D_x} R_s.$$

The usual errors of this method are due to leakage and absorption. Leakage may be reduced considerably by the use of a guard ring, so connected as to shunt the leakage current around the galvanometer. The deflection of the galvanometer will vary with time due to absorption, and the resistance of the material will apparently vary with the time of electrification. To facilitate comparison of the insulation resistance of dielectrics, it has become common practice to take the resistance obtained after one minute's electrification. Owing to the large negative resistivity temperature coefficient of most dielectrics, it is essential that the temperature of the material be noted when tested.

ENERGY LOSS IN THE DIELECTRIC—EFFECTIVE CONDUCTANCE. — Energy loss in dielectrics is difficult to measure on account of both the small amount to be measured and the low power factor. The compensated

nethod and the electrostatic wattmeter method have
ometimes the dielectric loss is expressed as the effect-
h is equal to the watts lost divided by the square of

YNAMOMETER, WATTMETER METHOD.—
is subjected to a high voltage from a test transformer
y it is measured by means of a delicate, mirror type

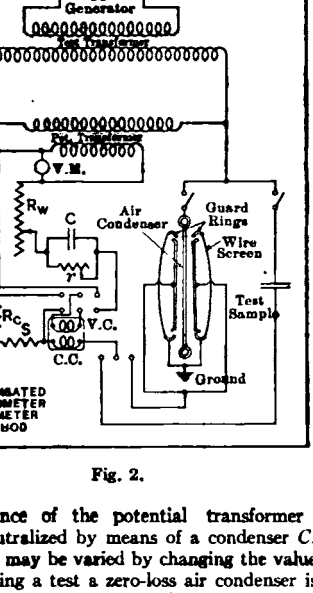


Fig. 2.

nce of the potential transformer and wattmeter
ıtralized by means of a condenser *C*. The effective
may be varied by changing the value of the shunting
ing a test a zero-loss air condenser is substituted for
esistance *r* is varied until the wattmeter shows zero
ple is then substituted for the air condenser and the
on indicating the power lost in the sample.
the potential coil of the wattmeter is connected across
the variable resistance R_c. This puts the current in
the instrument will read as an ammeter.
rated by direct-current, using a potentiometer and
e separately calibrated if used as an ammeter.

Grover, *Bull. Bur. Stand.*, Vol. III, p. 371; Hen-
11, Vol. XXX, p. 167; Laws, *Notes for use in Stand.*
Rosa, *Bull. Bur. Stand.*, 1907, Vol. III, p. 43; Skinner,
227, 1905, Vol. II, p. 538; Sumpner, *Jour. Soc. Tel.*
344; Tobey, *Trans. A.I.E.E.*, 1910, Vol. XXIX, p.
Zeit., 1903, Vol. 24, p. 796; Zelleny, *Phys. Rev.*, 1906,

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INSULATOR PINS. — (*See also Cross Arms; Insulators for Overhe*
Insulator pins are made of wood, iron and various combinations of w
and porcelain.

WOODEN PINS. — Wooden pins are usually made of locust but s
of oak, birch, maple or eucalyptus.

The forest service reports: "Black locust is admitted to be the b
woods used for insulator pins, but of late years other woods are bein
into use. Among those which will probably prove satisfactory as subs
the black locust are Osage orange, various oaks, yellow birch, gum, ha
elm, etc." Also: "The value of eucalyptus, particularly blue gum, fo
pins has been thoroughly demonstrated. After fifteen years' service, s
are still in use."

Standard Distribution Pins (Fig. 1). — The standard wooden p
tribution lines is of locust, 9 inches long, 1½-inch diameter shank, a
diameter thread, as shown in Fig. 1. It is often described simply as
by 9-in. pin." It is standard for use with double-petticoat deep-gr
insulators and is also used for some insulators designed for higher vol

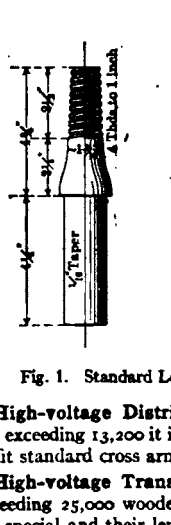


Fig. 1. Standard Locust Pin

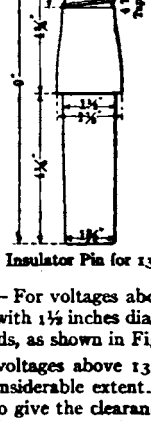


Fig. 2. Insulator Pin for 13,00

High-voltage Distribution Pins (Fig. 2). — For voltages above
not exceeding 13,200 it is desirable to have pins with 1½ inches diame
to fit standard cross arms, but with larger threads, as shown in Fig. 2

High-voltage Transmission Pins. — For voltages above 13,20
exceeding 25,000 wooden pins are used to a considerable extent. T
are special and their length must be sufficient to give the clearance
lator to cross arm required by the design of insulator used. The shan
be larger than those of standard pins.

On high voltages wooden pins are too weak for the high stress impo
great pin leverage of large insulators and present practice is toward
to secure the required strength. The use of paraffined wood pins has
tically discontinued.

IRON DISTRIBUTION PINS. — Iron pins (malleable iron
forged iron) are made with 1 ½ inch shanks and 1-inch threads so as t
changeable with standard wooden pins. They are used at points of he

Pins with Iron Shanks consisting of ¼-inch, ⅜-inch or ½-inch
are also used. These have a nut and washer on the lower end used

the base of the pin firmly into contact with the top of the arm. This type of pin has the advantage that the smaller hole removes less wood from the arm. For heavy stresses the shank of the pin should be stiff, or the base of the pin broad to prevent local crushing of wooden cross arms due to the pin leverage.

ATTACHMENT OF INSULATORS TO PINS. — Insulators are usually attached to wooden pins by a screw thread having a pitch of 4 threads per inch. The threaded portion of the pin is tapered, the diameter increasing downward from the top about $\frac{1}{16}$-inch per inch of length. Standard thread diameters are 1 inch for distribution insulators and 1$\frac{5}{8}$ inches for high-tension insulators measured at the small end over the thread. Good fit in the thread between pins and insulators is not commonly attained because: (1) the threads are often imperfectly cut on the pins, (2) the wood of the pin shrinks so that it ceases to be circular or warps so that the axis of the pin is not truly straight, (3) the porcelain of the insulator warps in manufacture so that the hole ceases to be circular or the surface of the thread may not be smooth. Where a pin does not screw into the insulator to full depth intended, or where it is loose or bears unequally, the strength of the attachment is much reduced. The weakest point is usually at the root of the bottom thread.

Attachment of Insulators to Iron Pins. — Insulators are sometimes attached to iron pins by a screw thread similar to that used for wooden pins. The thread on the iron pin is often made of lead to get a more uniform bearing.

In later types the thread is made in the form of a coiled spring to better distribute the load stresses.

High-tension insulators are frequently cemented to iron pins. The pin hole of the insulator may be threaded as usual. The end of the pin is usually corrugated or fluted instead of being threaded. The pin is grouted to insulator with neat Portland cement.

ATTACHMENT OF PINS TO ARMS. — The standard wooden distribution pin has a shank of 1$\frac{1}{2}$-inch nominal diameter. The actual diameter at the top is the same as the nominal diameter, the shank tapering so that the bottom is about $\frac{1}{16}$ inch smaller. The pin hole in the cross arm is bored to the nominal diameter but often becomes smaller (across the grain) due to shrinkage of the wood, so that a standard pin, although smaller than nominal size of the pin hole except at extreme top, will often make a good driving fit. Pins which are too small (or pin holes which are too large) will make a loose fit and should not be used. Pins are often made considerably oversize at the top and undersize at the bottom to allow for inaccuracy of workmanship. Such pins will not drive completely in, and they weaken the construction by increasing the pin leverage and decreasing the bearing surface between the pin and cross arm. At the top of the shank a shoulder should be provided to limit the distance the pin can be driven in. For maximum strength the shank should be long enough to go completely through the arm and the taper should be small enough so that it will bear against the arm for the full depth without leaning far to one side. The standard 1$\frac{1}{2}$-inch by 9-inch pin has a 4$\frac{1}{4}$-inch shank length corresponding to the old "standard" depth of cross arm, and, therefore, does not develop the full strength of the later standard arms which are 4$\frac{1}{2}$ inches or 4$\frac{3}{4}$ inches deep.

Pins are prevented from pulling out of the arm (especially where the wire exerts an uplift on the insulator and pin) by driving a nail (usually six-penny) through arm and pin.

Wooden pins for high-tension insulators are made with larger diameter shanks, 2 inch, 2$\frac{1}{4}$ inch and 2$\frac{1}{2}$ inch being used.

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Comparative Strength of Some Special High-tension Pins. — The lowing are the results of tests made on pins fitted into wooden cross arms. pins broke at the top of the shank.

Material	Dimensions of shank, inches		Pin leverage, inches from center of stress to top of arm	Breakl strengt pound
	Diameter	Length		
Oak	2¼	6	12	140
Oak	2¼	6	16	120
Oak	2½	6	12	205
Oak	2½	6	16	120
Eucalyptus	2¼	6	about 10	260
Red oak	2½	7¼	12½	495
White oak	2½	7¼	12½	738
Locust	2½	7¼	12½	1121

COSTS. — The following figures, giving the cost, are rough approximati

Material	Dimensions in inches			Approxima cost per 1
	Diam., Shank	Overall length	Diam., Top	
Standard Oak (Fig. 1)	1½	9	1	$ 7.50
Standard Locust (Fig. 1)	1½	9	1	14.00
Special Locust	1½	10¾	1⅜	22.00
Solid Drop-forged Galvanized Iron	1½	9	1⅜	500.00

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INSULATORS FOR OVERHEAD LINES. — (*See also Distribution Lines; Insulator Pins; Transmission Lines.*) Insulators for overhead lines may be classified as insulators for distribution lines, pin insulators for transmission lines and suspension insulators for transmission lines. The general features of design common to all classes of line insulators will first be considered.

DESIGN OF LINE INSULATORS. — Glass is commonly used for making small low-voltage insulators and porcelain for large insulators. Porcelain has greater mechanical strength, condenses less moisture on its surface and parts may be cemented together, but faults cannot be as readily detected as in glass. Glass insulators are often completely shattered by a blow while porcelain insulators usually are only chipped under similar circumstances. Various compositions are also used to a limited extent for line insulators.

Properties of Porcelain and Glass. — Following are some of the more important characteristics of porcelain and glass:

Property	Glass	Porcelain
Tensile strength, lb. per sq. in	2,500–9,000	1,500–2,300
Crushing strength, lb. per sq. in	6,000–10,000	14,000–16,000
Elastic limit, lb. per sq. in	3,200 approx.	.....
Modulus of elasticity, lbs. per sq. in	8,000,000	2,500,000 (*b*)
Coeff. of expansion per °F	0.0000046	0.00000585 (*b*)
Coeff. of expansion per °C	.....	0.00000413 (*a*)
Weight per cubic foot in lbs	160	155
Puncturing strength in volts per inch for very thin samples	300,000	400,000
for commercial sizes and quantities	150,000	225,000
Specific inductive capacity (air = 1)	5 to 10 (*a*)	4.38 (*a*)

(*a*) Smithsonian Physical Tables. (*b*) Austin, A. O., Proc. N.E.L.A., 1913.

In American practice porcelain parts are made from ¼ inch to 2½ inches in thickness. In European practice porcelain is used in thicknesses up to 1 inch. The working voltage usually averages from 10,000 to 20,000 volts for each thickness of porcelain used. 15,000 volts is about an average figure, so that a 30,000-volt insulator usually has two parts, a 40,000-volt insulator 3 parts and a 60,000-volt insulator 4 parts.

An insulator must be designed to stand extreme and sudden temperature changes, sleet and rain, as well as smoke, dust, and often special conditions such as salt fogs, salt water sprays, and chemical fumes, without deterioration from chemical action, breakage from mechanical stresses or electrical failure. The design of high-tension insulators is a process of compromise between requirements often antagonistic in nature.

Some of the principal points in the electrical design of high-voltage insulators are:

Shape. — The insulating surfaces should conform to the flow lines of the electrostatic field, the surfaces of the rain sheds or petticoats should conform to equipotential surfaces, the leakage resistance per shell should be about equal, the plane of mechanical rupture should not coincide with the plane of electrical stress, and the unit should have approximately equal capacitances per shell.

Thickness to Resist Puncture. — The porcelain must be thick enough to resist puncture by the combined working voltage of the line and any probable

transients whose time lag to spark over is great. If this thickness is greater than desirable from a manufacturing standpoint, two or more pieces are used to give the proper aggregate thickness.

Arcing Distance; Free Arcing. — The porcelain must extend beyond the charged conducting connections (i.e., tie wire or cap at the top and pin at the bottom) sufficiently so that the distance between the connections through the air around the porcelain is greater than the arcing distance of the maximum voltage to be carried. The arcing distance required for a given voltage may be determined roughly (but only very roughly) from the tables of arcing distances between needle points; see article on *Spark Gap*. The greater radius of curvature (compared with needle points) of such metal parts as the insulator pin decreases the potential gradient at the terminals. Also the porcelain has a much greater specific inductive capacity than the air and its proximity to the arcing path disturbs the electrostatic field through the air. Surface charges on the porcelain because of surface leakage or corona also modify the field.

Free arcing is the property of arcing over along a line which does not touch the porcelain body from the point where the arc leaves the metal cap to where it strikes the metal pin. Where the arc touches any part of the porcelain the great heat fractures the porcelain in a few seconds; hence the desirability of designing the insulator so that it is free arcing. A properly designed insulator will arc over as a whole before any individual part (i.e., shell or unit) arcs over. In many defective designs the insulator will fail by some parts arcing over, thereby increasing the voltage on others which then fail by puncture or arcing over.

Factor of Safety Against Puncture. — The thickness of a porcelain part must be so related to the distance around it that it will arc over before it will puncture. The ratio of puncture strength to arc over-voltage is the factor of safety of the part, or of the insulator, against puncture.

This ratio should be high to give sufficient margin to protect the insulator from puncture by the transients before mentioned.

Guard Rings and Rods. — Where an insulator is not naturally "free arcing" from cap to pin, properly located rings or rods will divert the arc so as to accomplish an equivalent result. Rings used for this purpose are known as Nicholson guard rings. Where a pin insulator is improperly designed so that it is liable to puncture before flashing over, a Nicholson ring around the base may be used to redistribute the potential or to reduce the arcing distance so as to reduce trouble from puncture. Such rings and rods are also sometimes used in connection with suspension insulators.

Leakage Surface. — Leakage surface is ordinarily measured as the number of (linear) inches from cap (or equivalent) to pin taken radially along the surface; see Fig. 4. This, however, is only a rough measure as it neglects the varying width of leakage path. The figures in the accompanying table on pin insulators from a manufacturers' catalog give approximately the total amount of leakage surface used in practice. The amount of surface allowed varies considerably between different designs and makes.

Rated voltage	Length of leakage surface, inches
5,000	4
6,600	5½
10,000	6¾
23,000	12
44,000	29
66,000	53

Spread of Petticoats of Pin Insulators. — In two concentric shells the two surfaces which lie opposite to each other are at different potentials

except where they are cemented together. The difference in potential between two points on opposite surfaces is greater the further they are removed from the joint. Unless the shells diverge correspondingly so as to increase the distance between the shells as the potential increases the air will break down and part of the leakage surface will be short-circuited by a corona discharge. This divergence is shown in Fig. 4, where the top is a disc made slightly convex to shed water and the inner shells are a series of cones which radiate from the top of the pin.

Color and Glazing. — Brown, slate and white are the common colors used in glazing porcelain. Brown is the most common color since it is more of an aid in determining faults. Slate-colored glazing of the same color as galvanizing on towers makes insulators a less conspicuous target for malicious destruction.

Cementing of Insulators. — Insulator parts are cemented together with neat freshly burned and finely ground Portland cement which is usually allowed to set under water from ten to fourteen days before testing mechanically. The more freshly burned and finely ground the cement and the higher the temperature, the less time required for setting. The cemented surfaces of porcelain are unglazed and corrugated to obtain good bond.

Faults in Insulators. — The more common faults in porcelain are porosity, folds and flaws in moulding and the development of checks and hair cracks in process of drying, incomplete and non-uniform glazing, warping, air bubbles, conducting impurities, under- and over-firing and chipping of edges. Only 50 to 75 per cent of moulded shapes ordinarily pass final test and even a less number of the more difficult shapes. Inspection and testing are essential to eliminate faults in both design and manufacture.

DISTRIBUTION-LINE INSULATORS, STANDARD (Fig. 1). — For ordinary distribution circuits, including constant-potential circuits up to 2200 volts nominal and series-arc circuits of all voltages, the double-petticoat deep-groove (D.P.D.G.) insulator, of the type shown in Fig. 1, is standard.* Such insulators are usually of glass, though occasionally of porcelain, and in cases where there are heavy stresses, as at dead ends where iron pins are required, the insulators are made of moulded mica. The dimensions vary with different manufacturers.

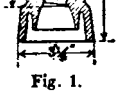


Fig. 1.

These insulators are used with the standard pin shown in Fig. 1 in the article on *Insulator Pins*.

Pony Insulators. — These are small insulators used for telegraph and telephone wires. They are unsuitable for electric light and power wires. The groove is too small (sometimes only ¼ in.) to properly support the larger wires used for lighting and the leakage surface is insufficient for proper insulation.

Insulators with Top Groove. — The standard distribution insulator has a groove in the side to which the wire is tied. For very heavy cables special insulators with groove in top are used. Insulators for higher voltage usually have both side and top groove. the former used where there is horizontal stress due to angle in line, and the latter on straight parts of line where the weight is the principal force.

DISTRIBUTION-LINE INSULATORS, HIGH-VOLTAGE (Fig. 2). — For circuits exceeding 2200 volts but not exceeding 13,200 volts nominal, it is convenient to have insulators which can be used on the standard distribution

* The same size insulator is used for 110-volt and 2200-volt circuit. This has the advantage that only one kind of insulator is kept in stock, and a wire can be transferred from use on a low-voltage circuit to one of higher voltage without reinsulating it.

pins. A number of insulators are made with 1-in. threads to fit the standard 1 ½ in. by 9-in. pin. It is better, however, to use stronger special pins with 1⅜-in. top; see article on *Insulator Pins*. Fig. 2 shows an insulator which has been used on these voltages. It is used with the pin shown in Fig. 2 in the article on *Insulator Pins*. The manufacturer rates this insulator at 23,000 volts with a factor of safety (wet) of 2.

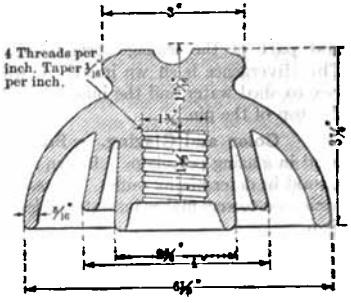
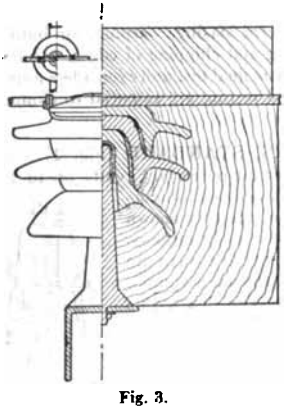


Fig. 2.

TRANSMISSION-LINE INSULATORS, PIN-TYPE (Figs. 3 and 4). — The pin-type insulators are similar in mechanical construction to the low-voltage insulators used for distribution lines, but are larger and designed for heavier mechanical stresses as well as higher voltages. The conductor is supported on a top groove except where an angle in the line causes a lateral pressure, in which case the side groove is used. For voltages up to about 10,000 volts the insulator usually consists of but a single porcelain part. For higher voltages from two to five parts are cemented together. The size and expense of pin-type insulators increase rapidly with the voltage so that while they may be used for operating potentials of 70,000 and even more, their use is generally restricted to potentials of not over 50,000. Typical three-part insulators are shown in Figs. 3 and 4. The separate parts are called parts, shells or cones and are numbered in order beginning with the top.


Fig. 3.

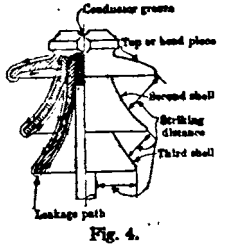
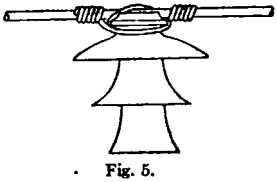
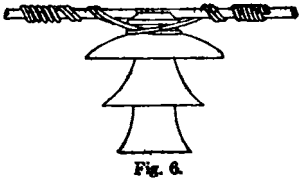


Fig. 4.


Fig. 5.


Fig. 6.

On a cost per mile basis, the suspension insulator construction is often less

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than the pin type for pressures above 44,000 volts, due to the longer spans thus made possible.

Tie Wires and Clamps. — Tie wires consisting of the same material as conductors are commonly used for fastening conductor to insulator. Two common types of ties are shown in Figs. 5 (single tie wire) and 6 (double tie wire). For copper conductors the tie wires are usually soft-copper wires which are three sizes on the A.W.G. (B. & S. gage) smaller than the conductor. Metal caps carrying clamps for the conductor are cemented to tops of insulators when more strength is required than can be obtained by tie wires.

TRANSMISSION-LINE INSULATORS, SUSPENSION TYPE (Figs. 7 to 10). — The suspension type insulator is always used in tension, the con-

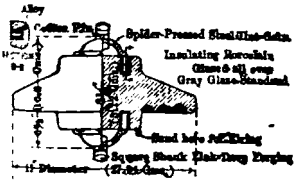


Fig. 7.

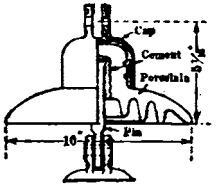


Fig. 8.

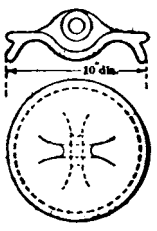


Fig. 9.

nections at the two ends being made so that the insulator is free to swing in any direction; the insulator takes such a position that its axis coincides with the direction of the mechanical stress. This type is used hanging below the cross arm with axis vertical as a suspension insulator for sustaining the weight of cable at points where there is little horizontal force, and also with axis approximately horizontal as a "strain" or "dead-end" insulator at points where the horizontal force predominates.

The suspension type consists of one or more complete insulators, called "units," connected in a string. Each unit consists of one or more insulating parts usually with a metal cap above and a metal pin below, all cemented together. Three typical designs now in general use are shown, Figs. 7 to 9.

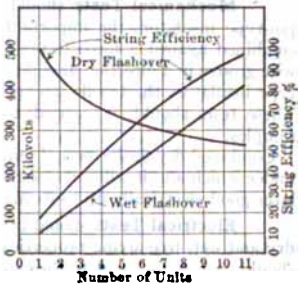


Fig. 10.

Relation Between Electrical Strength of Single Unit and a String of Units. — The potential per unit required to flash-over a suspension insulator composed of units of the same design decreases with an increasing number of units as shown in Fig. 10. This is due to an unequal potential gradient. See *Bibliography*.

Connections Between Suspension Units. — The caps and pins of suspension insulators are commonly made of galvanized malleable iron castings, but where strength is required the pins are steel drop forgings, and pressed steel for these fittings is coming into general use.

The common types of connection between the pin of one insulator and the cap of the one next below are ball and socket, clevis and pin (Figs. 7 and 8) and hook and eye. The hook and eye is the simplest type, but there is danger of its becoming unhooked and, in order to obtain strength, the design requires more space between units than other types of connection. The clevis and pin has the disadvantage of loose parts. The ball-and-socket connection requires special terminal fittings and a rigid connection to prevent the clamp from turning when used on deadend insulators for conductors which tend to untwist. It can, however, be designed with less space between units than other types.

A type of suspension insulator which does not require caps and pins is shown in Fig. 9. These units are connected together by cable loops. This was one of the first types of suspension insulators. It is not commonly used on account of cost of manufacturing. A very close inspection is often required to find punctured units that are not shattered by the failure.

Conductor Clamps for Suspension Insulators. — A common form of insulator clamp is shown in Fig. 8 in the article on *Wires and Cables, Bare.*

Other forms are in use (see Manufacturers' catalogues). They are usually made of malleable castings or pressed steel. A requirement to be remembered when using steel cored cables is provision for clamping the steel core independently of the aluminum or copper wires in strain clamps. Strain clamps should have an ultimate strength at least equal to that of the cable supported.

TESTS OF INSULATORS. — Tests of insulators may be classified as (1) design tests, made on a very few insulators to determine the characteristics of new designs, and (2) routine tests made on each insulator manufactured to detect defects of material or workmanship.

Design Tests. — Design tests are quite expensive for very high-voltage insulators because of the difficulty of securing suitable testing apparatus.

Mechanical Tests should be made to determine the strength. With pin-type insulators the important point is the strength of pin and insulator combined against a force (representing a horizontal wire pull) applied at the wire groove in a direction at right angles to the axis of the pin. For suspension-type insulators the tensile strength is the important mechanical consideration. These tests should be carried to the point of destruction of a number of samples.

Combined dry flashover and tension tests are important to determine the load under which a unit will fail electrically. Proper design should produce an insulator good electrically up to its maximum mechanical strength.

Electrical Tests should be made for puncture strength, arc-over voltage dry and wet, free arcing properties and corona formation. The electrodes used should conform in shape to the cap and pin used in practice so that all surface exposed to puncture when the insulator is in use will be tested. Design tests of the electrical properties of suspension insulators should be made on complete strings of insulators as well as on single units, assembled under field conditions as to proximity of towers, etc.

Puncture Test. — As the air surrounding a properly designed insulator acts as a safety valve, it is necessary to immerse the insulator in oil in order to test the material of which the insulator is composed up to its puncture strength at normal frequency. Such a test may be used to ascertain the margin by which the puncture strength exceeds the flash-over voltage and to verify the dielectric strength of the porcelain. Tests in air made with high frequencies, however, are found to puncture insulators which arc over at normal operating frequencies. The frequencies used for normal tests include all commercial frequencies or say

from 25 to 125 cycles per second with 60 cycles the most common. For high-frequency testing a 200,000 cycle oscillator is found suitable.

Arcing Tests. — Arcing tests, both dry and wet, are made to determine the voltage at which an insulator will arc over when the voltage is raised with the insulator in its normally dry condition and when wet as in rainy weather. The dry arcing test is the most common one made because of its simplicity, the voltage merely being raised on cap and pin until arc over occurs. Wet test in new designs is very important as there is danger of puncture or arc over of individual parts which appear safe on dry test. The standard precipitation for a wet test is ¼ inch of distilled water per minute inclined at an angle of 45° with the axis of the insulator. The wet arcing test usually gives a lower arc-over voltage and hence gives a measure of the electrical factor of safety of the line (ratio of voltage at which failure occurs to working voltage) under the weather conditions when the factor is usually the lowest.

Free Arcing Tests. — In order to test the free-arcing properties the testing transformer must be large enough so that the flash at time of arc over will continue as a true power arc; even then the phenomena of fracture will rarely occur, even if the insulator is not free-arcing, because of the comparative feebleness of the power used in testing.

Corona Formation is indicated by the emission of a sound (i.e., the insulator is not "quiet") and may be still more accurately detected by the light from the corona when insulator is tested in the dark. Corona is considered an evidence of defective design and it is considered desirable that the voltage of corona formation should not be much below the arc-over voltage and certainly not below working voltage. However, many and perhaps most, high-voltage insulators show some corona at working voltage, though the amount is so small that it is difficult to detect.

Routine Tests. — No high-voltage insulator should be used without having been tested at the factory. Mechanical tests, except on a few selected samples, are not ordinarily made on pin-type insulators. On suspension insulators a tension test on each unit is desirable, but should not exceed about one-half the expected ultimate strength, for this is sufficient to eliminate defective ones, and most insulators are permanently injured electrically at a point below this ultimate strength.

Flash-over or arcing tests should be made on each porcelain part before assembly (so that no poor part will get into any insulator) and on the whole insulator when assembled. Each part should be tested to flash-over potential for five minutes, on normal frequency, or two minutes at 200,000 cycles.

The cup-shaped parts (also complete pin-type insulators) may be tested by setting them inverted in a pan of water used as one electrode, and partly filling the cup with water for the other. A large number of similar parts are ordinarily tested simultaneously in this way. Assembled suspension units are tested by using pin and cap as electrodes. The string of units forming a complete suspension insulator is not tested, except for a few selected samples (design tests). Factory tests of parts can be made at the factory with a transformer which will give a moderately high voltage, and no special measuring instruments are necessary, as the fact that parts are tested to arc-over voltage is evidenced by the fact that the arc-over is visible. A certain number of all units fired should be submitted to a test for porosity by immersing broken units in fuchsine dye under pressure of about 200 pounds per square inch for about two hours.

Testing on the Line. — Periodic testing of insulators on the line should be carried out to eliminate deteriorating units before they fail and interrupt service.

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SPECIFICATIONS FOR INSULATORS. — (*See also Article on Specifications.*) Several specifications for high-voltage insulators have been suggested as suitable for "Standard Specifications"; see papers by Peek, Sanford and Thomas in *Transactions of A.I.E.E.*, 1913, Vol. 32–2, pp. 1457–1508. Specifications covering the inspection and tests of porcelain high-tension line insulators for over 25,000 volts, which had been prepared by the High Tension Transmission Committee of the A.I.E.E., were presented at the 1914 annual convention of the Institute. The reader is referred to the above-mentioned papers for details.

INSTALLATION OF INSULATORS. — See the articles on *Distribution Lines* and *Transmission Lines*.

PIN TYPE

Material	Operating voltage, volts	Test voltage		Diameter, inches	Height, inches	Number of parts	Weight, pounds	Cost, dollars
		Wet, volts	Dry, volts					
Glass.....	110-2200	.....	.....	3¼	4	1	1¼	.08
Porcelain .	13,200	40,000	80,000	6½	3¾	2	3⅝	.36
Porcelain .	22,000	45,000	72,000	7	5	2	5	.81
Porcelain .	33,000	60,000	90,000	9	8	2 or 3	8	1.62
Porcelain .	44,000	80,000	110,000	10½	10	3	13	2.03
Porcelain .	50,000	95,000	120,000	12	11	3	18	4.28
Porcelain .	60,000	115,000	150,000	14	13	4	27	5.22

SUSPENSION TYPE UNITS

Diameter, inches	Number of parts	Spacing, inches	Test voltage		Ultimate strength, pounds	Working stress, pounds	Weight, pounds	Cost, dollars
			Wet, volts	Dry, volts				
10	1	5½	50,000	75,000	8,000	4,000	11	2.20
11	1	6¼	55,000	100,000	9,000	4,500	15½	2.45
12	1	6½	50,000	75,000	9,000	4,500	13	3.15
14	2	9	65,000	90,000	12,000	6,000	20	5.50

WEIGHTS AND COSTS. — The approximate dimensions, weights and costs of glass and porcelain pin-type insulators and for porcelain suspension units for different operating and test voltages are given in the preceding table.

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INTEGRALS. — (*See also Derivatives; Equations, Differential.*) If the function $y = f(x)$ be plotted as a curve (see Fig. 1) and the axis of x be divided into a number of very small sections, each of width dx, the area between the curve and the axis of x may be conceived as the sum of the products obtained by multiplying each length dx by the corresponding altitude or ordinate y. Then

$$\text{Area} = \int y\,dx,$$

where $\int$ stands for "sum."

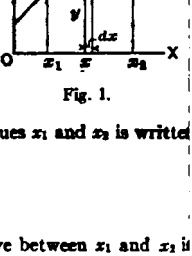


Fig. 1.

The Definite Integral. — The area between the values x_1 and x_2 is written

$$\int_{x_1}^{x_2} y\,dx.$$

Such an expression is called a "definite integral."

It is evident from the figure that the area of the curve between x_1 and x_2 is equal to the difference between the area from o to x_2 and the area from o to x_1. Hence calling the former area $F(x_2)$ and the latter area $F(x_1)$, we have

$$\int_{x_1}^{x_2} y \cdot dx = F(x_2) - F(x_1).$$

This equation is the general expression for any definite integral.

Indefinite Integrals. — The above equation may also be written

$$F(x_2) = \int_{x_1}^{x_2} y\,dx + F(x_1)$$

and if x_2 is considered a variable, the subscripts are omitted, as follows:

$$F(x) = \int y\,dx + A,$$

where A is a constant for any given reference point x_1. This constant A is an arbitrary constant, since any point x_1 may be chosen as the reference point, but when a point is once chosen, A is fixed. The expression $\int y\,dx$ is called an "indefinite integral" and A is called the "integration constant."

From the definition of a derivative (*see Derivatives*), the derivative of $F(x)$ is

$$\frac{dF(x)}{dx} = \frac{\int_{x_1}^{x+dx} y dx - \int_{x_1}^{x} y\,dx}{dx}$$

and from the figure, it is evident that the difference between the area from x_1 to $x + dx$ and the area from x_1 to x is simply $y\,dx$. Hence

$$\frac{dF(x)}{dx} = y,$$

that is, the integral $F(x)$ of any function y, with respect to x, must be such a function that when differentiated with respect to x, the result is the function y.

Formulas for Integration. — u, v, x and z are variables; a, m and n are constants.

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$$\int (u+v)\,dx = \int u\,dx + \int v\,dx$$

$$\int y\,dx = \int y\,\frac{dx}{ds}\,ds$$

$$\int u\,dv = uv - \int v\,du$$

$$\int \frac{F'(x)}{F(x)} = \log F(x)$$

where $F'(x)$ stands for $\frac{dF(x)}{dx}$.

TABLE OF INTEGRALS

Function $f(x)$	Integral $\int f(x)dx$	Function $f(x)$	Integral $\int f(x)dx$
x^m	$\frac{1}{m+1}x^{m+1}$	$\frac{1}{\sqrt{a^2-b^2x^2}}$	$\frac{1}{b}\sin^{-1}\frac{b}{a}x$
$\frac{1}{ax}$	$\frac{1}{a}\log_e ax$	$\frac{1}{\sqrt{a^2+b^2x^2}}$	$\frac{1}{b}\sinh^{-1}\frac{b}{a}x$
e^{ax}	$\frac{1}{a}e^{ax}$	$\frac{1}{a^2+b^2x^2}$	$\frac{1}{ab}\tan^{-1}\frac{bx}{a}$
a^{bx}	$\frac{1}{b\log a}a^{bx}$	$\frac{1}{(a^2-b^2x^2)_{bx<a}}$	$\frac{1}{ab}\tanh^{-1}\frac{bx}{a}$
$\cos ax$	$\frac{1}{a}\sin ax$	$\frac{1}{(a^2-b^2x^2)_{bx>a}}$	$\frac{1}{ab}\tanh^{-1}\frac{a}{bx}$
$\sin ax$	$-\frac{1}{a}\cos ax$	$\frac{1}{(x-a)(x-b)}$	$\frac{1}{a-b}\log\frac{x-a}{x-b}$
$\tan ax$	$-\frac{1}{a}\log(\cos ax)$	$\frac{1}{\sqrt{2ax-x^2}}$	$2\sin^{-1}\sqrt{\frac{x}{2a}}$
$\cosh ax$	$\frac{1}{a}\sinh ax$	$\frac{1}{x\sqrt{x^2-a^2}}$	$-\frac{1}{a}\sin^{-1}\frac{a}{x}$
$\sinh ax$	$\frac{1}{a}\cosh ax$	$\frac{1}{x\sqrt{x^2+a^2}}$	$\frac{1}{a}\cos^{-1}\frac{a}{x}$
$\tanh ax$	$\frac{1}{a}\log(\cosh ax)$	$\frac{1}{x\sqrt{a^2+x^2}}$	$-\frac{1}{a}\sinh^{-1}\frac{a}{x}$
$\tan x\sec x$	$\sec x$	$\frac{1}{x\sqrt{a^2-x^2}}$	$-\frac{1}{a}\cosh^{-1}\frac{a}{x}$
$\sec^2 ax$	$\frac{1}{a}\tan ax$	$\frac{x}{\sqrt{a^2\pm x^2}}$	$\pm\sqrt{a^2\pm x^2}$
$\frac{1}{\cos^2 ax}$	$\frac{1}{a}\tan ax$	$\frac{x}{\sqrt{x^2-a^2}}$	$\sqrt{x^2-a^2}$
$\frac{1}{\sin^2 ax}$	$-\frac{1}{a}\cot ax$		

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Function $f(x)$	Integral $\int f(x)dx$
$\sqrt{a^2-x^2}$	$\frac{1}{2}\left(x\sqrt{a^2-x^2}+a^2\sin^{-1}\frac{x}{a}\right)$
$\sqrt{x^2+a^2}$	$\frac{1}{2}\left[x\sqrt{x^2+a^2}+a^2\sinh^{-1}\frac{x}{a}\right.$
$\sqrt{x^2-a^2}$	$\frac{1}{2}\left[x\sqrt{x^2-a^2}-a^2\cosh^{-1}\frac{x}{a}\right.$
$\sin ax \sin bx$	$\frac{\sin(a-b)x}{2(a-b)}-\frac{\sin(a+b)x}{2(a+b)}$
$\cos ax \cos bx$	$\frac{\sin(a-b)x}{2(a-b)}+\frac{\sin(a+b)x}{2(a+b)}$
$\sin^2 ax$	$\frac{1}{2}x-\frac{1}{4a}\sin 2ax$
$\cos^2 ax$	$\frac{1}{2}x+\frac{1}{4a}\sin 2ax$
$\sinh ax \sinh bx$	$\frac{\sinh(a-b)x}{2(a-b)}-\frac{\sinh(a+b)x}{2(a+b)}$
$\cosh ax \cosh bx$	$\frac{\sinh(a-b)x}{2(a-b)}+\frac{\sinh(a+b)x}{2(a+b)}$
$\sinh^2 ax$	$\frac{1}{2}x-\frac{1}{4a}\sinh 2ax$
$\cosh^2 ax$	$\frac{1}{2}x+\frac{1}{4a}\sinh 2ax$
$e^{ax}\sin bx$	$\frac{e^{ax}(a\sin bx-b\cos bx)}{a^2+b^2}$
$e^{ax}\cos bx$	$\frac{e^{ax}(a\cos bx+b\sin bx)}{a^2+b^2}$
$\frac{e^{mx}}{x}$	$\log_e x+\frac{mx}{1}+\frac{m^2x^2}{2!}+\frac{m^3x^3}{3!}+$
$\sin^m x\cos^n x$	$-\int\sin^{m-1}\cos^n x\,d\cos x$

Double Integrals. — Just as the area of a surface may be represe the expression

$$\int y\cdot dx$$

so the volume of a solid may be represented by

$$\int\left[\int y\cdot dx\right]ds$$

or adopting the usual notation, by

$$\int\int y\,dx\cdot ds$$

taken between limits determined by the data of the problem.

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INTEREST, ANNUITIES AND SINKING FUND. — Let

P = principal invested in dollars;
n = number of years principal is invested;
r = rate of interest, per cent per annum;
A = total amount of principal and interest at end of n years.

Note. — The following relations hold irrespective of the unit of time selected, provided r is taken as the interest earned per $100 during that time.

Simple Interest. — If the principal is invested at simple interest, then

$$A = \left(1 + \frac{nr}{100}\right)P.$$

Compound Interest. — If the principal is invested at compound interest, i.e., if the interest earned each year is invested at the end of that year at the same rate as the original principal, then the total amount due at the end of n years is

$$A = PR^n,$$

where

$$R = 1 + \frac{r}{100}.$$

R^n is the amount of the principal of 1 dollar and interest at the end of n years. The following table gives the value of R^n for n ranging from 1 to 50 years and r from 3 to 6 per cent.

VALUES OF $R^n = \left(1 + \frac{r}{100}\right)^n$.

Years n	Per cent interest $= r$				Years n	Per cent interest $= r$			
	3	4	5	6		3	4	5	6
1	1.03	1.04	1.05	1.06	16	1.6047	1.8730	2.1829	2.5403
2	1.0609	1.0816	1.1025	1.1236	17	1.6528	1.9479	2.2920	2.6928
3	1.0927	1.1249	1.1576	1.1910	18	1.7024	2.0258	2.4066	2.8543
4	1.1255	1.1699	1.2155	1.2625	19	1.7535	2.1068	2.5269	3.0256
5	1.1593	1.2166	1.2763	1.3382	20	1.8061	2.1911	2.6533	3.2071
6	1.1941	1.2653	1.3401	1.4185	21	1.8603	2.2787	2.7859	3.3995
7	1.2299	1.3159	1.4071	1.5036	22	1.9161	2.3699	2.9252	3.6035
8	1.2668	1.3686	1.4774	1.5938	23	1.9736	2.4647	3.0715	3.8197
9	1.3048	1.4233	1.5513	1.6895	24	2.0328	2.5633	3.2251	4.0487
10	1.3439	1.4802	1.6289	1.7908	25	2.0937	2.6658	3.3863	4.2919
11	1.3842	1.5394	1.7103	1.8983	30	2.4272	3.2433	4.3219	5.7435
12	1.4258	1.6010	1.7958	2.0122	35	2.8138	3.9460	5.5159	7.6862
13	1.4685	1.6651	1.8856	2.1329	40	3.2620	4.8009	7.0398	10.2858
14	1.5126	1.7317	1.9799	2.2609	45	3.7815	5.8410	8.9847	13.7648
15	1.5580	1.8009	2.0789	2.3965	50	4.3838	7.1064	11.4670	18.4204

The following table gives the number of years required for a given principal to double itself at compound interest.

Interest Rate	3	4	5	6
Years to Double	23.5	17.7	14.2	11.9

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Annuities. — An annuity is a fixed sum of money paid yearly, or at other equal times agreed upon.

One dollar invested at interest at r per cent at the beginning of every year will at the end of n years amount to

$$R \cdot \frac{R^n - 1}{R - 1} \text{ dollars,}$$

where $R = 1 + r/100$, the interest being compounded at the end of each year.

One dollar invested at the beginning of a period of n years will yield at the end of each year an annuity of

$$\frac{R^n (R - 1)}{R^n - 1} \text{ dollars,}$$

where $R = 1 + r/100$, the interest being compounded at the end of each year.

Sinking Fund. — A sinking fund is a fund built up from fixed yearly payments or annuities. Sinking funds are usually provided to retire bonds, which are issued for a given number of years. The annuity required to retire a bond of $1000 at the end of n years is

$$1000 \left(\frac{R - 1}{R^n - 1} \right).$$

Values of this annuity for various rates of interest and for various values of n are given in the following table.

ANNUITY REQUIRED TO REDEEM $1000

At end of years	Rate of interest, per cent								
	2	2½	3	3½	4	4½	5	5½	6
2	495.05	493.78	492.69	491.42	490.20	489.00	487.80	486.62	485.43
3	326.72	325.14	323.56	321.94	320.36	318.77	317.21	315.63	314.10
4	242.63	240.84	239.02	237.26	235.50	233.74	232.01	230.29	228.60
5	192.16	190.24	188.35	186.49	184.63	182.79	180.98	179.13	177.39
6	158.53	156.56	154.61	152.67	150.79	148.88	147.02	145.18	143.36
7	134.52	132.49	130.51	128.57	126.61	124.67	122.82	120.96	119.13
8	116.51	114.47	112.46	110.48	108.53	106.60	104.72	102.86	101.03
9	102.52	100.46	98.44	96.44	94.49	92.57	90.69	88.83	87.02
10	91.33	89.25	87.21	85.24	83.29	81.38	79.50	77.67	75.87
11	82.18	80.11	78.07	76.09	74.15	72.25	70.39	68.57	66.79
12	74.56	72.49	70.46	68.48	66.55	64.67	62.83	61.03	59.28
13	68.12	66.05	64.03	62.06	60.14	58.27	56.45	54.68	52.96
14	62.60	60.54	58.53	56.57	54.67	52.82	51.02	49.28	47.58
15	57.83	55.77	53.77	51.82	49.94	48.11	46.34	44.62	42.96
16	53.65	51.60	49.61	47.68	45.82	44.01	42.27	40.58	38.95
17	49.97	47.93	45.95	44.04	42.20	40.42	38.70	37.04	35.44
18	46.70	44.67	42.71	40.82	38.99	37.24	35.54	33.92	32.36
19	43.78	41.76	39.81	37.94	36.14	34.40	32.75	31.15	29.62
20	41.15	39.14	37.22	35.36	33.58	31.87	30.24	28.68	27.18
25	31.22	29.27	27.43	25.67	24.01	22.44	20.95	19.55	18.23
30	24.65	22.78	21.02	19.37	17.83	16.39	15.05	13.80	12.65
35	20.00	18.20	16.54	15.00	13.58	12.27	11.07	9.97	8.97
40	16.55	14.84	13.26	11.83	10.52	9.34	8.28	7.32	6.46
45	13.91	12.27	10.78	9.45	8.26	7.20	6.26	5.43	4.70
50	11.82	10.26	8.87	7.63	6.55	5.60	4.78	4.06	3.44

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INTERNAL-COMBUSTION ENGINES. — (*See also Gas; Gas Producers, Power Stations, Gas-Electric.*) An internal-combustion engine is an engine in which combustible gas, vapor, or oil is burned in a cylinder, generating high temperature and high pressure in the gases of combustion, which expand behind a piston driving it forward. (Rotary gas engines or gas turbines are still, 1922, in the experimental stage.)

Gas Engine. — A gas engine in its simplest form is similar to a reciprocating single-acting steam engine, comprising a cylinder, a piston, crank, flywheel, etc. The pressure to move the piston is obtained by exploding or burning with great rapidity a compressed mixture of air and combustible gas.

Oil and Gasoline Engines. — The lighter distillates of petroleum, such as gasoline, are easily vaporized at moderate temperatures, and a gasoline engine differs from a gas engine only in having an atomizer attached, for spraying a fine jet of the liquid into the air-admission pipe. With kerosene and other heavier distillates, or crude oils, it is necessary to provide some method of atomizing and vaporizing the oil at a high temperature, such as injecting it into a hot vaporizing chamber at the end of the cylinder, or into a chamber heated by the exhaust gases.

Diesel Oil Engine. — The distinguishing features of the Diesel engine are: It compresses air only, to a predetermined temperature above the firing point of the fuel. This fuel is blown as a cloud of vapor (by air from a separate small compressor) into the cylinder when compression has been completed, ignites spontaneously without explosion, solely by reason of the heat of the air generated by the compression, and burns steadily with no essential rise in pressure. The temperature of gases, developed and rejected, is much lower than with engines of the explosive type. The engine uses crude oil and residual petroleum products.

Diesel engines sizes run from 6¾ by 8¼ inches, two-cycle, four cylinder, 110 b.h.p. for four cylinders to 32.2 × 39.4 inches, two-cycle, one cylinder, 1250 b.h.p. for one cylinder

The largest for land service are four-cylinder engines of approximately 2400 b.h.p. These engines are running for electric light service with admirable results on a guaranteed oil consumption not to exceed 0.4 pound of oil per brake horsepower-hour. They are of the two-cycle type. Four-cycle engines have an oil consumption of practically 90 per cent of this figure, or about 0.36 pound of oil per brake horse-power-hour.

The thermal efficiency of these engines is between 30 and 40 per cent. Twenty-five to 30 per cent of the heat is carried away in the cooling water and the rest in the exhaust gases.

The variation of economy with variation of load as shown by tests is reported to be:

Per cent rated load	30	50	75	100	120
Lb. oil per b.h.p. hour	0.71	0.55	0.46	0.43	0.44

Alcohol Engines. — Due to the relatively high cost of alcohol, even when "denatured," alcohol engines are not used extensively in this country.

CLASSIFICATION OF INTERNAL-COMBUSTION ENGINES. — Internal-combustion engines are classified as four-cycle and two-cycle engines, single- and double-acting engines, and single-and multi-cylinder engines.

Four-cycle Engines. — In what is known as a four-cycle engi tion of gas takes place in one end of the cylinder every two revol flywheel, or every two double strokes. The following sequence takes place during four consecutive strokes: (*a*) inspiration of gas and air during an entire stroke; (*b*) compression during (return) stroke; (*c*) ignition at or near the dead-point and expa the third stroke; (*d*) expulsion of the burned gas during the fo stroke.

Fig. 1 is an indicator diagram of a four-cycle engine. *AB*, th shows the admission of the mixture, at a pressure slightly below the on account of the resistance of the inlet valve. *BC* is the compres clearance space, ignition taking place at *C* and combustion with pressure continuing from *C* to *D*. The gradual termination of the is shown by the rounded corner at *D*. *DE* is the expansion line, *E* pressure drop as the exhaust valve opens, and *FA* the line of exp burned gases, the pressure being slightly above the atmosphere on account of the resistance of the exhaust valve.

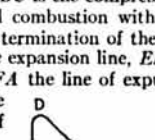


Fig. 1. Indicato Four-cycle

Two-cycle Engine. — In a two-cycle single-acting engine an explosion takes place with every revolution, or with each forward stroke of the piston. Referring to the diagram, Fig. 1, and beginning at *E*, when the exhaust port begins to open to allow the burned gases to escape, the pressure drops rapidly to *F*. Before the end of the stroke is reached an inlet port opens, admitting a mixture of gas and air from a reservoir in which it ha pressed. This mixture being under pressure assists in driving the out through the exhaust port. The inlet port and the exhaus early in the return stroke and during the remainder of the str mixture, which may include some of the burned gas, is compres ignition takes place at *C*, as in the four-cycle engine.

In one form of the two-cycle engine only compressed air is ad the exhaust port is open, the fuel gas being admitted under press exhaust port is closed. By this means a greater proportion of the is swept out of the cylinder. This operation is known as "scaveng

Single- and Double-acting Engines. — These terms have t nificance as in the case of steam engines (q.v.). Comparativel engines are single-acting.

Multi-cylinder Engines. — In small multi-cylinder engines t are in "parallel," i.e., each has a separate piston connected to the In large engines two cylinders are frequently arranged in tandem. "twin cylinder" is used to designate two cylinders operating in contrasted with the "two-cylinder tandem" arrangement, in wh cylinders are in "series." A "twin-tandem" engine has four cyli or two pairs of tandem cylinders.

RATING. — In contrast to steam prime movers the gas engine h limit of power with the usual methods of governing and its econon until this limit is almost reached. This characteristic makes a m ing more significant than a normal rating with overload capacity narily rated, however, engines can develop 20 per cent overload for and will care for momentary swings much greater. Due to their low efficiency (75 to 85 per cent) gas engines are preferably rated in te brake horse-power instead of indicated horse-power.

ating of Automobile Engines. — Automobile engines are sing as a rule multi-cylinder, the cylinders all being in parallel. The nsed Automobile Manufacturers Association have adopted the rrary formula for the rating of automobile engines

$$\text{Brake horse-power} = \frac{D^2N}{2.5},$$

e D = diameter of each cylinder in inches, N = number of rating is usually referred to as the A.L.A.M. rating. It co oximately to the actual brake horse-power when the piston spee per minute and the mean effective pressure is 55 pounds per squ

he following ratings are derived from the formula:

re. in.	2½	3	3½	4	4½	5	5½
re. mm.	64	76	89	102	114	127	140
rse-power, 1 cylinder	2½	3.6	4.9	6.4	8.1	10	12.
rse-power, 2 cylinders	5	7.2	9.8	12.8	16.2	20	24.
rse-power, 4 cylinders	10	14.4	19.6	25.6	32.4	40	48.
rse-power, 6 cylinders	15	21.6	29.4	38.4	48.6	60	72.

ESIGN AND CONSTRUCTION. — Only a few of the more i ures in the design and construction of internal-combustion engin d here. See *Bibliography* at end of this article for references t tises on the subject.

rrangement of Cylinders in Large Engines. — The number gement of cylinders depends upon the space, the power required formity of rotation to be produced. Vertical-cylinder engines izes up to 750 horse-power. They require less floor space than tal types but the superior mechanical properties of the latter wan ction when space economy is not important. The tandem doul ngement is standard in horizontal engines. As it is not pract elop more than 1500 horse-power in a single cylinder, engines of t s are twin, tandem, double-acting.

Cooling is one of the most important problems of gas-engine design ll sizes provision for air cooling or a simple water jacket about th lls suffices, but the large sizes require the cooling of the piston, p l valve stems. The superficial area of the cylinders increases le n their cubical contents and this fact tends to aggravate the cooling the size of the cylinders is increased. Cooling is more difficult es than with lean. One practical result of these difficulties is fou t that engines of large capacity are little if any cheaper per ho n small ones and that maintenance is apt to be proportionately lar ount of cooling water required per horse-power-hour is stated by estigators to be from 0.75 to 1.00 cubic foot. Figures for a large r nmercial plants average 2.4 cubic feet. This high average is un e to the fact that water cost little in most of these plants.

Ignition. — The "hot-tube" method of igniting the compressed gas and air in the cylinder is practically obsolete, and electric sy d instead. Of these the "make-and-break" and the "jump-spa ns are in common use. In the former two insulated contact pieces a the end of the cylinder, and through them an electric current pa ey are in contact. A spark coil is included in the circuit, and when t suddenly broken at the proper time for ignition, by mechanism oper

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the valve-gear shaft, a spark is made at the contacts, which ignites
the "jump-spark" system two insulated terminals separated abo
apart are located in the cylinder, and the secondary or high-tensio
an induction coil causes a spark to jump across the space between
the circuit of the primary current is closed by mechanism operated b
See article on *Ignition, Electric*.

In some oil engines the mixture of air and oil vapor is ignited au
by the temperature generated by compression of the vapor, in a
the end of the cylinder, called the vaporizer, which is not water-j
therefore is kept hot by the repeated ignitions. Before starting th
vaporizer is heated by a Bunsen burner or other means.

Timing. — By adjusting the cam or other mechanism operated b
gear shaft for causing ignition, the time at which the ignition take
reference to the end of the compression stroke, can be regulated.
is usually ignited before the end of the stroke, the advance dependi
inflammability of the mixture and on the speed of the engine.

Governing. — Two methods of governing the speed of an engine
mon use, the "hit-and-miss" and the throttling methods. In the
engine receives its usual charge of air and gas only when the engin
at or below its normal speed; at higher speeds the admission of t
suspended until the engine regains its normal speed. One metho
plishing this is to interpose between the valve rod and its cam or o
ing mechanism, a push rod, or other piece, the position of which w
to the end of the valve rod is controlled by a centrifugal governor s
the valve rod if the speed is at or below normal and misses it if
above normal.

The throttling method of regulating is similar to that used i
steam engines; the quantity of mixture admitted at each charge
by varying the position of a butterfly valve in the inlet pipe. Cut-
of governing are also used, such as varying the time of closing th
valve during the suction stroke, or varying the time of admissio
alone, or "quality regulation."

Lubrication of cylinders is best provided by a time force-feed
jecting oil between the piston rings at dead-center positions.
should be closely regulated, as an excess carbonizes on the cylind
becomes a source of trouble. Bearings are commonly ring-oiled or

Owing to the high temperatures that prevail in the cylinder of
combustion engine, the question of proper lubrication is a serious on
oil should be exceedingly pure, free from acids, and composed of h
that leave no residue after combustion. Only mineral oils, therefo
able for the purpose. The ignition point of good cylinder oil sh
lower than 535° F. The losses in power due to poor lubrication o
may amount to 10 or 15 per cent.

The amount of oil required per horsepower-hour varies with t
of the installation and the method of operation. For full load 24-
the proportion per horsepower-hour is, of course, greater than for a p
under a light load for a 9 or 10-hour day. The average of several
by the engine manufacturers for the amount of engine oil required
per 1000 horsepower-hour. The operators of commercial plants re
however, that average about double this amount, and an equal
cylinder oil.

Starting Devices. — In large engines starting is now univers
plished by compressed air. In some small stationary engines
cartridge is inserted into the cylinder head and set off by percussio

are now almost universally used for automobile engines
arting and Lighting Systems for Automobiles).

asoline engines are usually designed for speeds of from
s per minute. Large gas engines, for central-station ser-
ds about as follows:

..... 275 rev. per min.
..... 200 rev. per min.
..... 150 rev. per min.
..... 100 rev. per min.

OPED BY AN INTERNAL COMBUSTION EN-

calculate the power developed by an internal-combustion
o know the mean effective pressure in the engine cylin-
f the cylinder and either (1) the length of stroke and
er minute, or (2) the piston speed and number of explo-

essure. — The mean effective pressure can be obtained
ram (*see Steam Engines*), or if a test diagram is not avail-
e pressure either has to be assumed from a knowledge of
ines of the same type and working under the same condi-
esign, or it may be calculated from the ideal air diagram
se of a coefficient or diagram factor depending on the
he compression pressure.

are given by C. P. Poole as a rough approximate guide
pressures obtained with different fuels in a four-cycle
e engine the mean effective pressure of the pump diagram
The delivery pressure is usually from 4 to 8 pounds
the atmosphere, and the corresponding mean effective
bout 3.8 to 7.

EFFECTIVE PRESSURE, POUNDS PER SQUARE
, FOUR-CYCLE ENGINES

Compression pressure	Engine horse-power						
	5	10	25	50	100	250	500
100	..	55	60	65	70	75	80
130	..	65	70	75	80	85	90
160	..	..	..	80	85	90	90
100	..	..	60	65	65	70	75
130	..	65	65	70	75	80	85
160	..	..	75	80	85	90	90
65	..	60	65	70	80	85	..
100	..	75	80	90	90	95	100
130	..	..	..	..	100	105	110
65	70	75	80	85	..	..	..
100	85	90	90	95	..	..	..
65	50	55	60	65	..	..	..
115	70	75	80	85	..	..	..

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Number of Explosions per Revolution. — The number of expl
revolution depends upon the type of engine as given in the acco
table.

Formulas for Horse-power Output. — (*See also Lemp, H., B.H.P.
for Internal Combustion Engines, G. E. Rev. 22, p. 808, Oct., 1919.*)

p = mean effective pressure, lb. per sq. in.
d = diameter of cylinder bore, inches,
N = number of revolutions per minute,
e = total number of explosions per revolution,
S = piston speed, feet per minute,
L = length of stroke, feet,
ϵ = mechanical efficiency, as a fraction,
P_i = indicated horse-power.

Type of engine	Ex per c
Single-acting, 4-cycle	
Single-acting, 2-cycle	
Double-acting, 4-cycle	
Double-acting, 2-cycle	

Then

$$P_i = \frac{pLd^2eN}{42{,}000} = \frac{pd^2eS}{84{,}000}.$$

The brake horse-power is

$$\text{Brake h.p.} = \epsilon P_i.$$

The brake horse-power is frequently expressed by the formula

$$\text{Brake h.p.} = Cd^2,$$

where $C = peS\epsilon/84{,}000$ is called the "engine constant." For $\epsilon = 0$.
explosions per revolution the values of C for various mean effective
are as follows:

VALUES OF C FOR 2 EXPLOSIONS PER REVOLUTIO

M.E.P., lb. per sq. in.	Piston speed, feet per minute				
	500	600	700	800	900
50	0.50	0.60	0.70	0.80	0.90
60	0.60	0.72	0.84	0.96	1.08
70	0.70	0.84	0.98	1.12	1.26
80	0.80	0.96	1.12	1.28	1.44
90	0.90	1.08	1.26	1.44	1.62
100	1.00	1.20	1.40	1.60	1.80
110	1.10	1.32	1.54	1.76	1.98

These values of C apply to 4-cylinders, 4-cycle, single-acting, to 2-
2-cycle, single-acting, and to 1-cylinder, 2-cycle, double-acting. F
cylinders, 4-cycle, single-acting, divide by 4; for single cylinders, 4-cycl
acting, or 2-cycle, single-acting, divide by 2.

TESTING INTERNAL-COMBUSTION ENGINES. — The t
gas or oil engine includes the measurement of its power by a friction
the number of cubic feet of gas or pounds of oil used per brake hor

rific value of the gas or oil. In connection with the tests ay be taken, the air supply and the jacket cooling water exhaust gas analyzed, the temperatures of air, water and t balance calculated showing the thermal efficiency and f loss of energy. For details see *Code of 1922 of the*

D FUEL CONSUMPTION. — The thermal efficiency stion engine is considerably higher than that of the best or steam turbine. It is probable that the maximum uch engines under the most favorable operating conditions ased on the indicated horse-power or 30 per cent, based on r. The mechanical efficiency of an internal combustion hat of a reciprocating engine, ranging from 70 to 85 per 5 per cent for a high-class reciprocating engine and 92 to turbines.

cy. — The conditions which appear to give the highest gas and oil engines are: (1) high temperature of cooling (2) high pressure at the end of compression; (3) lean iming of the ignition; (5) maximum load. The higher xture may be due to the fact that high compressions may xture, while with rich mixtures high-compression pressures t danger of preignition.

equal, the hotter the walls of the cylinder the less heat from the hot gases, and therefore the higher the efficiency. llow of higher compression without preignition, and high e of high efficiency. Cool walls also tend to give the y, since with hot walls the fuel mixture expands more on reducing the weight of charge admitted in the suction

at Losses. — The heat losses are: (1) the heat carried ter, (2) that carried away in the waste gases, and (3) that he relative amounts of these three losses vary greatly, f the engine and on the amount of water used for cooling. ichs quote the following:

P., er n.	Ratio air to gas	Heating value of charge, B.t.u.	Work done by 1 B.t.u., ft. lb.	Exhaust temp., deg. F.	Distribution of heat losses, per cent		
					Work	Jacket water	Exhaust
3	7.11	18.5	140	1022	18.0	51.2	30.8
5	7.35	17.4	141	1137	18.1	45.6	36.3
3	7.43	17.0	190	867	24.4	53.8	21.8
2	7.40	16.8	184	992	23.7	49.5	26.8

ibution of the heat losses varies with the rate of compres- ed.

y and Fuel per Brake Horse-Power. — The over-all

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efficiency of internal-combustion engines is the product of the thermal efficie by the mechanical efficiency. A more convenient expression is

$$\text{Over-all efficiency} = \frac{2546}{HQ} \qquad \text{as decimal fraction}$$

where H = heat of combustion, B.t.u. in one cubic foot, and Q = numbe cubic feet of gas supplied per brake horse-power hour. In the case of a liq fuel it is more convenient to take H = heat of combustion, B.t.u. per pou and Q = pounds of liquid supplied per brake horse-power hour. See articles *Gas and Fuels*. The product HQ in either case is the number of B.t.u. brake horse-power.

In Fig. 2 are given the results of tests on several internal-combustion engi using different kinds of fuels, and also, for comparison, the performance three steam turbines. These curves were supplied by Prof. W. E. Wickend

These curves bring out very strikingly the relatively poor performance

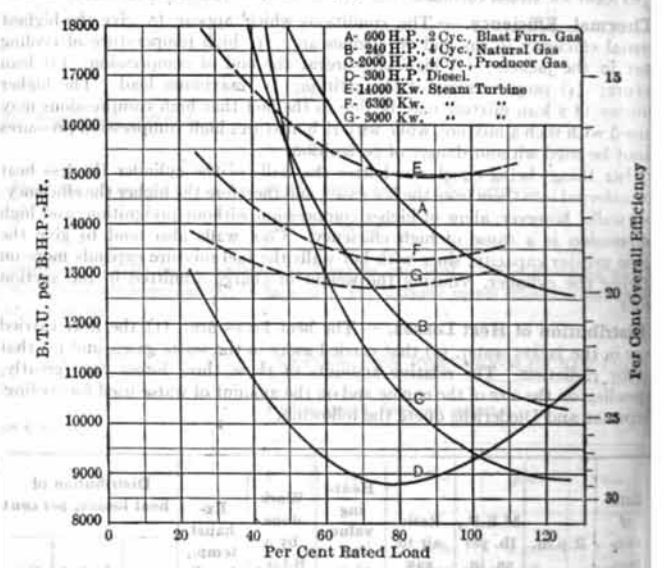


Fig. 2. Fuel Consumption of Gas and Oil Engines

internal-combustion engines at light loads. Under working conditions ga engines are expected to produce a brake horse-power hour for every 9000 t 12,000 B.t.u. in the fuel. The average of several quotations from differen manufacturers is as follows:

Per cent rated load	100	75	50	25
B.t.u. per b.h.p.-hr.	10,500	12,000	14,700	20,000

Coal per Brake Horse-power Hour. — Figures giving the coal con sumption of a producer per brake horse-power hour of the gas engine supplied

ue unless the type of producer and type of engine as well al are stated. Let H = B.t.u. per pound coal, ϵ_1 = effici- *as Producers*), ϵ_2 = over-all efficiency of gas engine. Then

$$\text{coal per brake horse-power hour} = \frac{2546}{H\epsilon_1\epsilon_2}.$$

ting value of the coal used is 14,000, the over-all efficiency er cent and the efficiency of the producer 80 per cent, $3 \times 0.8 = 0.76$ pound coal will be required per brake gures as low as 0.7 pound coal per brake horse-power ed, but they are exceptional.
ns are:

Fuel	Lb. per b.h.p.-hr.	
	As fired	Dry
cite.....	1.3	1.3
nous coal.....	1.3	1.2
.....	2.0	1.6
.....	2.6	2.0
.....	3.3	...

NGINE TROUBLES. — Among the causes of troubles position of the fuel; too much or too little air supplied; right for the kind of fuel; ignition timer set too late or backfiring; electrical and mechanical troubles with the n deposits in the cylinder and on the igniting contacts.

NGINES (Pre-war figures). — Differences in the ratings tial development of the art and the close competition of iite variable. The following methods of estimating are of installations and probably represent average conditions n. Let P = brake horse-power rating; then

Gas Engines, cost in dollars..... $36 \times P$

es:
power, cost in dollars..... $400 + 40 \times P$
power, cost in dollars..... $2500 + 24 \times P$
power, cost in dollars..... $34 \times P - 2500$

gines:
power, cost in dollars..... $3000 + 47 \times P$
power, cost in dollars..... $3000 + 45 \times P$

gines:
less than four-cycle for the larger sizes.

— For theory of the internal-combustion engine, see k, *Proc. Inst. C. E.*, 1882, Vol. 69; and Van Nostrand's See also Wood's *Thermodynamics*. Standard works on *xt-book on Gas, Air, and Oil Engines*, by Bryan Donkin; *ne*, by Dugald Clerk; *Internal Combustion Engines*, by chs; *Gas Engine Design*, by C. E. Lucke; *Gas and Petro-*

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leum Engines, by W. Robinson; *The Modern Gas Engine and the Gas* by A. M. Levin; *The Gas Engine*, by C. P. Poole; and *Internal C Engines*, by Hugo Guldner, translated by H. Diederichs. For pract tion of gas and oil engines, see *The Gas Engine*, by F. R. Jones, an *Engine Handbook*, by E. W. Roberts. For descriptions of large g using blast-furnace gas, see papers in *Proc. Iron and Steel Inst.*, a *A.S.M.E.* See also Fernald and Orrok, *Engineering of Power Plant* W. H., *The Diesel Engine and its Applications in So. California*, Trans., Vol. 37, p. 447; Goldingham, A. H., *The Heavy Oil Engine*, Trans., Vol. 37, p. 477.

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IRON, PIG AND CAST. — (*See also Iron, Wrought; Castings, Iron and Steel; Magnetic Properties of Iron; Steel.*) Chemically pure iron is not a commercial product. Iron of a very high degree of purity may be obtained, however, by electrolytic deposition. The microscopical constituent of pure iron is called ferrite, and pure iron is said by metallographists to be composed of polyhedral crystalline grains of ferrite. Commercial products are pig iron, cast iron, malleable cast iron, wrought iron and steel.

PIG IRON. — Pig iron is the crude product obtained from iron ore by smelting in a blast furnace. The name is applied either to the molten material or to rough castings varying in length from 30 inches to 36 inches and in cross-section from about 10 sq. in. to 30 sq. in. A mass of piled pig iron 8 by 12 ft. weighs approximately 100 tons. Pig iron is made by burning a mixture of iron ore, coke or other fuel and limestone in a high furnace through which a blast of heated air is forced under pressure. The liquid iron when drawn from the furnace is either run into sand molds formed on the ground near the furnace, or into cast-iron molds forming a part of a conveyor chain which receives the molten iron, chills it by contact, and delivers it at the car. A pig is the bar of iron formed in either of these types of molds. The molten iron is also occasionally conveyed to the steel furnace without being allowed to cool.

Classification. — Pig iron may be classified as follows:

a. Gray, white or mottled as determined by the color of its fracture and its chemical composition.

b. Coke, anthracite or charcoal iron as determined by the fuel used in reducing the ore.

c. Foundry iron, Bessemer iron, etc., according to the use to which it is to be put.

Use of Pig Iron. — The product of the blast furnace is irregular in composition and physical properties and is not used directly. By forming it into pigs it is possible to grade it, and also transport it to foundries and iron and steel furnaces. Pig iron is sometimes used by engineers because of its great weight to form counterweights in unbalanced structures such as movable bridges, but concrete is more economical for this purpose.

Strength. — See below in the section on *Cast Iron.*

Specifications for Pig Iron. — See Standard Specifications for Foundry Pig Iron in American Society for Testing Materials Standards.

Cost. — The cost of pig iron is an important factor in commerce. Quotations are given weekly in *The Iron Age* and in the first issue of each month of the *Engineering News-Record.* The fluctuations in price are very considerable, ranging in normal times, Bessemer pig at Pittsburg varying during 1912 from $14.90 to $18.15 per long ton of 2240 pounds. Since the World War the increase has been great. Bessemer pig was quoted at $50.46; Pittsburgh, Aug. 31, 1920, and at $26.96, May 16, 1922.

CAST IRON. — Cast iron may be defined as iron containing so much carbon that it is not malleable at any temperature, specifically, iron cast into articles of specific form and purpose as distinguished from pig iron. Except for special cases castings are made of gray iron. Cast iron is made from pig iron by melting the latter and casting in sand or iron (chill) molds. The furnace commonly used is a cupola furnace although reverberatory furnaces are sometimes employed.

Composition of Cast Iron. — The composition of an iron casting is identical with that of the pig iron from which it is made and usually consists of metallic

iron (ferrite) accompanied by from 2.5 per cent to 4 per cent (by w carbon, together with silicon, phosphorus, manganese and other in The carbon may be chemically combined with the iron, giving hom white iron, or some of it may be precipitated in cooling in the form of making gray iron or mottled iron. The influence of carbon upon th ties of the cast iron is of great importance and may be summed up as fo

Uncombined Carbon or Graphite. — Porosity and workability and shrinkage decreases, with an increase in the percentage of graphite. also generally decreases with an increase in graphite, although it s noted that an iron may be weak by having too much combined car that treatment which changes some of this combined carbon to gra creases its strength.

Combined Carbon. — In slowly-cooled white iron all the carb in the form of an alloy, called cementite, which forms in cooling, and partakes of the characteristics of cementite, being hard and brittle, t characteristic increasing with an increase in the percentage of the c The carbon in this condition is called combined carbon.

Silicon. — This acts as a precipitant of carbon, drawing it out bination into graphitic form. The maximum precipitation occurs w 2.5 per cent to 3.5 per cent of silicon. Beyond this percentage the effect is noted. Increase of silicon up to 3.5 per cent therefore so iron, decreases shrinkage, imparts fluidity and reduces the streng maximum density of gray iron occurs with about 1 per cent of silico than 2 per cent causes porous iron.

Sulphur. — Sulphur increases the amount of combined ca effect in this direction being far greater than that of silicon in redu combined carbon, it being generally considered that 0.01 per cent *S* tralize 0.15 per cent Si. The amount of sulphur should be restricted low percentage. In the Standard Specifications of the A.S.T.M. th content is limited to not over 0.08 per cent for light castings, not over cent for medium castings and not over 0.12 per cent for heavy castin

Manganese. — This increases the total carbon and the prop carbon in combined form, although by combining with sulphur and the effect of the latter, the net result may be a decrease in the comb bon. It strengthens the iron if below 1 per cent, strengthens but brittleness if between 1 per cent and 1.5 per cent, and if over 1.5 per creases strength and toughness and increases hardness and shrinkage.

Phosphorus. — This causes expansion after solidification, making the iron useful for very thin castings. It, however, tends the iron weak and brittle and should be kept below the following value

	Per cent
Chilled castings	0.3
Malleable castings	0.2
Gray castings	0.7

Use of Cast Iron. — Cast iron should in general not be used whe or bending strength is required. Its cheapness and high crushing make it useful for heavy parts of machinery, and for pieces where patterns not easily made by tools are needed. It is frequently used pipes, despite its low tensile strength, and often for columns in buil though cast-iron columns have been superseded to a considerable e steel columns, except for the simplest forms of construction. Car cast iron with the outer surface chilled by iron molds are much used.

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ngth. — The ultimate compressive strength of cast iron is
00 lb. per sq. in. A safe working value for cases where
occur is 16,000 lb. per sq. in. For columns the following
if the applied load is not eccentric.*

$$\frac{P}{A} = 6100 - 32\frac{l}{d},$$

le load in pounds,
area in square inches,
rained against lateral deflection in inches,
shortest side of rectangular column, in inches.

— Ultimate strength may vary from 15,000 to 35,000 lb.
inarily from 18,000 to 22,000 lb. per sq. in. For cast-
usual to specify 3,300 lb. per sq. in. or ⅛ of the tensile
latter to be 16,500 lb. per sq. in.

ticity varies from 10,000,000 to 30,000,000 lb. per sq.
ndry iron the modulus of elasticity may be taken as
000,000 lb. per sq. in.

ast iron has no well-defined elastic limit.

Cast Iron. — See *American Society for Testing Materials*

n. — See *Castings, Iron and Steel.*

AST IRON. — This is the name given to cast iron which
the combined carbon changed to graphitic carbon in the
er by reheating white iron to a temperature somewhat
oint. The process used in the United States generally
entirely from the outer layer. Malleable cast iron is
ultural machinery, pipe fittings which have to be threaded,
nas a much higher tensile strength (from 40,000 to 50,000
ordinary cast iron and is more ductile. It is frequently
orm of steel, and should be carefully guarded against by
ticles such as bevel gears, hammers and automobile drop

Malleable Cast Iron. — See Standard Specifications
in *American Society for Testing Materials Standards.*

Iron Castings. — See *Castings, Iron and Steel.*

. — See *Bibliography* in article on *Steel.*

ure, Simple, for effect of eccentricity on building columns. It
e allowable loads on cast-iron columns as given in the building
d summarized in the article on *Buildings, Allowable Unit Stresses*
s too high for conservative practice.

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IRON, WROUGHT. — (*See also Iron, Pig and Cast; Magnetic of Iron; Steel.*) If commercial iron is mechanically mixed with amount of slag (*see article on Steel*) there results a malleable mate wrought iron which does not harden when suddenly cooled. It me white heat, but becomes pasty at a lower temperature, in which co can be readily welded. It is ductile when cold.

PROCESS OF MANUFACTURE. — Practically all wrought ir duced from pig iron by indirect processes although direct processes f tion from the ore exist. These indirect processes may be divided general classes based upon the type of furnace used: (*a*) reverberato dling furnaces; and (*b*) charcoal hearths. The best iron is made upo but puddling furnaces produce the larger quantity. The essential between the two processes is that in hearths the chief source of o atmospheric air, and the fuel is burned in contact with the iron, wh dling furnaces the chief source of oxygen is magnetic oxide of iron, an is burned in a chamber separate from that containing the iron. tion of these processes follows.

Puddling. — This method consists of melting pig iron in a atory furnace heated either by coal or natural gas. The furnace lined with oxide of iron. The pig is exposed for about two hours t tinuous action of a flame hot enough to melt it and to remove m impurities, but not hot enough to keep pure iron in a molten state action of the flame the molten iron becomes less fusible and fina After reaching this condition it is puddled by being worked into ball labor. It is then taken from the furnace and squeezed or hamm blooms, and then rolled into small bars about ¾ inch thick and fr inches wide, called "muck bars." After cooling, these muck bars a short pieces about 2 feet in length, piled into bundles, fastened by reheated to welding heat and re-rolled into merchant bars. If t subjected to a second piling, heating and re-rolling, it is called " fined iron."

Charcoal Hearths. — The following are the more important he esses.

1. **Finery Process.** — Charcoal fineries produce "knobbled" high degree of softness which is much used for boiler tubes.

In the finery process the pig iron is first melted down in a coke coal refinery to remove the silicon, phosphorus, and sulphur, and is t ferred in a molten condition to a charcoal hearth which is still hot previous charge. Damp charcoal is thrown in, a low-pressure, unhe turned on and the metal agitated to keep it in contact with the bla an hour or more the metal is collected into a ball and hammered some of the slag, cut up and reheated in piles. Gray iron may b this process.

2. **Walloon Process.** — The Walloon process is used in S producing wrought iron from Dannemora pig iron, the resulting prod shipped to England, particularly to Sheffield, for conversion into bl for use in fine toolmaking.

In the Walloon process long pigs are melted gradually by bein forward into a charcoal fire. The molten iron drops through the blas ing decarburized, and collects in a pasty mass at the bottom of th The partially refined iron is then raised to the top of the charcoal melted down with the addition of rich slag and hammer scale. T is then balled, reheated and hammered.

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e Process. — The Lancashire process is used principally
o used in the United States.
ocess somewhat resembles the Walloon process. Pig iron
vo layers of charcoal, the liquid dropping down through
ng oxidized. The molten metal collects in a pasty mass
n where it is allowed to remain for twenty or twenty-five
mixed with decarburizing slag and remelted in a similar
pasty mass is removed from the hearth and hammered.
- "Busheled iron" is made of scrap instead of pig iron. The
urnace, squeezed and rolled into bars. The resulting prod-
ity.

. — Wrought iron consists of a mass of ferrite interspersed
les of slag. Commercial shapes of wrought iron, such as
nade from piles of muck bars, and have a fibrous char-
st of a series of welds.

iron has been gradually replaced by steel for most struc-
l quality of iron, however, is still in demand where tough-
necessary, and where welding or other blacksmith work
of a high degree of purity is sometimes specified for use
material is needed.

ught iron is on sale in the eastern states under the following

lish Iron). — Best grade; used for fine wrought work
It is particularly fibrous.
or Best Refined. — This is the best domestic iron. It
lding or machine work.
This is the cheapest grade. Used for nails, horseshoes,
as readily as other grades.

D ELASTICITY; WEIGHT. — The values stated in
ch follow indicate the tensile strength of wrought iron of
The following values are from tests made upon merchant
etts Institute of Technology, and show the variations that
e various grades bought in the market without specifica-
tions which follow show the strength which may be
f the grades specified therein.

GTH, MODULUS OF ELASTICITY, ELONGATION, ETC., OF WROUGHT IRON

(M.I.T. Tests)

	Single Refined	Double Refined	Swedish
. per sq. in.....	47,000	51,700	40,600
.....	32,000	25,800	20,900
.....	35,000		
.....	27,700,000	29,700,000	29,100,000
n in 10 inches..	.....	22.7	26.4
.....	20.6	37.5	75.0

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Compressive Strength. — For all practical purposes this may be ta as the yield point, or from 3000 lb. to 4000 lb. above the elastic limit.

Weight. — Wrought iron weighs 480 lb. per cu. ft. A bar 1 yard in len and 1 sq. in. in cross-section weighs 10 lb.

STANDARD SPECIFICATIONS FOR WROUGHT IRON. — *American Society for Testing Materials Standards.*

COST. — In the *Iron Age* for May 18, 1922, refined iron bars were quo at 2.10 cents per pound, f.o.b. Pittsburgh.

BIBLIOGRAPHY. — See *Bibliography* in article on *Steel.*

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LAMPS, ARC. — (*See also Arc, Electric; Distribution and Transmission Systems; Lamps, Incandescent; Illumination, Street; Photometric Quantities; Photometry; Rectifiers.*) The theory of the electric arc is discussed in detail in the article on *Arc, Electric.* Arc rectifiers are discussed in the article on *Rectifiers.* This article deals with the use of the electric arc as a source of illumination.

The positive and negative electrodes are termed respectively anode and cathode. The active conducting medium of the arc is supplied by the electro-vaporization of the cathode. The wasting of the anode is due only to its oxidation and can be prevented without interrupting the arc by cooling or by isolation from air. With the exception of the carbon arc, it is more difficult to maintain an arc with alternating than with direct current.

Voltage Drop Across an Arc. — The voltage drop across an arc comprises three elements, (1) a sensibly constant drop at the anode, (2) a similar but much smaller drop at the cathode and (3) a variable drop in the arc stream. The electrode drops depend only on the nature of the electrodes. The drop in the arc stream varies with the current according to Ohm's law, but the relation is greatly complicated by the changes in the resistance of the arc stream. Steinmetz (*Radiation, Light and Illumination, p. 139*) proposes the following general expression for arc conduction in air:

$$E = E_0 + \frac{k\,(l + l_1)}{\sqrt{I}},$$

where E is the total voltage, E_0 the electrode drop, l the arc length in inches, I the current, and k and l_1 constants depending on the cathode material.

For carbon electrodes, $E_0 = 36$, $k = 130$, $l_1 = 0.33$.
For magnetite-copper electrodes, $E_0 = 30$, $k = 123$, $l_1 = 0.05$.

Steadying Resistance. — When the arc is employed in a series circuit its instability is overcome by supplying it with a constant current. Arcs in multiple on constant-potential circuits must each be compensated by a considerable ballast of stable series resistance or reactance; see article on *Arc, Electric.*

Power Factor. — Due to the distortion of the current wave by the varying resistance of the arc, the alternating-current carbon arc has a power factor of about 85 per cent, although the current and voltage pass through their zero values simultaneously; see *Alternating Currents.* Reactive ballast coils used in constant-potential lamps reduce the over-all power factor to values between 60 and 75 per cent.

Sources of Luminosity. — There are three distinct modes of light production by electric arcs, viz., (1) by incandescence of the electrodes due to their high temperature, (2) by the luminescence in the arc of salts derived from mineralized carbon electrodes, and (3) by the luminescence in the arc of the conducting vapors from the cathode. The first is exemplified by the ordinary carbon arc. The second mode is exemplified by the flame arc. The color of the light and its efficiency depend on the nature of the luminescent salts and the temperature attained in the arc. Carbon electrodes heavily mineralized with calcium salts yield a yellow light of high efficiency. Barium salts yield white light and strontium red, but the efficiencies are lower than those attained with yellow light. The third mode is exemplified in the metallic arcs, the chief practical representatives being the magnetite and the mercury arcs. Here the color of the light depends solely on the natural spectrum of the cathode vapor and the efficiency depends on the richness of that spectrum in highly luminous components.

Steadiness of Light. — Light from arc lamps is inferior to that from incandescent lamps in the matter of steadiness. The conditions requisite for

steady light are constant arc length, constant current, fixity of arc position uniform feed, homogeneous electrodes and complete protection from draft When well ballasted the mercury arc in the vacuum tube best meets these conditions. The alternating-current arc displays instantaneous variations i intensity which are very annoying at low frequencies. Arcs should not be oper ated at less than 40 cycles per second where considerations of hygiene are im portant. The three-phase arc is free from this defect.

CARBON ARC LAMPS.— Unless used for indirect light the upper elec trode of a direct-current carbon arc should be the anode in order to gain th fullest advantage of downward light distribution from the crater. In th alternating-current arc semi-craters of lower temperature are formed on both electrodes, resulting in lower efficiency of light production than in the direct-current arc. The performance of typical carbon arc lamps is given in Table I and Fig. 1.

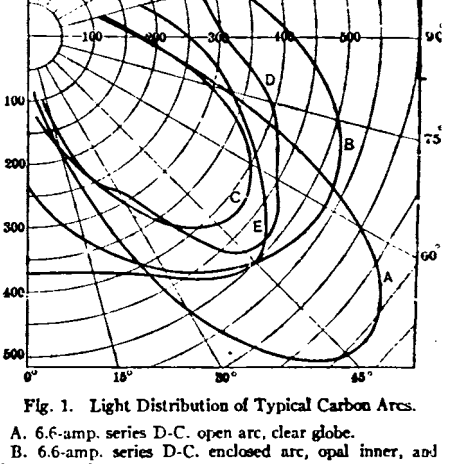


Fig. 1. Light Distribution of Typical Carbon Arcs.

A. 6.6-amp. series D-C. open arc, clear globe.

B. 6.6-amp. series D-C. enclosed arc, opal inner, and clear outer globe.

C. 7.5-amp. series A-C. enclosed arc, opal inner, and clear outer globe, small reflector.

D. 5.5-amp. multiple D-C. enclosed arc, 110 volts, opal inner, clear outer globe.

E. 5-amp. multiple D-C. intensified arc, 110 volts, opal inner, and clear outer globe.

Open Carbon Arcs. — The open arc is characterized by the rapid oxidation of the electrodes due to the free access of air. The anode of a direct-current open arc wastes at a rate between 1 and 2 inches per hour and the cathode at about half the rate of the anode. The electrodes of open alternating-current arcs burn from 1 to 1.5 inches per hour. A life per trim sufficient for all-night operation may be obtained by the use of a single pair of very long, heavy carbons or by providing two sets for successive consumption. The open arc is very sensitive to drafts. It is operated with short arc length, low voltage, usually 45 to 55, and heavy current, usually 6.6 to 10 amperes, to improve the steadiness of the light. The short arc length impedes downward light distribution and the intense crater casts harsh shadows. The erratic travel of the arc about the electrodes makes the light very unsteady. The use of the open arc is now confined to series circuits.

Inclosed Carbon Arcs. — The inclosed carbon arc with closely restricted air supply affords a greatly increased electrode life over the open type. It is also much less liable to extinction by wind, and hence can effectively employ greater arc length, higher voltage and lower current than the open arc. The crater of the inclosed arc is less pronounced, entailing some loss of efficiency compared with the open arc, but the greater length of the arc reduces the interference of the lower carbon with downward distribution. The light is much steadier than

ORMANCE OF TYPICAL CARBON ARC LAMPS

Multiple d-c. inclosed	Multiple d-c. inclosed	Intensified d-c. inclosed	Multiple 220-volt d-c. inclosed	Multiple a-c. inclosed
110	110	110	220	110
80	·80	80	150	72
5	6.5	5	3.25	6
550	715	550	715	430
....	....	....	....	0.65
½	½	Two ¼ One ⅜	½	½
orcelain reflector. Opal inner, no outer globe.	Porcelain reflector. Opal inner, no outer globe.	Porcelain reflector. Opal inner, no outer globe.	Porcelain reflector. Opal inner, no outer globe.	Porcelain reflector. Opal inner, no outer globe.
50 hours 00 at 60°	100 hours 580 at 60°	75 hours 600 at 35°	150 hours 240 at 60°	125 hours 310 at 60°
215	318	225	160	160
2.56	2.25	2.44	4.44	2.68
379	559	414	215	276
1.45	1.28	1.33	3.33	1.56

ultiple a-c. closed	Series d-c. open	Series d-c. open	Series d-c. inclosed	Series a-c. inclosed	Series a-c. inclosed
10	50	50	75	77	77
72	48	48	73	72	72
7.5	6.6	9.6	6.6	6.6	7.5
40	330	480	495	425	480
0.65	.....	.....	.....	0.84	0.84
½	½ 2 pairs	⅝ 2 pairs	½	½	½
rcelain flector. pal inner, no ter obe	Clear globe.	Clear globe.	Porcelain enamel reflector, Clear globes.	Porcelain enamel reflector, Clear globes.	Porcelain enamel reflector. Clear globes.
hours at 60°	18 hours 720 at 45°	18 hours 1250 at 45°	125 hours 530 at 60°	125 hours 250 at 70°	100 hours 305 at 70°
15	265	460	290	144	173
2.51	1.25	1.02	1.71	2.95	2.77
71	395	690	479	232	291
1.45	0.82	0.71	1.03	1.83	1.65

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that from the open arc. It is bluer in color, due to the greater pro rived from the arc proper. Electrodes of moderate length afford trim of from 80 to 100 hours in alternating-current lamps and of hours in direct-current lamps. The range of currents in common from 3 to 7.5 amperes.

Intensified Carbon Arc. — The intensified carbon arc, us direct-current circuits, employs a short, thick vertical lower carbon as two long, thin, inclined carbons as anode. The upper carbons co above the cathode and feed downward at the rate of consumption aid of any regulating mechanism. The lower carbon is controlled b solenoid and tends to maintain an arc of constant length at a fixed high current density in the positives produces a very intense dual crater which emits light of somewhat whiter quality and of higher efficiency than that of the ordinary inclosed arc. The fixed level of the arc and the absence of crater travel aid in the effective use of reflectors and diffusing globes and in the maintenance of a definite form of light distribution. Under standard conditions of use the 5-ampere arc has a life per trim of from 80 to 100 hours.

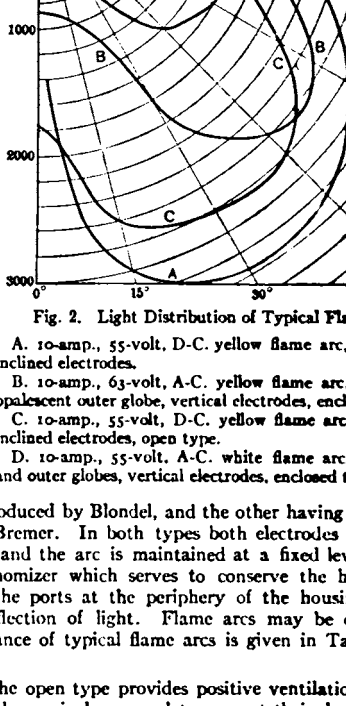


Fig. 2. Light Distribution of Typical Fl

A. 10-amp., 55-volt, D-C. yellow flame arc, inclined electrodes.

B. 10-amp., 63-volt, A-C. yellow flame arc opalescent outer globe, vertical electrodes, encl

C. 10-amp., 55-volt, D-C. yellow flame arc inclined electrodes, open type.

D. 10-amp., 55-volt, A-C. white flame arc and outer globes, vertical electrodes, enclosed

FLAME ARC LAMPS. — The flame arc depends for light production on the luminescence of salts impregnated in carbon electrodes. In its electrical characteristics it is essentially a carbon arc. The evolution of this type of lamp has been along two structural lines, one having vertical electrodes, introduced by Blondel, and the other having electrodes, introduced by Bremer. In both types both electrodes the regulating mechanism and the arc is maintained at a fixed le a vitreous canopy or economizer which serves to conserve the h arc, deflect the fumes to the ports at the periphery of the housi assist in the downward reflection of light. Flame arcs may be or inclosed. The performance of typical flame arcs is given in Ta Fig. 2.

Open-flame Arcs. — The open type provides positive ventilatic the fumes of the arc from the arc inclosure and to prevent their dep inclosing globe. The unrestricted air supply causes a rapid wasting trodes. To obtain a practicable life per trim the electrodes are

PERFORMANCE OF TYPICAL FLAME ARCS

	Open d-c. inclined carbons	Open a-c. inclined carbons	Open d-c. vertical carbons	Open d-c. vertical carbons
..	55	55	110	78
..	45	45	75	75
..	12	12	6.5	6.5
..	660	500	715	510
..	.....	0.75	.....	.....
s	¼	¼	½	½
	Impregnated yellow. Light opal globe.	Impregnated yellow. Light opal globe.	Lower impregnated. Alba globe.	Lower impregnated. Alba globe.
..	17	17	20	20
..	2150 at 0°	1350 at 0°	2425 at 60°	2350 at 60°
..	1890	1270	2058	2050
P..	0.35	0.39	0.35	0.25

	Inclosed d-c. multiple vert. carbons	Inclosed a-c. series vert. carbons	Inclosed a-c. multiple vert. carbons
.....	110	60	110
.....	70	55	70
.....	6.5	10	7.5
.....	715	450	510
.....	.....	0.75	0.62
es, inches	⅞	⅞	⅞
.....	Impregnated yellow.	Impregnated yellow.	Impregnated yellow.
.....	Clear inner, opalescent outer globe.	Clear inner, opalescent outer globe.	Clear inner, opalescent outer globe.
.....	100–125	100–125	100–125
.....	.....	.....	.....
.....	1740	1595	1600
P.....	0.41	0.28	0.32

great cross-section. The co-axial arrangement of very viously impracticable; hence the converging arrangement. es afford additional advantages through the high current bsence of arc travel and low heat loss by conduction. A employed to hold the arc in its proper position below the os of this type have a maximum luminous intensity in the nd hence must be hung very high to produce uniform illumi- me arc with converging electrodes has a life per trim of . The open type with vertical electrodes has a life per hours, but produces a less steady light than the converging el.

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The ventilating system of open-flame arcs requires very careful de
less the fumes are positively removed from the inclosing globe, the ac
of powder on the globe during the life of a single pair of electrodes r
the light transmitted by as much as 40 per cent.

Lamps of the open type are greatly handicapped by the high cost of maintenance and electrodes.

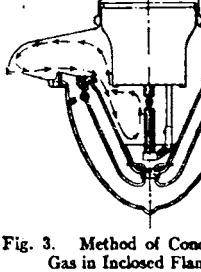


Fig. 3. Method of Con
Gas in Inclosed Flam

Inclosed Flame Arcs. — The inclosed type of flame arc is provided with a condensing chamber into which the fumes of the arc are carried by convection, as shown in Fig. 3. The gases are thus cooled and freed from their solids without rapid ingress of air. The life of the electrodes is thus prolonged about ten times, giving a life per trim of from 100 to 150 hours. The electrodes used in inclosed flame arcs are less highly mineralized than those used in open arcs and the gain in life is accompanied by some loss in efficiency. verging carbon type of flame arc has not been developed in the inclo

MAGNETITE ARC LAMPS. — The magnetite arc depends fo duction solely on the luminescence of the conducting vapors produ cathode. The cathode consists of a thin iron tube closely packed v form powdered mixture of magnetite, oxide of titanium and oxide of The positive electrode is a block of copper of large heat-radiatin The magnetite produces an arc of excellent conductivity, but of rela spectrum. The titanium oxide enriches the spectrum of the arc, im color and efficiency. The oxide of chromium serves to restrain t vaporization of the active elements and so prolong their life. Th light is of excellently balanced white color. The copper anode i sumed and requires infrequent replacement. The cathode has a li 100 to 250 hours depending on the current and arc length. It is cable to operate the magnetite arc in an inclosure with limited air acc the need of ventilation to remove the copious brown fumes. The l magnetite arc is relatively unsteady, a feature which is aggravated termittent method of feeding employed.

The two commercial types of magnetite arc differ principally in the electrode arrangement. In the General Electric type the positive is the upper; in the Westinghouse type the negative is the upper. The advantages claimed for each type conflict sharply.

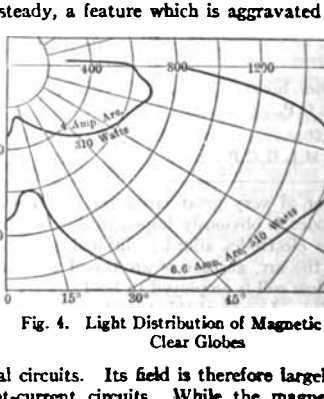


Fig. 4. Light Distribution of Magnetic
Clear Globes

Unlike other types of arc lamps the magnetite arc is poorly adapted to interior use on constant potential circuits. Its field is therefore largel to street lighting on constant-current circuits. While the magne solely a direct-current device, it is readily adapted to use in connecti

pply by the use of the mercury arc rectifier combined
rent transformer; see *Rectifiers*.
per lamp on series circuits is from 75 to 80. The stand-
and 6.6 amperes. The performance of typical magnetite
III and Fig. 4.

RFORMANCE OF TYPICAL MAGNETITE ARCS

	Series type	Series type	Multiple type
.....	78	78	110
.....	75	75	75
.....	4	6.6	6.5
.....	312	515	715
.....	Clear globe.	Clear globe.	Clear globe.
.....	175	125	80
.....	700 at 80°	1650 at 80°	1650 at 80°
.....	545	1340	1340
°.....	0.59	0.38	0.53

LE POWER OF CARBON AND FLAME ARCS. — H types of arc lamps falls off gradually during the life of , due to the accumulation of ash and fumes on the glass- of this loss varies greatly with the conditions. Matthews *n., 1901, p. 296*) reported tests of inclosed carbon arcs of results are typical, viz., reduction of light output in 100 carbons 5 per cent, low-grade carbons 30 per cent. In depends chiefly on the purity of the carbons employed. s depends on the scheme of ventilation and the extent to re mineralized. Composite results of many tests on in- orted in *Good Lighting*, Vol. 7, p. 515, show a loss in 100 per cent of the initial mean lower hemispherical candle- neral Electric inclosed white flame arcs made at the Massa- f Technology (*Wright and Sprowls, 1912*) showed the light in 150 hours burning to be 18 per cent. The loss of cs is relatively small, due to the positive character of the portance of very careful cleaning of glassware of arc lamps pparent from the above data.

DIFFUSING GLOBES. — The intrinsic brilliancy of all igh to seriously interfere with good vision when in the Diffusing globes reduce the light by from 25 to 40 per cent but generally serve to increase the effectiveness of vision ully compensates for the loss of light. Diffusing globes distribution toward greater uniformity at various vertical nced side-wise distribution must be attained by a properly

MECHANISMS FOR CARBON AND FLAME ARCS. echanism of an arc lamp serves the following functions: upon lighting, (2) to feed one or both electrodes at the and (3) to maintain approximately constant the arc length, Feeding systems are of two general classes. In the first d by gravity upon the releasing of a clutch controlled by eding steps are small and frequent the process approaches s feed. In the second type the arc is restruck at each gnetite arc.

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Gravity-feed Mechanism for Multiple Carbon Arcs. — The m
of constant-potential lamps are practically all of the gravity-feed t
commonest type has a ballast of resistance or reactance in series with a solenoid and with the arc itself; see Fig. 5. When the arc is not lighted the carbons are in contact. When the switch is closed the solenoid is energized and draws its plunger, tightens the clutch and strikes the arc by drawing the carbons apart. As the arc lengthens the current falls until the forces on the plunger are balanced. As the arc lengthens by burning away, the current tends to fall, releasing the clutch and permitting the carbon to feed until checked by the rising of the plunger. In a well-adjusted lamp this process is practically continuous. In alternating-current mechanisms of this type the plungers are laminated ballast consists of a reactive coil.

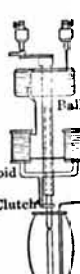


Fig. 5. Multiple Carbon Arc Lamp

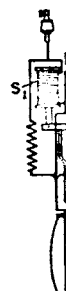


Fig. 6. bon A

Gravity-feed Mechanism for Series Carbon Arcs. — The
type of mechanism for gravity-feed lamps of the series class employs
ential action of two solenoids to control the feeding clutch. Fig. 6
type of mechanism as applied to the inclosed carbon arc. It provides
S_1 in series with the arc, a solenoid S_2 and resistance coil in parallel with the arc, and a short-circuiting cut-out. The solenoids act differentially on the clutch. The shunt solenoid when strengthened tends to release the clutch, the series solenoid to lift it.

When the lamp is idle the carbons are normally in contact. When current is switched on, the series solenoid is energized and draws out the arc. The cut-out opens, S_2 is energized and tends to oppose the drawing action of S_1, equilibrium being attained when the arc has the proper length. As the carbons burn apart S_2 is strengthened and releases the clutch momentarily, allowing the upper carbon to feed by gravity. If the circuit through the arc is accidentally broken, S_2 alone is energized and the cut-out is immediately closed, preventing the interruption of the circuit. Alternat
mechanisms have laminated plungers, but differ in no essentials fro
direct-current lamps.

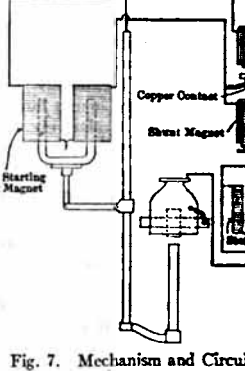


Fig. 7. Mechanism and Circui
4-amp. Arc Lamp

Intermittent Feed Mechanism. — The intermittent type of feedi
ism for series lamps is shown in Fig. 7. When the current is switcl
starting magnets are energized, bring the electrodes together and ca
to strike. As the electrode burns away the arc gradually increase

il the shunt coil is sufficiently energized to momentarily
nd cause the striking process to be repeated. As the
er with considerable force the accumulated slag is broken
thode.

for Flame Arcs. — The mechanisms of flame arcs with
only in details from those of carbon arcs of analogous
n that the feeding device is dual and acts on both carbons,
e arc at a fixed level. Mechanisms for converging car-
a great variety. The most generally-used type for con-
on has a series coil whose plunger acts laterally on one
he arc and gravity feed. In many cases an escapement
shunt solenoid is used to regulate the rate of feed. In
f feed is controlled by a metal fin attached to each elec-
s fin rests against a refractory lug. The fin is vaporized
e arc at a rate exactly corresponding to the required rate

R LAMPS. — (*See also Rectifiers.*) The luminous ele-
mp is a luminescent arc, in a highly evacuated tube of
between a mercury cathode and an anode of mercury or
ed by it. The voltage required to sustain such an arc,
tive electrode) is mercury, consists of a constant drop at
13 volts and an arc stream voltage which is directly pro-
n. The arc voltage per inch increases with the vapor
r pressures the arc is an unstable conductor and the
lls with a rising current. At high pressures, as in the
arc voltage rises very rapidly with the current.
actinic radiation from mercury-arc lamps gives them
the fields of photography and blue-printing. The large
rom quartz-tube lamps not inclosed in glass may be uti-
of processes for bleaching, sterilization, etc.

Mercury-arc Lamps. — The mercury arc can be sus-
tages only when the mercury electrode is the cathode;
l in the mercury-arc rectifier (*see Rectifiers*).
y-arc lamp with alternating current the tube is provided
are attached to the respective terminals of a reactance
The cathode is attached to the middle point of this
e power factor of this type of arrangement, including
d the lag produced by the reactance coil, is from 50 to
ecent types have power factors from 50 to 85 per cent,
egulation of the line. In other words, when the line
ny great extent, say from 10 to 15 volts from normal, the
mp is used. When the line voltage is kept within say
ver factor lamp can be used as less regulation inductance

ry-arc Lamps. — The glass-tube type of lamp operates
e and temperature. Its spectrum is that characteristic of
is entirely deficient in red lines and has a great prepon-
n and violet.
ic brilliancy of this type of lamp renders diffusing glass-
simple color composition tends to enhance the acuity of
se the spectrum is perceptibly improved by combining
olic reflector coated with rhodamine enamel, which by
part of the blue and violet radiation incident upon it to

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Methods of Starting. — The mercury arc is started either the tube until mercury from the cathodes makes metallic contact anode and strikes the arc or by breaking down the gap by a hig spark discharge. As installed for general lighting the mechanism usua an automatic starter operating on one of the two methods referr tilting mechanism is operated by a solenoid which is cut out as the a The spark-discharge device is essentially an automatic quick-br which opens the circuit of an induction coil so as to cause it to discha the tube. The tube is mounted in an inclined or vertical position. cury vapor condenses at the top in a condensing chamber and is rest cathode by gravity.

Performance of Mercury-arc Lamps. — Performance data typical lamps of this class are given in Table IV.

TABLE IV.—CANDLE-POWER CHARACTERISTICS OF HEWITT MERCURY VAPOR LAMPS

Rating of lamp in average watts	Voltage	Type	Length of tube in inches	Mean lower hemispherical c.p.	Watts per mean lower hemispherical c.p.	Total lumens
Lamps for Alternating-current Circuits						
210	100–125	E	35	400	0.53	3,179
380	100–125	F	50	850	0.45	6,283
For Direct-current Circuits						
192	Series on 100–125	H	21	300	0.64	2,388
385	100–125	HH	21	600	0.64	4,712
385	100–125	K	45	700	0.55	5,529
220	100–125	L	35	400	0.55	3,142
385	100–125	P	50	850	0.45	6,283
770	200–250	PP	50 (2)	1600	0.48	12,400
Quartz Lamps for Direct-current Circuits						
726	200–240	Z	4	2400	0.3	18,839

Life of Glass Tubes. — Tubes fail ultimately through l through deterioration of vacuum. The life per tube varies considera usually several thousand hours of operation.

Loss of Candle Power with Age. — The light output of lamps deteriorates quite rapidly during the early portion of tube reported by Harrison (*Trans. Ill. Eng. Soc., Vol. 6, p. 545*) give th average value on two type *H* tubes operated at 3.3 amperes;

Per cent initial candle power...	100	83	80	77	73	70.5	67
Hours burning.....	0	250	500	1000	2000	3000	4000

Quartz-tube Mercury-arc Lamps. — The quartz-tube lamp operates at a high temperature and pressure. Its luminescent spectrum is richer than that of the low-pressure lamp and has superposed upon it a continuous spectrum of incandescence including all luminous elements. The light of the high-pressure lamp is therefore much nearer white than that of the low-pressure lamp. On account of the high pressure of the arc in the quartz tube the length required for circuits of commercial voltage is very much less than the length of glass-tube arcs. The quartz-tube lamp emits a considerable amount of invisible ultra-violet radiation which is capable of doing serious injury to the eye. Ample protection is afforded by surrounding the tube by an envelope of clear glass. Quartz tubes are nominally indestructible, but may require occasional repumping.

COST OF ARC LAMPS (Pre-war prices). — Open carbon-arc lamps are no longer sold. Magnetite and metallic oxide arc lamps cost from $23 to $27. The first cost of flame-arc lamps is from $33 to $45. Glass-tube mercury-arc lamps cost complete, including reactance coil, from $27 to $35. The renewal cost of short glass tubes is approximately $9, that of long glass tubes $12; the average cost per lamp per year will run around $3 per lamp.

Annual Costs. — The following comparative costs of arc-lamp operation under street lighting conditions for a total of 4000 hours (one year, all night service) are given by Friedman (*Elec. World, Vol. 55, p. 1071*).

ANNUAL COST OF OPERATING ARC LAMPS

Type.....	Open d-c.	Open d-c.	Enc. a-c.	Enc. d-c.	Enc. a-c.	Magnetite	Magnetite
Amperes.....	9.6	6.6	7.5	6.6	6.6	4.0	6.6
Electrodes.....	$5.50	$5.50	$1.50	$1.20	$1.20	$1.55	$2.85
Trimming.....	6.00	6.00	2.00	2.00	2.00	1.00	2.00
Repairs.....	2.50	2.50	1.00	1.00	1.00	0.75	0.75
Inner globes.....	.....	.....	0.45	0.45	0.45	.....	.....
Outer globes.....	0.30	0.30	0.30	0.30	0.30	0.50	0.50
Renewals of station equipment	1.50	1.50	.....	1.50	.....	2.00	3.00
Energy, 1.5 cts. per kw-hr	50.00	32.70	34.50	42.90	30.30	22.80	38.82
Totals.....	$65.80	$48.50	$39.75	$49.35	$35.25	$28.60	$47.92

* The above costs do not include fixed charges. Interest may properly be taken at 6 per cent and depreciation at from 7.5 to 10 per cent.

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LAMPS, INCANDESCENT ELECTRIC. — (*See also Illumination, Laws of; Illumination, Interior; Illumination, Street.*) Incandescence denotes the emission of light by a solid or liquid body due to its temperature elevation. The performance of incandescent bodies is referred to a standard *black body*, or one which, at any temperature, emits the maximum possible intensity of radiation at each wave-length of the spectrum. The percentage of luminous radiation from incandescence is low, but increases markedly with the temperature. Hyde computes the luminous radiation from a black body as 1.9 per cent at 2000° C. Abs., 8.8 per cent at 2500° C., 16.9 per cent at 3000° C., 32.5 per cent at 4000° C., 44 per cent at 5000° C. and a maximum of 50 per cent at 6500° C. Certain materials excel the black body in relative light radiation due to *selectivity* or the relative depression of heat radiation as compared with light.

The efficiency of the incandescent lamp depends on: (a) the temperature which its filament can sustain without an undue rate of decay; (b) the degree of selectivity manifested; and (c) the prevention of thermal leakage by conduction and convection. These conditions require a filament of the highest obtainable melting point and lowest vapor tension, which must be supported by a system of low thermal conductivity. So fully are the two latter conditions met that the thermal leakage of modern lamps is less than 5 per cent.

Electrical and Mechanical Properties of Lamps. — The specific resistance of the filament material should be relatively high to insure favorable dimensions in units of low power and high voltage. A relatively large positive temperature coefficient of resistance is desirable as this tends to lessen the variations in performance caused by voltage fluctuations. The filament should be of great mechanical strength, especially in its resistance to fracture. The material required should be obtainable in ample quantities, readily workable and uniform in its finished state. Experience indicates that alloys are distinctly inferior to pure metals and metalloids in all essential features.

Vacuum. — Incandescent lamps require the highest practicable vacuum for the chemical and thermal protection of the filament. In the manufacture of lamps the first stage of evacuation is mechanically produced. Final exhaustion is produced chemically by burning within the inclosure a small amount of phosphorus compound. During the latter stage the filament is raised to incandescence to drive off residual gases. To prevent the loss of vacuum through the unequal expansion of the glass and the leading-in wires the latter are made of a copper-steel alloy.

TYPES OF LAMPS. — There are described in the following paragraphs the types of incandescent lamps which have become of commercial importance. Of the several types the tungsten filament is the most widely used.

Carbon Lamps. — Carbon vaporizes at about 3900° C. and exists in a variety of forms which vary greatly in other physical properties. *Base carbon*, prepared as lamp filaments by carbonizing squirted threads of dissolved cellulose, is of low conductivity, high vapor tension and of negative temperature coefficient of resistance. *Graphitic carbon*, which is deposited from hydrocarbon vapors on incandescent filaments of base carbon, has a high conductivity, low vapor tension and a small positive temperature coefficient. *Metallized carbon*, prepared from the two preceding types by heat treatment in an electric furnace, has a greatly increased conductivity, a small positive temperature coefficient, low vapor tension and a fair degree of selectivity. The common carbon lamp has a core of base carbon on which a shell of graphitic carbon has been deposited by the process of flashing. The hot resistance of this type is

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approximately half the value cold. The chief advantage of this type is its low cost and great ruggedness.

Gem Lamps. — These have filaments of metallized carbon prepared from the two preceding forms by heat treatment in an electric furnace. Such a filament has a greatly increased conductivity, a pronounced positive temperature coefficient, low vapor tension and a fair degree of selectivity. These features give the gem lamp a higher efficiency and a better color of light than the carbon lamps. The hot resistance of the gem lamp is 2.6 times its value cold.

Tungsten Lamps. — Tungsten melts at about 3200 deg. C.; has a low vapor tension, its atomic weight being 184; has a conductivity of 6.2 microhms per cm. cube at 25° C. for the hard-drawn variety and 5 microhms for the annealed; has a mean temperature coefficient of + 0.0051 between 0° and 170° C. and is selective in radiation to a valuable degree. The hot resistance of the filament is from 10.8 to 13 times the cold resistance, depending on the type of lamp. Tungsten is exceedingly hard and is worked with difficulty. Early filaments were produced by sintering finely divided tungsten reduced from tungstic oxide; they were extremely fragile and were uncertain in performance.

Drawn wire filaments superseded the former pressed filaments and revolutionized lamp manufacture, simplifying the processes very considerably and reducing the cost. It is possible to draw filaments exactly to size, which increases the practical efficiency by eliminating weak points and also makes it possible for the first time in lamp manufacture to produce all lamps of a lot for a predetermined voltage. Some early difficulties with erratic blackening of bulbs have been eliminated by the introduction of special chemicals known as "getters" in the bulb. The tungsten lamps made by the principal American manufacturers are commonly known as "Mazda B" lamps.

Non-Vacuum Tungsten Filament Lamps. — This type of lamp has a closely coiled helical filament of drawn tungsten wire mounted in a glass chamber filled with nitrogen or other inert gas. The pressure of the gas retards the decay of the filament so that it may be operated with a satisfactory life at a higher temperature than is practicable in a vacuum. The gain in radiant efficiency so obtained is offset in part by the convection of heat from the filament by the gas. When the diameter of the filament is minute there is little or no net gain in efficiency. When the filament is relatively heavy the net efficiency may be doubled. The helical coiling of the filament increases its effective diameter as a radiant and simplifies the problem of its support, for the filament is distinctly soft when incandescent. The gas-filled lamp has an elongated bulb, the upper portion of which serves as a cooling chamber. The walls of this chamber receive the black deposit from the filament, but are so placed that they absorb but little of the useful light. The larger sizes of gas-filled lamps are standard for operation in a pendent position only. If it is desired to operate these at some other angle, they should be ordered for up-right or universal burning, the lamps in such cases being supplied with slightly modified filament supports. Such lamps are much more brilliant than vacuum lamps and should be fully shaded. The light of the gas-filled lamp is decidedly whiter than that of the vacuum tungsten lamp. The gas-filled tungsten filament lamps manufactured by the principal American firms are commercially known as "Mazda C" lamps.

Use of Various Types of Lamps. — The following table shows the relative use of the various types of lamps produced for domestic sale in recent years, as secured from various sources. It will be noted that the inefficient types have been rapidly superseded by the more efficient "Mazda" lamps. For 1919, the total sales of incandescent lamps, excluding miniature lamps, amounted, accord-

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ing to Schroeder, to 183,000,000 for domestic use, 170,000,000 of these being the tungsten filament type.

RELATIVE USE OF VARIOUS TYPES OF LAMPS

Type of lamp	1907	1910	1913	1916	1919
	per cent	per cent	per cent	per cent	per cent
Carbon	93.27	63.08	11.85	16.32	7.0
Gem	5.88	14.88	31.41		
Tantalum	0.75	3.57	.09	.....	.....
Mazda	0.10	18.47	55.65	83.68	93.0

TYPES OF BULBS AND FILAMENTS. — The more common form of bulbs and filaments are illustrated in Fig. 1. In the bulb designation, suc

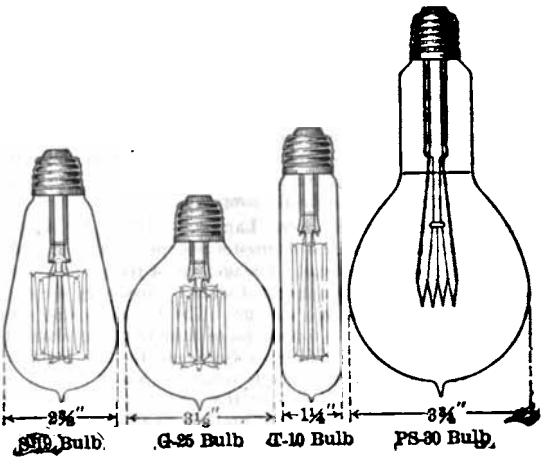


Fig. 1. Bulb Classification (Lamps Illustrated ¼ Scale)

as S-19, the letter indicates the type of bulb, and the number the diameter of the bulb in eighths of an inch. "S" indicates a straight side bulb, "G" a round, or globular, bulb, "T" a tubular bulb, and "PS" a pear-shaped bulb.

Coiled Filaments. — One of the results of the use of ductile tungsten in the manufacture of Mazda lamps, has been the possibility of winding the tungsten wire around a mandrel, thereby producing a helically coiled filament. The first application of this was the so-called "focus" type of lamp, in which the filament was concentrated into a small space, more or less approximating a point source. In this way the automobile and the locomotive headlight lamps became available, also a more effective stereopticon lamp.

The advantages of the concentrated light source in connection with lenses and reflectors is illustrated in the following table, according to Stickney, which shows the maximum beam candle-power obtained with a 16-in. parabolic

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of approximately 100 watts, but with widely varying fila- these tests the lamps were focussed so as to give maxi- wer and operated at 100 mean spherical candle-power.

M CANDLE-POWERS (G. H. Stickney)

lamp used		Light source dimensions mm.		Beam candle power
ulb	Type	Dia.	Length	
-30	C headlight	2.0	6.5	462,000
-30	C headlight	5.0	5.0	223,000
-25	C stereopticon	6.5	6.5	142,000
-30	B stereopticon	8.0	8.0	32,600
-25	C regular	25	0.5	12,700
-35	B regular	30	68	3,800

g the filament, however, is most pronounced in gas-filled

ps. — Lamps of this type are designed for use with lenses ors, and are employed with stereopticons, small moving, nals, and for spotlighting, floodlighting, headlighting, and

. — This term covers a wide variety of small lamps used rposes. Such lamps are usually operated at low voltage ith small size bases. Important uses of miniature lamps hemes like the Christmas tree and in "flashlights."

— **Daylight Lamps.** — For color matching, photography ve purposes, various colored lamps are available. Colors ter by dipping the bulbs or by the use of colored glass in ter is less expensive but the latter is more permanent. A as "Mazda C-2" or "Daylight" is standard. These are ed construction, but the filament is operated at a higher o produce whiter light, and a specially determined blue The light from these lamps is approximately daylight in

S AND PERFORMANCE. — Constant potential lamps at the watts and voltage at which they are designed to mically. Constant current lamps are rated by candle- Secondary ratings are given in lumens per watt and candle-power. From these values the light output in e mean spherical candle-power can readily be determined. ating of street-series or constant-current lamps is nominal candle-power per 10 lumens output; thus, an 80 candle- 800 lumen lamp, while a 600 candle-power lamp is a 6000

Lamps are made in the following sizes: 75, 100, 150, 200, hese lamps having the following lumen ratings respectively: 3360 and 5600 lumens.

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DATA ON CONSTANT POTENTIAL LAMPS 110 TO 125 V

Watts	Lumens	Lumens per watt	Watts per spherical candle-power	Watts per horizontal candle-power	Reduction factor
		"MAZDA B" LAMPS—REGULAR TYPE			
10	75	7.52	1.67	1.30	0.78
15	125	8.32	1.51	1.18	0.78
25	226	9.04	1.39	1.08	0.78
40	372	9.31	1.35	1.05	0.78
50	480	9.59	1.31	1.02	0.78
60	575	9.59	1.31	1.02	0.78
		"MAZDA C" LAMPS—REGULAR TYPE			
50	450	White mazda lamp			
75	865	11.53	1.09	....	....
100	1,260	12.57	1.00	....	....
150	2,040	13.66	0.92	....	....
200	3,100	15.51	0.81	....	....
300	4,840	16.11	0.78	....	....
500	8,750	17.45	0.72	....	....
750	13,000	18.48	0.68	....	....
1000	19,300	19.33	0.65	....	....
		"MAZDA B" LAMPS—ROUND BULBS			
15	126	8.38	1.50	1.20	0.80
25	220	8.79	1.43	1.14	0.80
25	232	9.31	1.35	1.08	0.80
40	392	9.82	1.28	1.02	0.80
		"MAZDA B" LAMPS—TUBULAR BULBS			
25	222	8.91	1.41	1.10	0.78
40	362	....	....	....	....

In addition to the lamps listed in the following tables, a complete line B and Mazda C lamps are available for operation on constant potent of 220 to 250 volts. Other lamps are standard for stereopticon se motive and railway headlights, floodlights, train lighting, country hou sign lighting, and similar special service.

Candle-power Distribution. — In earlier practice nearly all in

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ON MAZDA STREET SERIES LAMPS

nens watt	Watts per spherical candle power	Average volts	Average watts	Position of burning
IPS—4.0 AMPERES—NOT FOR RECTIFIER CIRCUITS				
.93	1.15	7.3	29.3	Any
.42	1.10	8.7	35.0	Any
.57	1.00	11.9	47.8	Any
.23	0.95	15.1	60.4	Any
.96	0.90	17.9	71.6	Any
.00	0.90	44.7	179.0	Tip down
.00	0.90	71.5	287.0	Tip down
IPS—5.5 AMPERES—NOT FOR RECTIFIER CIRCUITS				
.47	1.20	5.6	30.5	Any
.42	1.10	6.4	35.0	Any
.32	1.02	8.9	48.7	Any
.37	0.94	10.9	59.9	Any
.96	0.90	13.0	71.6	Any
.32	0.82	29.7	163.0	Tip down
.32	0.82	47.4	261.0	Tip down
IPS—6.6 AMPERES—NOT FOR RECTIFIER CIRCUITS				
.05	1.25	4.8	31.8	Any
.93	1.15	5.5	36.6	Any
.20	1.03	7.4	49.2	Any
.23	0.95	9.2	60.5	Any
.96	0.90	10.9	71.6	Any
.11	0.78	23.5	155.0	Tip down
.11	0.78	37.6	248.0	Tip down
.11	0.78	56.4	372.0	Tip down
IPS—7.5 AMPERES—NOT FOR RECTIFIER CIRCUITS				
.82	1.28	4.4	32.6	Any
.74	1.17	5.0	37.2	Any
.86	1.06	6.8	50.6	Any
.09	0.96	8.2	61.1	Any
.96	0.90	9.6	71.6	Any
.71	0.80	21.2	159.0	Tip down
.11	0.78	33.1	248.0	Tip down
.53	0.76	48.4	363.0	Tip down
"MAZDA C" LAMPS—15 AMPERES				
.95	0.70	14.9	223.0	Tip down
"MAZDA C" LAMPS—20 AMPERES				
.76	0.67	16.0	320.0	Tip down
.33	0.65	25.9	517.0	Tip down
.95	0.63	37.6	752.0	Tip down

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lamps had the same distribution of candle-power, thus causing horizontal candle-power to bear practically a fixed relation to spherical candle-power and to the total light output. In rec

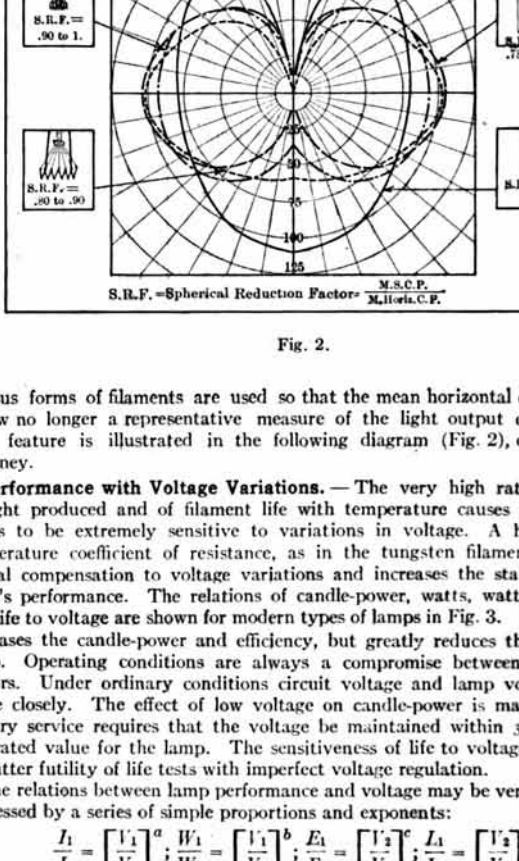


Fig. 2.

various forms of filaments are used so that the mean horizontal is now no longer a representative measure of the light output This feature is illustrated in the following diagram (Fig. 2), Stickney.

Performance with Voltage Variations. — The very high rat of light produced and of filament life with temperature causes lamps to be extremely sensitive to variations in voltage. A h temperature coefficient of resistance, as in the tungsten filame partial compensation to voltage variations and increases the sta lamp's performance. The relations of candle-power, watts, watt and life to voltage are shown for modern types of lamps in Fig. 3. increases the candle-power and efficiency, but greatly reduces th lamp. Operating conditions are always a compromise between factors. Under ordinary conditions circuit voltage and lamp vo agree closely. The effect of low voltage on candle-power is ma factory service requires that the voltage be maintained within the rated value for the lamp. The sensitiveness of life to voltag the utter futility of life tests with imperfect voltage regulation.

The relations between lamp performance and voltage may be ver expressed by a series of simple proportions and exponents:

$$\frac{I_1}{I_2} = \left[\frac{V_1}{V_2}\right]^a; \frac{W_1}{W_2} = \left[\frac{V_1}{V_2}\right]^b; \frac{E_1}{E_2} = \left[\frac{V_2}{V_1}\right]^c; \frac{L_1}{L_2} = \left[\frac{V_2}{V_1}\right]$$

where V = voltage, I = candle-power, W = watts, E = watts per ca

The values of the exponents in the above expressions, as deter Nat. El. Lamp Assoc., are as follows:

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	a	b	c	d
Carbon	5.55	2.05	3.51	20.5
Gem	4.80	1.75	3.06	17.6
Tungsten	3.68	1.59	2.10	13.8

These exponents apply to variations within a moderately limited range and it should be kept in mind that an extreme variation in voltage would not follow the same law.

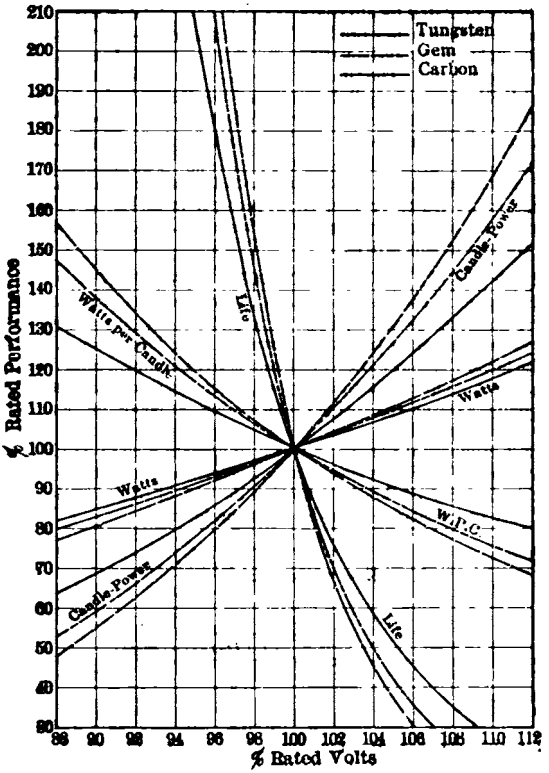


Fig. 3. Characteristic Curves of Incandescent Electric Lamps

Life Performance. — The rated life of incandescent lamps applies to the average of a very large number and not to individual performance. All lamps deteriorate with continued burning in candle-power, efficiency and strength. This decay is partly due to the slow vaporization of the filament and partly to

growing light absorption in a black deposit on the inner side of the bulb. The frosting of bulbs, while not accelerating filament decay, hastens the decline o candle-power and efficiency due to the added absorption by the bulb deposit of internally reflected light and the greater tendency of the lamp to accumulate exterior dirt. The effect of bowl frosting is practically negligible. The life curves of Fig. 4 are typical of present-day lamps.

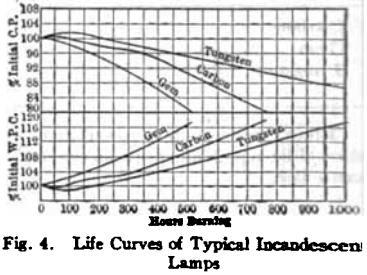


Fig. 4. Life Curves of Typical Incandescent Lamps

Effect of Frequency. — Incandescent lamps operated by alternating current of low frequency produce a flickering light due to cyclic variations of temperature. The flicker is greatest in filaments of small diameter and low thermal capacity, and increases in magnitude as the frequency is reduced. 110-volt carbon lamps of low efficiency have been successfully used with a frequency of 25 cycles. Tungsten street series lamps are satisfactory at 25 cycles. On account of the low heat capacity of slender filaments, 110-volt Mazda lamps of 25 watts or less and 220-volt lamps of 60 Watts or less, show perceptible flicker on 25 cycle circuits. Lamps made for higher amperage avoid this effect. See reference in *Bibliography* at the end of this article.

COST OF LIGHT BY INCANDESCENT LAMPS (Pre-war figures). — The main factors in the cost of light are the renewals of lamps and the cost of energy. Minor factors are the labor of inspection, the cost of renewals and the interest on investment in lamps and fixtures. The longer the lamp remains in service the less is the rewewal cost chargeable to each lumen-hour and the greater the energy cost. Operating the lamp at better efficiency increases the renewal cost and reduces the energy cost per lumen-hour; at poorer efficiency the reverse is true.

The most economical voltage at which to operate a lamp which is rated at a definite voltage V is RV, where R is a factor which is a function of the ratio of the cost of energy per kilowatt-hour to the cost of renewing the lamp. This factor R may be calculated from the following formula,

$$R = \sqrt[12.28]{0.000208\frac{EID_eL}{D_r}}$$

$$= 0.139\sqrt[12.28]{\frac{EID_eL}{D_r}}$$

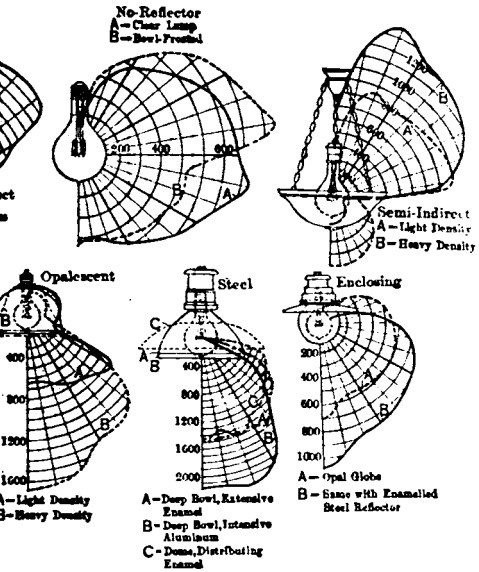
in which

E = watts per candle at rated voltage,
I = candle-power at rated voltage,
D_e = cost of energy per kilowatt-hour in dollars,
D_r = cost of lamp renewal in dollars,
L = life of lamp in hours at rated voltage.

DIFFUSERS FOR INCANDESCENT LAMPS. — Diffusers soften light and reduce its brilliancy by the increase in the area of its apparent source. This is at the expense of considerable absorption (*see table on Absorption of*

in article on Illumination, Laws of). The chief diffusing ass, produced by sand-blasting or acid etching; translucent s, such as alabaster, opaline, opal, milk, etc., which has in ely-divided mineral oxides; and prismatic glass. These rosted bulbs, globes and bowl reflectors partially covering sion from ground glass is inferior to that from other media, s partially visible as a bright spot in high contrast to the Opaline and alabaster transmit a subdued image of the fila- considerable portion of the light very effectively. Opal and diffusing, but may be highly absorbing if the glass is very lopments have enabled glass manufacturers to blow this ch is a combination that gives excellent diffusion with low tic globes transmit by refraction innumerable images of e filament distributed over the entire surface of the globe. y the diffusion is imperfect, but to averted vision the effect fracting prisms enable the light distribution to be modified erable range. Other diffusing globes tend to equalize light ions.

FOR INCANDESCENT LAMPS. — Reflectors serve light distribution and incidentally to shade the illuminant,



Distribution of Typical Reflector and Globe Equipments—500-watt (Mazda C) Lamps.
furnished by Illum. Eng. Laboratory, Schenectady.)

partially and to produce artistic effects. The chief reflect- shed metal, silvered glass, prismatic glass, opal glass, enam-

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elled metal and aluminum paint. Polished metals, silvered glass and prismatic glass afford a wide latitude in the distribution of light, depending on the contour and depth of the bowl. Diffusely-reflecting surfaces afford less range of control and are not capable of producing strong downward concentration. Prismatic and opal glass reflectors transmit a moderate amount of diffused light and afford some direct illumination for surfaces not receiving the directed beams from the unit. Practically all reflectors are designed for mounting at a definite position with reference to the luminous center of the filament and produce their normal distribution only in this position. The table below gives data on the mean performance of representative groups of reflectors for incandescent lamps.

The curves shown in Fig. 5 indicate the distribution of light from various forms of equipment when used with Mazda C lamps, according to G. H. Stickney

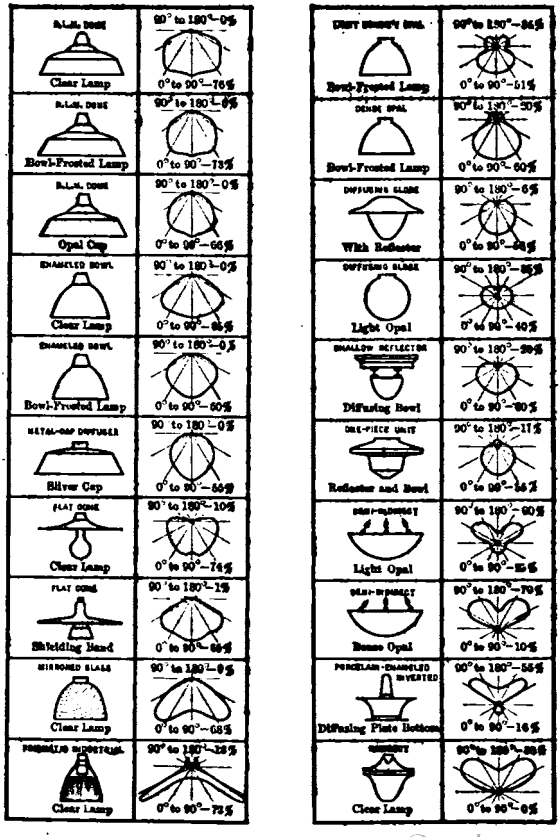


Fig. 6. Examples of Typical Incandescent Lighting Equipment.

In Fig. 6 are shown additional examples of typical incandescent lighting equipment.

MEAN PERFORMANCE OF TYPICAL GROUPS OF REFLECTORS FOR MAZDA B INCANDESCENT ELECTRIC LAMPS *

Item	Clear lamp	Industrial types, metal				Opalescent glass types				
		Flat dome enamel, 5 makes, 7 types	Radially fluted enamel, 2 makes, 2 types	Bowl enameled, 2 makes, 2 types	Bowl aluminized, 4 makes, 5 types	Blown bowl, 6 makes, 9 types	Pressed bowl, 8 makes, 16 types	Blown flared, 5 makes, 7 types	Pressed flared, 7 makes, 9 types	Prismatic bowl, 4 makes, 11 types
Mean lower hemispherical c-p.	70.7	104.0	92.6	81.1	75.5	72.3	73.0	88.3	85.7	80.6
Mean spherical c-p.	67.3	54.0	61.7	40.7	37.8	56.0	57.6	58.5	60.0	58.1
Per cent total flux absorbed	1	20	9	40	44	17	14	13	11	13
Lumens, 0°–60° zone	177	398	287	442	419	303	304	349	395	331
Lumens, 0°–90° zone	444	654	583	510	475	454	458	553	537	506
Total lumens	846	677	774	510	475	703	723	735	755	732

* Table adapted from data by A. L. Powell, *Gen. Elec. Review*, Vol. 15, p. 717.

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See also *Bibliography* in article on *Illumination, Interior.*

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LIGHTING PLANTS. — (*See also Distribution and Transmission Systems; Illumination, Interior; Illumination, Street; Lamps, Arc; Lamps, Incandescent; Power Stations; Substations.*) Electric lighting systems divide broadly into two classes, viz., series or constant-current, and parallel or constant-potential. The former system is appropriate where a large number of similar lamps in scattered locations are to be controlled simultaneously and where a high voltage can be safely applied to the circuit, as in street lighting. The parallel system is extremely flexible, is adapted only to low voltages and permits the independent control of single lamps and groups.

More recently there has been a tendency in street lighting to adopt a scheme possessing characteristics of both the series and the constant-potential systems. These combination systems have been termed "constant-potential series" systems by Dr. Steinmetz in their relation to street lighting distribution problems.

LOAD CONDITIONS. — The load of a lighting plant varies greatly with the season and with the hours of the day. There is usually a sharply-defined peak load in the early evening which reaches its annual maximum in midwinter. Storms attended by darkness often give rise to sudden and heavy increases of load. Such conditions demand generating equipment of great flexibility in operation. Sufficient generating capacity must be available to carry the maximum peak load and to provide an ample reserve against accidents. The brief duration of the peak load in many plants makes desirable the selection of types of equipment having large temporary overload capacity in order to decrease the reserve needed. Typical load curves are shown in Figs. 1 and 2.

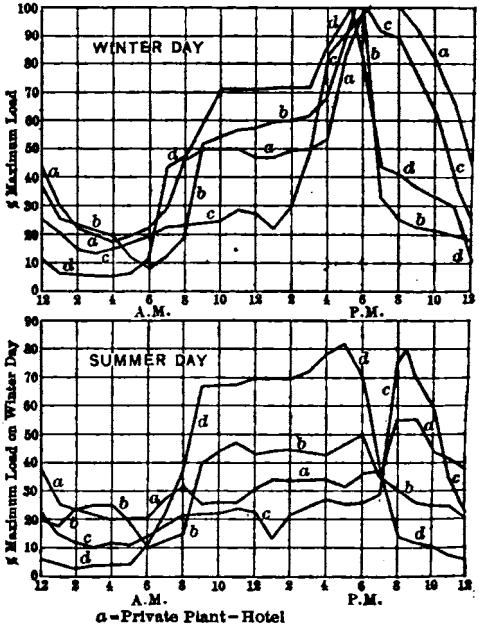


Fig. 1. Load Curves of Lighting Plants

Load Factor and Diversity Factor. — (*See also Standardisation Rules of the A.I.E.E.*) The *load factor* of a machine, plant or system is the ratio of the average power to the maximum power during a certain period of time. The *diversity factor* is the ratio of the sum of the maximum power demands of the subdivisions of any system or part of a system

to the maximum demand of the whole system or the part of the system under consideration, measured at the point of supply. The investment in a lighting system is largely determined by the peak load to be provided for. The annual charges on this investment are practically independent of the output; hence the investment expense per kilowatt-hour varies in nearly inverse ratio to the annual load factor. The average annual load factors of lighting installations, of various types, as given by E. W. Lloyd (*Nat. El. Lt. Assoc., 1909, Vol. 2, p. 586*) range from 5 to 29 per cent, with the general average of complete systems less than 20 per cent. The economic advantages of high load factor can be secured in lighting service only by combining it with loads having non-coincident peaks, as commercial power and railway systems. Fig. 2 shows typical load curves and load factors for a typical winter and a typical summer day of (*a*) a city system of lighting and power, (*b*) a city street and elevated railway system and (*c*) the combined load of (*a*) and (*b*). (*Trans. A.I.E.E., 1912, Vol. 31, p. 240.*) The advantage of the diversity factor of these loads is apparent.

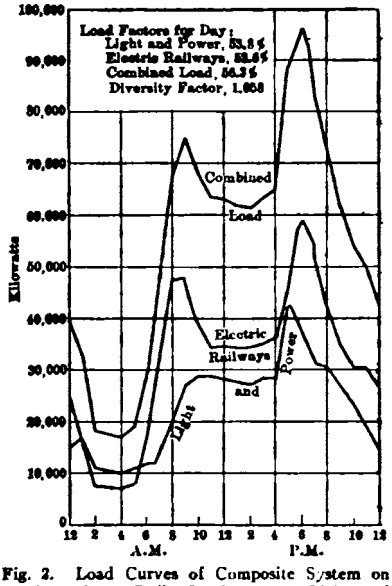


Fig. 2. Load Curves of Composite System on Winter Day. Daily Load Factor: Light and Power 53.8%, Electric Railways, 53.6%, Combined Load 56.3%, Diversity Factor, 1.058

In a general sense an appropriate scale of charges for electric energy should be graded according to the degree to which the load contributes to the system's peak as well as according to the energy consumed. Off-peak loads may appropriately receive low rates. The gain in load factor from diversity often makes it possible for a lighting station to sell energy at wholesale to a railroad system at a cost less than that at which the latter system could generate it independently.

Diversity factors exist between the various subdivisions of a lighting system and have an important influence on the rated capacity and investment required in the several elements of a system. H. B. Gear (*Trans. A.I.E.E., 1910, Vol. 29, p. 375*) reports the diversity factors of various classes of service and branches of the system of the Commonwealth Edison Company of Chicago to be:

DIVERSITY FACTORS OF A LIGHTING SYSTEM

Subdivision of the System	Residence lighting	Commercial power	Scattered power	Large users
Substation to feeders	1.15	1.15	1.15	1.15
Feeders to transformers	1.8	1.25	2.0	1.25
Transformers to meters	3.0	1.6	1.1	1.0
Total diversity factor	6.20	2.30	2.53	1.44

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Although these data are ten years old, they represent present conditions quite accurately. For a rediscussion of the question, see an article by H. B. Gear on "Increasing Demand Factor of Residence Consumers" on page 9 of the *Electrical World* for July 6, 1918.

DIRECT- VS. ALTERNATING-CURRENT SYSTEMS. — (*See also Distribution and Transmission Systems.*) Direct current has the following advantages for lighting: (1) safety, since the lines are in no way associated with high-voltage conductors; (2) freedom from power factor, reactance and skin effect, which results in superior voltage regulation in heavily loaded low-voltage circuits; (3) the direct availability of the storage battery as a reserve and a load regulator; (4) the self-exciting and self-regulating features of direct-current generators; (5) the superiority of direct-current motors for adjustable speed service and for the operation of elevators and cranes; and (6) the marked superiority of direct-current arc lamps. Direct current is generally used in isolated plants and in congested city districts because of the greater ease with which good voltage regulation is maintained.

The advantages of alternating current are chiefly those incidental to its flexibility of voltage transformation and control, which makes possible an extended range of economical transmission and the independent regulation of separate feeders and lines. Alternating-current generators are less expensive than direct-current machines, being free from commutator limitations and adaptable to much higher speeds.

Voltage. — The range of voltage from 100 to 125 is standard for electric lighting in America. In England and to some extent on the continent the 200- to 250-volt range has been extensively used. The higher range lends itself to more economical distribution of power, the lower range to the superior construction of incandescent and arc lamps. The Edison 3-wire system of distribution is largely used in direct-current systems. The voltage generated for alternating-current systems is usually the same as that used for primary distribution when the latter is below 15,000 volts, although steam turbo-alternators are often provided with raising compensators having a ratio of 1 to 2 when the line voltage supplied is in the range from 6000 to 15,000. In most systems of small and medium capacity the a-c. line voltage is 2300. The secondary distribution system is supplied by transformers and is usually at 110 to 115 volts between lines.

Small self-contained lighting outfits for train-lighting and similar service where a storage battery is used for regulating purposes are usually designed for a voltage range from 25 to 35 or from 50 to 65, and use lamps of the train-lighting and compensator types. See also *Lighting of Trains by Electricity.*

Phases. — The polyphase system affords distinct advantages in the first cost and voltage regulation of both generating equipment and lines. Primary distribution in all modern a-c. systems is either 2-phase or 3-phase, the latter predominating largely. Secondary distribution from transformers is either single-phase, 2-wire or 3-wire; 2-phase, 3-wire or 4-wire; or 3-phase, 3-wire or 4-wire. 6-phase connections are used only as a link between high voltage systemes and synchronous converters. See also *Converters, Synchronous; Transformers.*

Frequency. — The standard lighting frequency in America is 60 cycles, and that in Europe 50 cycles. A frequency of 25 cycles has many advantages for overhead transmission and for conversion to direct current by synchronous converters. Power transmitted at 25 cycles is frequently converted to 60 cycles for lighting purposes by the use of frequency changing motor generators. In a few cases where a large load of induction motors is associated with a lighting system the compromise frequency of 40 cycles is employed.

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rmance of electric lamps for interior lighting is not
n 25 cycles, due to flicker in the light, certain in-
ns have been operated with a fair degree of satisfaction
is obvious that a higher frequency for interior lighting is

. — (*See also Gas Engines; Steam Engines; Steam Tur-*
Prime movers for lighting plants should provide approxi-
without variation in angular velocity during each revo-
bine has a great advantage over the reciprocating engine
ue to its lower first cost and superior operating economy.
al advantages due to lighter foundations, smaller space
ion of fly-wheel, ease of attendance, and lower cost of
ton engine is preferred for the driving of direct-current
ts more appropriate speed.
engines surpass steam power in thermal efficiency, but
igher first cost and small range of overload capacity.
ver steam power may be large when the cost of coal is
ply of natural or by-product gas is available at low cost
or of the system is unusually good. Internal combustion
e successfully with steam units in plants furnishing both
rvice where a supply of exhaust steam has large value.
e involves a high investment and heavy maintenance
respects an excellent type of motive power where oil is a
an coal. Gas from a public source of supply and gasoline
ent in very small lighting plants to operate internal com-
are relatively expensive fuels, but may afford a saving
oducing plant on the premises. Gas-engines in lighting
lled by close-regulating governors and should be supplied
derable inertia.
ypes are well adapted to the driving of lighting generators
egulating governors.

s. — Steam prime movers are capable of carrying con-
ities of 50 per cent or more whereas gas engines and
mited in this respect. A large overload capacity enables
ler reserve equipment for emergencies. Current practice
cient boiler or gas producer capacity to carry the average
y and resort is had to forcing during peaks of short dura-
f a large number of modern stations of medium capacity
is provided for each kilowatt of generating capacity.

- (*See also separate articles on Generators.*) Direct-current
compound-wound and are operated at the voltage of the
A heavy direct current can usually be more economically
sion of alternating current than by direct generation.
onomic necessity when the direct-current load is more
from the station. Edison 3-wire systems may be sup-
generators in series, by special 3-wire generators or by
tors operated in conjunction with voltage balancing sets.
g-current generators are chosen for low cost and good
-speed alternators are usually provided with individual
me shaft, but large alternators are supplied with exciting
system comprising several exciters in parallel.
c. generators are now practically obsolete. Power for
nost economically obtained from constant-potential a-c.
ough constant-current transformers. Direct current for

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series circuits is obtained by operating the mercury arc rectifier in the secondary circuit of the constant-current transformer.

DISTRIBUTION. — (*See also Distribution and Transmission*) Distribution systems are designed with a view to the greatest possibl of service and the closest regulation of voltage consistent with reason ment. The 3-wire system is standard for local d-c. service. An int network of mains is used in extensive 3-wire systems and is fed at mar feeders from stations or substations. Alternating current is distribu volts or more, 3-phase, to transformers, from which secondary dis made to consumers by 2-wire and 3-wire systems. To obtain good v lation on polyphase systems it is necessary to maintain a close balan

SUBSTATIONS. — (*See also Substations, Lighting.*) Substatio for the following purposes: (*a*) to receive alternating current from h transmission lines or feeders and reduce it in voltage for local distri to convert alternating current from feeders into direct current for adjacent territory; (*c*) to convert alternating current received from 25 cycles to 60 cycles for distribution by local lighting circuits; (*d*) alternating current from constant potential sources to constant cur direct or alternating, for the supply of arc lighting circuits; (*e*) to ho batteries used as load regulators or reserves on d-c. systems; and (feeder regulators for the control of voltage on lighting circuits. Co direct current is accomplished either by motor-generator sets or by s converters. Motor-generator sets may be either of the synchron induction type and are usually operated without step-down tr Synchronous converters are usually 3-phase or 6-phase and are alway with voltage-lowering transformers. Converters may be of the spli the synchronous booster type or the compound type to provide aut trol of d-c. voltage, or may be operated in conjunction with voltag similar to those used on a-c. feeders.

Motor Generators versus Synchronous Converters. — (*See Generators; Converters, Synchronous.*) Motor-generator equipmer expensive and less efficient than converter equipment, but occupies affords more synchronous condenser capacity for power factor cor is more reliable in its operation, especially at an a-c. frequency o Synchronous converters are used almost exclusively for 25-cycle and are gaining in use at 60 cycles. Each converter is usually supp own bank of lowering transformers. Converters of larger capacity t are usually operated 6-phase. Converters supplying 3-wire d-c. s adjusted to give from 220 to 250 volts, d-c., and the neutral wire is d the neutral connection of the transformers.

Storage Batteries. — (*See also articles on Batteries, Storage.*) S teries are extensively used in stations and substations as a reserve failure of the primary source of direct current. It is difficult to oper tery as a load regulator on constant-voltage systems, especially by a f nection. A booster or end-cell arrangement is required to compen sloping volt-ampere characteristic. The substation battery commor the bus bars fully charged and assumes the load if the voltage of t falls a certain amount. The battery falls in voltage as its dischar and additional cells must be added in series to sustain the line voltage. cell switch for this purpose may be either hand-operated or automati matic, it is controlled by a relay switch operated by a solenoid conn the main bus bars.

* This comparison is on the basis of converter and transformers v generator set without transformers.

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QUIPMENT.—(*See also Switchgear Equipment for Power rotectors.*) As lighting systems are required to render prac- service the protective appliances are intended to discon- ircuits only in extreme emergencies and then only those in erators and exciters are not as a rule provided with auto- rs. Radial feeders and transmission lines have circuit with extreme overloads, often with inverse time elements mers operated in parallel at both ends are provided with open the circuit breakers at both ends in case of trouble, sturbance of other circuits.

ULATION.—Aside from the condition in which the ed and maintained, the quality of lighting service is almost ntinuity of service and close regulation of voltage. The require that the variation of voltage at the lamps shall at cent on either side of the mean. Service with less than 3.5 ay be considered fair and with more than 5 per cent de-

stems fairly constant voltage at the loads may be obtained tors properly over-compounded. A much more sensitive afforded by the Tirrill regulator (*see Regulators*), which s all but the most transient voltage fluctuations of the nous converters have fixed ratios of voltage conversion, to provide approximately constant voltage at load centers ove in the paragraph on *Substations*. A plan of voltage used in 3-wire networks is to provide in the station or sub- us bars differing somewhat in voltage. All feeders termi- es, by which they may be connected with either set of bus more heavily loaded feeders are connected to the higher he lower bus, with the result of nearly uniform volt- etwork of mains.

ge-control methods are employed in a-c. systems: (1) to by hand or by Tirrill regulators to constant voltage or to portion to the load; (2) to provide not only approximate rs but to equip each outgoing line with feeder regulators tion type, to be automatically controlled if desired, so that to supply approximately constant voltage at its center of tem is the more flexible and economical for extensive dis- ce each feeder is independently regulated and may be pro- tion with regard to economy rather than inherent voltage ase regulators are preferred for close control if the loads ncing.

e regulation at load centers voltmeters should be provided tions to indicate conditions at these centers. The volt- cted to the feeders at the distributing centers by small e feeders at the station through compensators which allow n the feeders. When a power load of low power factor is -c. lighting system, voltage regulation and economy in n be assisted by the use of the synchronous condenser to g current; see *Converters, Synchronous.*

.— Weingreen, J., *Electric Power Plant Engineering; louse Design;* Franklin, W. S., *Electric Lighting;* Crocker, g; Gear, H. B. and Williams, P. F., *Electric Distribution* rticles on this subject will be found in *Trans. A.I.E.E.* nd in the trade papers. See also *Bibliography* in articles

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LIGHTING OF TRAINS BY ELECTRICITY. — Electr
used almost exclusively by the railroads of the United States for th
trains.

At the present time there are over 20,000 cars lighted by electric
The gas cars are being converted to electricity as quickly as conditi

Systems Used. — The following systems are used for the purpo
lighting:

a. Axle Generator System.
b. Head End System.
c. Straight Storage System.

Axle Generator System. — This method of lighting is the m
The principal parts of the axle generator system are:

(1) *An axle generator* mounted either on the truck or under the c
driven by means of a belt from a pulley on the truck axle.

The generator is usually wound for 40 volts and delivers current t
lead storage battery through suitable regulating devices. The cap
generators vary from 1 kw. to 4 kw., depending upon the service re
A 1 kw. machine is found to be of sufficient capacity for a baggage ca
nary coach requires a 2 kw. machine while the additional load on a
often requires a generator of 4 kw. capacity.

(2) *A storage battery*, usually of 16 cells, of from 100 to 300 am
capacity.

The battery is installed in a suitable ventilated box hung under t
The amount of charge is regulated by an automatic device mou
panel board inside the car. When the car reaches a predetermin
automatic switch cuts in and connects the generator to the batter
matically disconnects the generator from the battery when the ca
below a predetermined limit.

(3) *A regulator panel* on which are mounted the apparatus cor
output of the generator and a lamp regulator which holds a constan
the lamps.

(4) *A drive* which consists of a belt connecting properly proportio
on the generator and on the car axle.

The development of a suitable shaft drive is at present occupyin
of axle generator manufacturers. This would obviate the use o
eliminate one of the sources of trouble especially in winter weather.

(5) *A suspension.* — The former general practice of suspendi
generator from the truck is being rapidly superseded by the body su
By mounting the generator under the car body a much lighter forn
sion can be used. The machine is also better protected from shock c
track, crossing switches, etc., than when mounted on the truck.

Head End System. — The so-called Head End Systems may be
three classes, viz.:

a. A Straight Generator System.
b. A Steam Generator Set with Batteries.
c. An Axle Driven Generator Set with Batteries.

(*a*) *The straight generator system* consists of a direct connected
usually installed in a baggage car next to the locomotive, steam bein
through a reducing valve at 90 pounds pressure. Current is furn
volts. A loop system of wiring is used in order to give uniform la
This system is applicable only when trains run solid between term

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of this system is that the train is without light as soon as onnected, or the set becomes inoperative.

tor set with storage batteries is used to good advantage on nd solid trains.

of the turbo generator type—80 volt and a capacity of

to have three or four cars in the train each equipped with hour battery. The batteries ensure the lighting of all times.

generator set with batteries has a generator mounted in riven by means of a chain drive through the car floor from

volts, 20 kw. capacity. The battery equipment and other as generally used in the axle generator system.

System. — This is the most simple method of lighting by

with one or two sets of 16 cell storage batteries suspended d arranged for convenient charging at terminal yards. es elaborate charging facilities at terminals where it is cars and either hold them long enough to give the battery or to have spare batteries fully charged to replace the dis-

stem appears inexpensive to operate. However, when the ration, together with fixed charges of the charging plant erhaps the most expensive method of lighting cars.

Considerable study has been given to car illumination ears. When cars were first lighted electrically no shades the glare of the lamp filament from the eye. Now great ect against objectionable glare and give as far as possible on the reading plane.

ing upon the style of fixtures employed, and their location e from 15 to 100 watts. The Mazda B type of lamp is used

ges in use are:

e and head end systems	60–64 volt
system	30–32 volt

reat improvements in the manufacture of lamps since the city for car lighting. The old type carbon filament operat- watts per candle power has been replaced by Mazda lamps nately 1 watt per candle power.

ordinary lighting three standard types of fixtures are semi-indirect, and indirect. Fixtures are in some case center deck while in other cases side deck mounting is

epartment of the U. S. Government after many exhaustive d specification for the lighting of railway mail cars. This he location of light units, limits for illuminating values, equirements, etc.

an operating standpoint the axle generator system is more ers. A car so equipped may be operated on any division ging facilities at the division terminal points or train line cars; it may also be cut out of one train at a junction

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point for connection to another train without special arrangements to supply light from an outside source.

COSTS. — The approximate first costs of the various sizes of ax equipments are shown below together with the approximate average costs. In this connection it should be noted that the costs given are (1921) figures and may be subject to considerable modification due in local and market conditions.

First Costs:

Type of car	Kw. rating of generator	First including
Baggage	1	$900
Coach	2	1200
Diner	4	1900

Maintenance Costs:

Type of car	Per 1000 miles	Per car pe
Average	$4.00–$5.00	$17.00

The above figures do not include interest or depreciation on in equipment or maintenance facilities.

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LIGHTNING PROTECTORS: GROUND WIRES, ARRESTERS, CHOKE COILS. — (*See also Distribution Lines; Ground Connections; Power Stations; Substations; Switch Gear Equipment for Power Stations; Transmission Lines.*) Abnormal rises of voltage in transmission and distribution circuits may be set up either by lightning discharges or by electrical oscillations caused by switching loads on and off the lines. The latter type of disturbances have been called "internal lightning." High-frequency oscillations are usually of small power and are generally called "statics." The term "surge" is used for any kind of oscillation.

A "ground wire" is a grounded wire which is run above and parallel to the main wires of an aërial line. A "lightning arrester" is any device shunted between wires or from wire to ground, which device under normal voltage permits practically no current to flow, but which becomes a fairly good conductor, usually by the formation of an arc, when the voltage rises a given amount above normal. A "choke coil" is a coil of wire of comparatively low resistance and small inductance, which is placed in series with the line. The coil has a very small impedance to normal line frequencies, but a high impedance to high-frequency oscillations.

GROUND WIRES. — A line completely inclosed in a grounded metallic sheath, as, for example, a lead-covered cable, is completely protected from induced electrostatic charges (*see Electricity and Magnetism, Principles of*). The ground wire used over aërial transmission lines acts as a partial screen and is one of the best means of protecting aërial lines against lightning. The protection is not perfect, however, since the wire forms only a partial screen.

Where systems operate with a thoroughly grounded neutral this neutral wire can form the overhead grounded conductor and the system becomes practically a three-phase four-wire system allowing the use of single-phase transformers of 58 per cent normal line voltage to be connected between any phase wire and the neutral. See articles on *Distribution Circuits; Transmission Lines.*

LIGHTNING ARRESTERS. — A lightning arrester consists essentially of a spark gap so set that excess voltage will cause the gap to arc over, allowing the charge due to this voltage to pass to ground. There is combined with the gap some means of suppressing the power arc which follows and which tends to continue after the abnormal voltage has ceased.

An ideal lightning arrester should take no current at the ordinary operating potential, but at any potential much higher than ordinary there should pass enough current to limit the abnormal potential to some fixed safe value. When the abnormal potential ceases the arrester should stop taking current from the line. The closer an arrester approaches these ideal conditions the better the arrester.

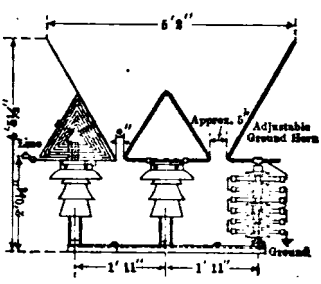


Fig. 1. Horn-gap Arrester

This arrester shown consists essentially of two horn gaps in series with a resistance to ground. One side of one of the horn gaps is made up into the form of a traingular choke coil and the sharp bend in this coil increases the tendency of the lightning to jump across the first air gap rather than to pass around the choke coil and thence to the apparatus to be protected. For 70,000 volt ser-

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vice there is an air gap of approximately two inches between the horn formed by the choke coil and the intermediate horn, and a further air gap of approximately five inches between the intermediate horn and the horn connecting through the resistors to the ground. For lower voltages the intermediate horn is omitted and the distance between the knees of the horn depends largely upon the voltage between line and ground, and has been based principally on actual test. It varies between about 1/16 inch to 9/32 inch for 2200 volts to about 6 1/2 to 10 inches for 110,000 volts.

The resistor in the ground circuit can be made either in the form of a resistance rod or in the form of a water resistor, the latter being the type usually employed in Europe. These water resistors usually are made of earthenware tubes containing a mixture of about 70 per cent glycerin and 30 per cent water, and the resistance is usually selected to allow approximately 1 ampere to flow to ground at the time of a lightning discharge.

The operation of the horn gap is based on the fact that a short-circuit once started at the base travels upward due to the heated gases and to the force exerted on the arc by the magnetic field of the current until the arc is ruptured by attenuation. On circuits of high voltage this rupture sometimes takes a second or two, but seems to act with but little disturbance of the line. The angle between the horizontal and the straight portion of the knee ranges from 55 to 60 degrees. The curvature of the knee should have a radius of from 3 to 5 inches.

Multipath Arresters have been developed for a-c. and d-c. service for voltages not exceeding 1000 by the use of a carborundum block fastened between two terminal plates, thus allowing the static discharge to spread itself over a number of minute discharge paths. The normal voltage between the line and the ground is divided into so many minute gaps that the voltage across each gap is too small to maintain an arc after the discharge has passed.

Nonarcing Arresters (Fig. 2) based on the discovery of "nonarcing metal" by Mr. A. J. Wurts, formed the first successful high-voltage arresters. The peculiar property of this metal is that an alternating current will not maintain an arc between adjacent cylinders of the metal provided the voltage is not too high and that the power current which follows the lightning discharge does not vaporize too much of the metal. The first condition is met by having a fairly large number of very small gaps in series, and the second condition gives no trouble where the amount of power current is comparatively small as was the case on the early high-voltage installations. For large amonuts of power it becomes necessary to use resistors in series with the spark gaps to limit the current, and these resistors reduce the effectiveness of the arresters. For very hight voltages different schemes are used to reduce the number of gaps required. It has been found that by shunting a certain number of these gaps by a non-inductive resistor the effectiveness of the arrester is increased.

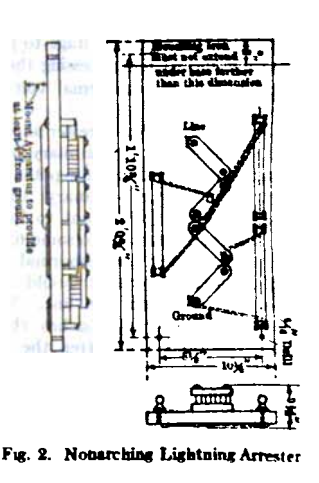


Fig. 2. Nonarching Lightning Arrester

Fig. 2 shows an arrester of this design intended for service on 6600-volt lines where the capacity does not exceed 2000 kv-a. The nonarcing cylinders are

in insulators in such a way that there is an air gap of
en adjacent cylinders in each one of the four sets of seven.
le slab forming the base of the arrester also has mounted
esistance rods shunting some of the gaps. Modifications
sed for the "low equivalent," "multigap," "multiphase"
gap" arresters that were installed before the electrolytic
t out and are still giving good satisfaction in many plants
s as high as 88,000 volts.

ters (Fig. 3) have been found after experimental research
nce of many years to be the best suited for high voltages
ctual service. See also *Power Stations, Hydroelectric.*

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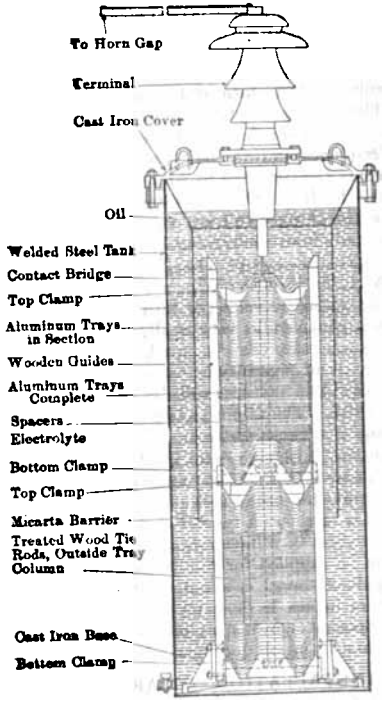


Fig. 3. Electrolytic Arrester

film on the trays it is necessary periodically to charge the
ne by closing the gaps and permitting current to flow into
gap is so arranged that it not only acts as a convenient
the arrester, but also serves as a disconnecting switch by
ps.
neral types of gaps in use, the horn or
horn or sphere gap when used at s

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diameter, discharge high frequency surges at values nearly the same cycle discharge value of a plain horn.

The most improved gap known to the art at this time is the imp This gap in addition to the advantages of the sphere gaps, selects the quency surges and discharges them at voltages of about 0.6 of the cycle discharge value of the gap. This property is obtained by an arrangement of resistors and condensers. In the commercial form densers take the form of line insulators.

Owing to the use of the liquid electrolyte, the necessity for periodi ing and the comparatively high price of the aluminum cell electrolyti other types of arrester such as the oxide film have been developed. film arrester depends for its functioning on the fact that certain dry compounds such as lead peroxide can be readily changed from a very ductor to an almost perfect nonconductor (litharge) by the application degree of heat, such as would be caused by the passage of a lightning d

CHOKE COILS (Fig. 4) are an important element in the protect cuits against static disturbances, in addition to the lightning arre The inductance of the choke coil acts as a reflector to high-frequency waves and prevents the potential to which the leads of the generator or transformer coil are subjected from undergoing excessive or abrupt changes. As at the operating frequency the value of volts per turn in a choke coil is very small, a surge may cause a spark to pass momentarily between turns but no arc will be formed. This is not usually true of a generator or transformer. Although extra insulation for the end turns of generators formers is desirable, it cannot entirely take the place of choke coils but permits the use of coils of a smaller choking power.

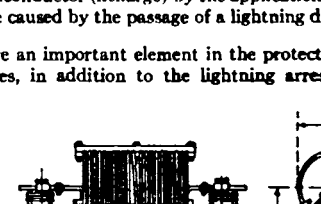


Fig. 4. Choke Coil

Fig. 4 shows a type of choke coil built in normal capacities up t peres and in voltage ratings up to 132,000 volts. Modifications of t can be supplied for heavier currents and for higher voltages. The made of copper or aluminum rod in the form of a cylinder 6 inche or 15 inches in diameter wound into about 20 turns. These are a supporing on insulators, or for suspension in the line circuits and are indoor or for outdoor service.

INSTALLATION OF ARRESTERS is dependent on their de electrolytic type is usually arranged for outdoor service, as is the type. The other types are usually mounted indoors and are connec cuit at the point where the lines pass from the building. Nearly a arresters can be furnished for outdoor service, if desired.

Ground Connection. — (*See also article on Ground Connections.*) most important features of a lightning-arrester installation is the se satisfactory ground connection to enable the static electricity to p into the earth. With a poor ground connection the value of lightnin Fig. 2 shows an arrester reduced. where the capacity doe

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A common method of securing a ground connection is to solder or rivet the ground wire to a large tinned copper plate which is buried in several layers of crushed coke or charcoal in permanently damp earth. Wrought-iron pipes driven deep into the moist earth will also make a good ground. In hydraulic plants the ground should include a connection to the penstock or some other portion of the piping system.

SPECIFICATION FOR LIGHTNING ARRESTERS. — (*See also article on Specifications.*) As the services to which lightning arresters are subjected are not capable of reproduction for testing purposes, lightning arresters cannot be specified in terms of performance. Hence it is necessary for the engineer to specify the type and essential features of construction after an examination of the various types. When calling for proposals, the following details should be stated: station or out-of-door service, voltage and frequency of circuit; details as to where arresters are to be located.

DIMENSIONS, WEIGHTS AND COSTS vary so much for the different voltages, class of service, whether grounded or ungrounded neutral, indoors or outdoors, that it is impossible to tabulate this information in the limited space available.

Lightning protection in a power house is almost independent of its capacity but depends on the voltage and number of feeders to be protected. A 200 ampere, 2300 volt, 3 phase feeder would require lightning protection costing about $12, while a 200 ampere, 110,000 volt feeder would require lightning protection costing about $5700.

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LOCOMOTIVES, ELECTRIC. — (*See also Cars, Electric; Collectors, Current; Locomotives, Steam; Railways, Energy Requirements and Motor Capacity for.*) For many years a new type of electric locomotive was designed for nearly every new proposition. However, with the very numerous applications of electric locomotives of from 30 to 50 tons weight for slow freight and switching service on interurban roads and in terminals, the double-truck bogie type finally demonstrated its superior fitness and came to be adopted almost universally in America for all work involving speeds less than 45 m.p.h. For higher speeds special provision must be made for guiding the locomotive around curves by the addition of guiding trucks or axles, for placing as much of the weight of the motors as possible on springs and for raising the center of gravity to a reasonable height (five feet or over). With a low center of gravity every sidewise movement of the mass of the locomotive strikes a blow side-wise on the track, but with a high center of gravity a side swaying is transformed into a downward thrust on the track. As the track is not usually designed to withstand great side thrusts it is better to avoid a low center of gravity in high-speed locomotives.

The coefficient of adhesion for electric locomotives has usual and safe values of from 18 to 22 per cent. It is higher for electric than for steam locomotives on account of the uniform torque of the electric motor. With clean dry rails the coefficient for electric locomotives may be as high as from 30 to 40 per cent.

CLASSIFICATION. — Locomotives are usually classified by the arrangement of their wheels and the subdivision of the wheels into driving wheels and guiding wheels. A series of numerals is used, each numeral representing a group of wheels of one form usually on one truck. Thus 4–4–0 designates a locomotive having four wheels on a guiding truck, four driving wheels connected and no trailing wheels or truck. This is the common "American" type of steam passenger locomotive. An ordinary double-truck four-motor freight locomotive or motor car would be designated as 4–0–4. (*See also Locomotives, Steam.*)

TYPES OF MOTORS.— Locomotives are built with various types of motors and operate from various systems of electrical distribution, e. g.,

a. Direct-current Motors at 600, 1200, 1500 or 2400 volts; for the higher voltages two motors are operated in series.

b. Single-phase Motors for 250 volts and 15 or 25 cycles, connected to the secondary of a transformer which receives its power from a 6000- or 11,000-volt trolley line.

c. Three-phase Induction Motors operating at about 500 volts supplied by the secondary of a transformer whose primary is connected to a 6000- or 11,000-volt three-phase trolley.

CONTROL SYSTEMS. — The control of all modern electric locomotives is by the multiple-unit system (q.v.), as the currents required are too large or the voltage too high for a drum control (q.v.). The possibility of one motorman operating and controlling two or three locomotive units at the same time is also advantageous.

TYPES OF ELECTRIC LOCOMOTIVES.— The simplest form of electric locomotive is a box car with a motor geared to each of the four axles on two bogie trucks. Such a locomotive would be geared for a very low speed and hence high tractive effort. To prevent slipping of the wheels the car would be weighted down with ballast or a load of freight.

The most common type of electric locomotive consists of a cab and framing carried on two heavy four-wheel trucks, each axle carrying a geared motor. Extra strength is provided in the cab framing to transmit the tractive effort of

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the motors to the couplers. The complete locomotive may weigh from 30 to 50 tons and is equipped with motors having an aggregate capacity of approximately 500 horse-power. It will haul trains of about 20 cars, weighing about 500 tons, at speeds from 20 to 30 miles per hour. The usual tractive effort at the one-hour rating of the motors is from 10,000 to 15,000 lb. Such locomotives are well adapted for switching purposes in terminal freight yards and for hauling freight trains on interurban electric railways.

Detroit River Tunnel Locomotives. — A further development of this type of locomotive is exemplified in the large locomotive used for pusher and grade service in the Detroit River Tunnel of the Michigan Central R.R. and other similar installations. Each of these locomotives weighs from 100 to 120 tons, all on drivers, and consists of two four-wheel trucks carrying geared motors of from 300 to 500 horse-power each. The two trucks are coupled together by a pin or hinge which causes them to guide each other. This is called the "Articulated" type. The cab, containing all the control and auxiliary apparatus, is mounted on the trucks. The Detroit River Tunnel locomotives operate on 600 volts d-c. Locomotives of this type are now in operation also on 2400 volts d-c. and on 6000 volts three-phase a-c. They are limited in speed to about 40 miles per hr. on account of their lack of guiding trucks.

New York Central R.R. Locomotives. — The locomotives constructed in 1910 have a leading and a trailing two-axle guiding truck and in the middle four driving axles with gearless motors. The armature of each motor is mounted directly on the driving axle and the bi-polar field of the motor forms a part of the mechanical frame work of the locomotive. The magnetic flux passes through all four motors in series and returns by the side frames. The motors are wound for 600 volts d-c. and have very large air gaps to allow for the play between the armature and the field as the wheels pass over irregularities in the tracks. The field structure is spring borne but the armatures are not.

The locomotives constructed in 1913 consist of two sections articulated, with two two-axle trucks on each section. One truck on each section is rigid and the other is a bogie or guiding truck. Every axle carries a motor and all wheels are of the same size. The single cab is carried on a king pin on each section.

New Haven R.R. Locomotives. — The type of electric locomotive adopted by the N. Y., N. H., & H. R.R. in 1911 has four gearless single-phase series motors, the armatures being mounted on quills concentric with the driving axles and driving the wheels by means of springs. The locomotive has two trucks, each having four large driving wheels and two smaller guiding wheels. The motors are designed to operate at from 250 to 300 volts either a-c. or d-c., two in series on the line for d-c. and on the secondary of a transformer for a-c. The line voltage is 11,000 at 25 cycles.

Pennsylvania R.R. Locomotives. — The locomotives of the Pennsylvania R.R. consist of two similar units coupled back to back. Each unit has a two-axle guiding truck and has two driving axles rigid with the body frame. There is one large motor per unit, mounted in the cab and driving the wheels by means of an inclined connecting rod from the motor to a jack shaft and horizontal side rods from the jack shaft to the drivers. The connecting rods on opposite sides are placed at right angles to avoid dead centers.

Chicago, Milwaukee & St. Paul Locomotives. — The freight locomotives delivered in 1916 (see table) consist of two similar units coupled together, each unit having a leading bogie truck of idle axles for guiding, and two four-wheel trucks with all axles driving. A motor is geared to each of the four driving axles of each unit. The motors are designed to operate with 1500 volts d-c. and two motors are permanently connected in series for 3000 volts, the line

LOCOMOTIVES, ELECTRIC

	Bush Terminal Steel Switcher	Piedmont	Detroit River Tunnel	Great Northern	Pennsylvania Terminal	St. Paul	Norfolk and Western	N. Y. Central	New Haven	New Haven	St. Paul	St. Paul
Date		1911	1909	1908	1910	1916	1914	1918	1919	1919	1920	1920
System	D-C.	D-C.	D-C.	3-phase	D-C.	D-C.	A-C.	D-C.	A-C.	A-C.	D-C.	D-C.
Trolley voltage	500	1,500	600	6,000	600	3,000	11,000	600	11,000	11,000	3,000	3,000
Service	Frt.	Frt.	Frt. and Pass.	Frt. and Pass.	Pass.	Frt. and Pass.	Frt.	Pass.	Pass.	Frt.	Pass.	Pass.
Total weight, tons	40	55	100	115	166	284	264	134	173	141	265	275
Number of motors	4	4	4	4	2	8	8	8	12	4	12	6
Horse-power per motor *	90	185	275	375	1,250	452	410	325	170	345	270	700
Weight of electrical equipment, tons	14	19	27	55	64	124	112	44	81	.....	117	100
Weight on drivers, tons	40	55	100	115	104	225	224	134	115	97	229	168
Diameter of drivers, inches	36	37	48	60	72	52	62	36	63	54	44	68
Rigid wheel-base, ft., ins.	6′–6″	7′–4″	9′–6″	11′	8′	10′–6″	11′–6″	5′	16′–9″	10′	13′–11″	16′–9″
Total wheel-base, ft., ins.	22′	25′	27′–6″	31′–9″	55′–11″	102′–8″	43′	46′–5″	59′–0″	54′	67′	79′–10″
Tractive effort, hour, lbs.	17,000	13,700	35,000	38,000	25,000	132,000	87,400	20,000	21,000	27,000	46,000	66,000
Speed per same, mile per hr.	8	20	12	15	32	10.2	14	49	36	23	26.4	22.7
Classification	404	0440	0440	0440	4444	444+ 444	2442	4444	262+ 262	4444	6886	462+ 264

* One hour rating.

potential. Special arrangements are provided for regenerative braking on downgrades by using the main motors as separately excited generators. The passenger locomotives of that date are similar except as to gear ratio. In 1920 two new types of passenger locomotives were installed, one using gearless motors like the New York Central and the other using twin motors geared to each driving axle (see *Bibliography*).

SPECIFICATION FOR ELECTRIC LOCOMOTIVE. — The following memoranda are intended to assist in writing specifications. See also article on *Specifications*.

On important high-speed systems it is usual for the design of the locomotive to be worked out by the purchaser and manufacturer working in collaboration, and in such cases, the design is usually specified in detail. In other cases, it is more usual to specify the operating characteristics and leave the design to the manufacturer. The following memoranda are to assist in the preparation of a specification of the latter type.

General Description of Service. — Whether for direct- or alternating-current, single-phase or three-phase, freight or passenger hauling, overhead trolley or third rail. Line voltage, etc.

Specific Details of Work to be Performed by Locomotive. — Weight of cars loaded and empty. Maximum train weight. Average train weight. Time to make typical run of stated length. Number and duration of stops in typical run. Ton miles per day per locomotive. Maximum speed on level with average load. Maximum speed on maximum grade with maximum load. Acceleration (miles per hour per second), with maximum load. Hours per day in regular service. Amount of time in shifting and yard service.

Profile and Plan of Line. — Grades and curves.

Clearances and Limiting Dimensions.—Gauge of track, clearance diagram of right-of-way. Maximum and minimum height of trolley wire or third-rail location. Height of coupler. Wheels, tread and flange (M.C.B. or special). Weight of rail. Minimum radius of curve. Wheel diameter. Maximum permissible weight per running foot of right-of-way.

Operating Characteristics. — Absence of nosing or lateral swing. Absence of rail pounding. Temperature-rise limitations. Efficiency.

Control. — See specifications under *Control Systems for Railway Motors*.

Motors. — See specifications in articles on *Motors*.

Air Brake. — Straight, automatic or combined. General characteristics.

COST, WEIGHT AND DIMENSIONS. — Electric locomotives cost about $800 per ton weight, which is considerably more than steam locomotives, but they are cheaper to operate and maintain as they can make more mileage per day. It costs, roughly, between 5 and 10 cents per locomotive mile to operate electric locomotives.

The characteristics of the most prominent types of electric locomotives are given in the table, page 938.

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LOCOMOTIVES, STEAM. — (*See also Locomotives, Electric; Railways, Energy Requirements and Motor Capacity for.*) Locomotives are classified broadly by the number of truck and driving wheels. Each arrangement of wheels has a definite name, but the various wheel arrangements are so numerous that the "Whyte classification" has come into extensive use.

Whyte Classification. — According to this scheme of classification three numbers are used; the first indicates the total number of leading or truck wheels in front of the drivers, the second indicates the total number of drivers, and the third indicates the total number of wheels behind the drivers and under the locomotive proper. Tender wheels are not included. This classification may be extended, by the use of more than three numbers, to cover engines of the articulated, or Mallet, type. The classification and names of some of the more important types are given in the table on the next page, the weights being in short tons. The tabular values are for comparatively recent engines of the largest size. Each type of engine has been made in a wide variety of sizes, ranging mainly downwards from the given weights to approximately half these values for standard gauge track, and much lower for narrow gauge or industrial tracks. The weight of the tender loaded ranges approximately from 60 to 100 per cent of the weight of the engine.

DESIGN AND PERFORMANCE. — A steam locomotive is essentially a moving power plant and as such it must transport its fuel and water with it. Its limitations as to size and weight are determined by roadway clearances, the curves upon which it must run, and the strength of the track supporting it.

Locomotive engines may be either simple or compound, but compound locomotives are not as extensively used now as formerly, except in the case of the articulated types.

The load upon a driving axle is generally limited to 30 tons, but this weight has been exceeded in a number of recent engines of large size.

Maximum Power. — The limit of power of a steam locomotive is measured by the size and steam-producing capacity of its boiler (*see Boilers*). Owing to the necessarily small grate area, coal must be burned very rapidly under an induced draft. The rate of combustion is quite commonly as high as 100 pounds and sometimes exceeds 200 pounds per square foot of grate area per hour. The use of brick arches and superheaters largely increases the power, adding from 30 to 40 per cent in some cases. On account of difficulties of lubrication, wear of valves, etc., piston valves must be used with superheaters. The use of superheaters is practically universal in modern high-powered engines.

The maximum horse-power which can be exerted by a steam locomotive is in some cases 4000, although this is unusual; from 2000 to 2500 is a fairer maximum figure for ordinary cases. The largest tenders have a capacity of 20,000 gallons of water and 20 tons of coal.

Tractive Effort. — The tractive effort of a single-expansion steam locomotive at slow speed is computed from the following formula:

$$\text{Tractive effort} = \frac{P \times D^2 \times S}{d},$$

where P = mean effective pressure in cylinders, in lbs. per sq. in. (usually taken as 0.85 of boiler pressure),

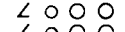
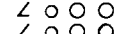
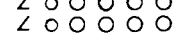
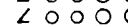
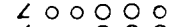
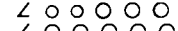
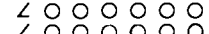
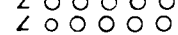
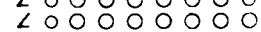
D = diameter of the piston, in inches,

S = stroke, in inches,

d = diameter of driving wheels, in inches.

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CLASSIFICATION OF STEAM LOCOMOTIVES

Type	Wheel arrangement	Name	Total wheels	Kind of service	Approximate weights, tons, engine only	Load on drivers, tons per axle
0-4-0		4-wheel switcher	4	Switching	50	25.0
0-6-0		6-wheel switcher	6	Switching	83	27.7
0-8-0		8-wheel switcher	8	Switching	107	26.8
2-6-0		Mogul	8	Freight	100	28.0
2-8-0		Consolidation	10	Freight	148	33.5
2-6-2		Prairie	10	Freight	124	29.2
2-8-2		Mikado	12	Freight	163	30.0
2-10-2		Santa Fe	14	Freight	209	33.7
4-4-0		American	8	Passenger	87	30.1
4-6-0		10 wheel	10	Passenger and freight	109	28.3
4-8-0		12 wheel	12	Freight	131	26.4
4-4-2		Atlantic	10	Passenger	120	34.3
4-6-2		Pacific	12	Passenger and freight	156	34.1
4-8-2		Mountain	14	Passenger and freight	184	30.4
0-6-6-0		Articulated	12	Freight	176	29.3
0-8-8-0		Articulated	16	Freight	240	30.0
2-6-6-2		Articulated	16	Freight	224	29.8
2-8-8-2		Articulated	20	Freight	280	31.2

Tonnage Rating. — By the tonnage rating of a locomotive is commonly meant the weight, in tons, of the train which it can pull, exclusive of the weight of the locomotive, but including the weight of the tender. Short tons (2000 lb.) are used. Let:

F = maximum tractive effort, usually taken as the tractive effort corresponding to a mean effective pressure equal to 0.85 of boiler pressure,
G = maximum grade, per cent.
L = weight of locomotive, in tons,
R = locomotive resistance, lbs. per ton,
r = train resistance, lbs. per ton,
T = "tonnage rating," i.e., weight behind locomotive.

Then

$$T = \frac{F - (R + 20\,G)\,L}{r + 20\,G}.$$

See article on *Railways, Energy Requirements and Motor Capacity for*, for values of r and R. On heavy grades this value of the tonnage rating will be limited by the ability of the fireman to keep up full steam pressure. This difficulty has been very satisfactorily overcome in recent years by equipping the engines with mechanical stokers.

Empty or partially loaded cars have a larger resistance per ton than fully loaded cars. With all empty cars on a straight track the capacity of an engine may be reduced as much as 47 per cent on a level stretch, 15 per cent on a 1 per cent grade, and 8.6 per cent on a 2 per cent grade. The corresponding figures with half loading would be 18, 4, and 2.3 per cent.

According to an extended series of experiments reported in a paper read before the American Society of Civil Engineers in December, 1902, by Mr. A. C. Dennis, freight train resistance is practically constant between 7 and 35 miles per hour, and may be regarded as made up of two parts—the dead load tonnage (cars) multiplied by the normal grade and curve resistance in pounds per ton plus 8.9, and the live load tonnage (freight) multiplied by the normal grade and curve resistance in pounds per ton plus 2.6, for any degree of loading. This is equivalent to regarding one ton of dead load as having a greater resistance than one ton of live load, with a variable ratio depending on grade and curvature. It is often convenient to consider the combined value of the live load and the product of the dead load by this ratio. This result is known as the tonnage rating of the train, with the understanding that a rating ton is a live load ton or its equivalent in the above sense.

The tonnage rating of a locomotive when used in connection with the above method of computation means its capacity in rating tons under the proposed conditions, a quantity which changes with grade and curvature, but remains constant under any condition of loading. The locomotive and tender are considered as dead load tonnage in computing their tractive resistance.

Reduction of Tonnage Rating in Stormy Weather. — Weather conditions also affect the steam locomotive's capacity. The worst condition is cold weather with a heavy wind at right angles to the track. This side wind always makes engines steam badly and increases flange friction against the rails. It is a common cause of delays.

Tonnage ratings are reduced a variable amount under severe weather conditions. Some roads have fixed rules and some have not. The maximum reduction, taken from a table published in Bulletin No. 59 of the University of Illinois Engineering Experiment Station, is 30 per cent for temperatures around 15 degrees below zero. On lines having heavy grades the grade resistance is

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such a large proportion of the total work to be done that the train resistance becomes a very small factor. Consequently the tonnage ratings for roads having very heavy grades are practically the same for all seasons and weather conditions.

Unbalanced Forces. — The necessity of partially balancing the heavy reciprocating parts by weights located on the wheels produces unbalanced vertical forces which are hard on roadbed and bridges.

Center of Gravity and Stability. — The boiler is necessarily placed almost wholly above the wheels and the center of gravity of the whole engine is therefore a considerable distance above the rails. Careful tests have shown this to be a positive advantage so far as ease of maintenance of track is concerned. By proper elevation of outer rails on curves, the overturning tendency of the centrifugal force may be wholly or sufficiently neutralized. This overturning tendency is much less than most engineers suppose. It is safe to state that it is impossible to *overturn* a locomotive at any practicable speed upon any ordinary curve by the action of centrifugal force unless the conditions are such (as in a cross-over, for instance) as to set up a rolling or oscillatory motion of the engine about its longitudinal axis. Generally speaking, the tender is the part of the train most likely to leave the rails. This is due to its varying and shifting load of coal and water.

Typical Large Locomotives. — The locomotives listed on the following page are typical of modern locomotive development. The information for the first three engines was kindly furnished by the Baldwin Locomotive Works, and for the last two was obtained from Bulletin No. 7 of the Locomotive Superheater Company. The first two engines were built by the Baldwin Company, the Pacific type for the Lehigh Valley Railroad, and the Mountain type for the A. T. and S. F. Railway. The Consolidation engine is now under construction by the Baldwin Company for the Western Maryland Railway, and is a very large engine for this type. The fourth engine is the heavy Mikado and the fifth the heavy Santa Fe of the United States Railroad Administration Standard Locomotives. All five engines are equipped with superheaters, piston valves and Walschaert valve gear. The first engine burns a mixture of hard and soft coal while the remaining four are soft coal burners. In computing the tractive effort of these engines the mean effective pressure is taken as 0.85 of boiler pressure. The total effective heating surface is taken as the total boiler heating surface plus 1.5 times the superheater heating surface.

OPERATION OF STEAM LOCOMOTIVES. — Below are given some of the more important facts in regard to steam locomotive operation.

Location of Coal and Water Stations. — Coal and water stations for replenishing the tender are required at intervals, depending upon the topography of the line and volume of traffic. On fairly level roads coaling stations are required at intervals of 50 or 60 miles for freight engines and 120 miles for passenger engines. Water stations are needed at about 50-mile intervals for passenger and 25-mile intervals for freight service. These distances may be much reduced on heavy grades. The location of water stations is also a matter of available water supply. Where possible water should be taken at regular stops.

Fuel and Water Consumption. — This is very variable depending upon topography and alignment of road, kind of service, frequency of stops, whether single or double track, climatic conditions, weight of trains, etc. The number of pounds of coal burned per locomotive mile averages about 104 for passenger, 208 for freight, 130 for mixed, 108 for switching and 150 for all types of service. The actual water evaporated varies from 4.5 to 6.5 lbs. per pound of coal burned. The first figure is for a coal consumption of 200 lbs. and the last for 65 lbs. per sq. ft. of grate per hour.

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TYPICAL STEAM LOCOMOTIVES

Item	Pacific (4 6 2)	Mountain (4 8 2)	Consolidation (2-8-0)	Mikado (2 8 2)	Santa Fe (2-10-2)
Service	Passenger	Passenger	Freight	Freight	Freight
Weight, engine and tender, working order, lbs.	469,100	610,100	526,000	497,000	586,100
Weight, engine only, working order, lbs.	311,900	367,700	296,000	325,000	380,000
Total weight on drivers, lbs.	204,560	243,100	268,000	240,000	293,000
Total tractive effort, lbs.	48,722	54,085	68,262	59,801	73,829
Weight on drivers ÷ tractive effort	4.20	4.49	3.93	4.01	3.97
Diameter of driving wheels	73"	69"	61"	63"	63"
Length of driving wheel base	13′ 8"	18′ 0"	17′ 6"	16′ 9"	22′ 4"
Total wheel base of engine	36′ 0"	39′ 5"	27′ 3"	36′ 1"	42′ 2"
Total wheel base of engine and tender	68′ 0⅛"	76′ 8⅛"	74′ 1⅛"	71′ 9½"	82′ 10½"
Size of cylinders	27" × 28"	28" × 28"	27" × 32"	27" × 32"	30" × 32"
Type of boiler	Conical wagon top	Conical wagon top	Straight top	Conical wagon top	Conical wagon top
Working pressure of boiler, lbs. per sq. in.	205	200	210	190	190
Diameter of boiler	83¾"	82"	88"	86"	88"
Size of firebox	120⅜" × 114¼"	122¼" × 84¼"	112" × 96¼"	120⅛" × 84¼"	132⅛" × 96¼"
Grate area, sq. ft.	95.2	71.5	74.9	70.8	88.2
Number of tubes	45-254	43-254	50-240	45-247	50-271
Diameters of tubes	5½"-2¼"	5½"-2¼"	5½"-2¼"	5½"-2¼"	5½"-2¼"
Heating surface of tubes, sq. ft.	3,734	4,428	3,242	3,978	4,727
Heating surface of firebox, sq. ft.	244	246	237	319	429
Minor heating surfaces, sq. ft.	138	128	30		
Total heating surface of boiler, sq. ft.	4,116	4,802	3,509	4,297	5,156
Heating surface of superheater, sq. ft.	980	1,086	870	993	1,230

ne United States oil is used for fuel on account of the results in a greater expense for upkeep of boilers on heat, but in the far west and southwest is economical

Kinds of Coal. — Exhaust nozzles and draft appliances any one of various kinds of coal, and arrangements should e kind of coal for which the engine is "drafted," as other less efficiency and consequently at what is probably a ough the cost per ton of the improper coal is less.

Whenever a locomotive is standing idle under steam, coal his idle time should be reduced to a minimum by avoid- while before an engine is needed, and by keeping trains on the road. Roads having traffic largely of one kind can his particular than those having a mixed traffic composed nds.

e friction in a locomotive is large, ranging from about 20 ower of the engine to a maximum of 50 per cent or more ns of passenger service. Probably 35 per cent is a fair ses an appreciable economy can be instituted by increasing llowed for an engine. Most motive power officials are respect. Generally oil consumption is kept at a minimum, urned to overcome the resulting friction. The proper ge the ratio of oil to coal that the total expense for the two

ilers must be blown off and washed out at intervals depend- f water used.

figures). — The first cost of a steam locomotive is from 6 f weight, including tender.

The cost of maintenence and repairs ranges from $2000 ve per year, an average figure being $2600.

a locomotive is about 20 years; hence in addition to the nd repairs an annual depreciation of 5 per cent of the first l against the locomotive. In addition, an interest charge he first cost should be included.

s are as follows, the figures being for ordinary mixed ser- ith moderate grades:

	10.6 cents per loco.-mile
per ton,	18.9 cents per loco.-mile
	0.3 cent per loco.-mile
	0.5 cent per loco.-mile
	11.3 cents per loco.-mile
cost,	41.6 cents per loco.-mile

f operation of a locomotive, including wages of conductor $50 per day, on the basis of 100 miles being a day's work. ost of a locomotive costing initially $20,000 and covering es per day would then be roughly:

	$10,000
repairs	2,600
	1,000
	1,000
	$14,600

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LOGARITHMS. — The logarithm of a number A, to a given base b, is the power n to which that base b must be raised in order to equal the number A. Thus, if $b^n = A$, then n is the logarithm of A to the base b, which may be written $n = \log_b A$. From this definition the following properties are readily deduced, where A and B are any two numbers.

$$\log AB = \log A + \log B.$$

$$\log \frac{A}{B} = \log A - \log B.$$

$$\log A^n = n \log A.$$

Characteristic and Mantissa. — These three equations hold irrespective of what is chosen as the base of the logarithms, provided the same base is used for each logarithm. In the common or Brigg's system of logarithms the number 10 is chosen as the base. In such a system the logarithm of any number may be expressed directly in terms of the logarithm of a number (including decimal fractions as numbers) between 1 and 10. For example:

$$\log_{10} 376.42 = \log (100 \times 3.7642)$$
$$= \log 100 + \log 3.7642$$
$$= 2 + \log 3.7642,$$

since the power to which 10 must be raised to give 100 is 2. Similarly, $\log_{10} 3764.2 = 3 + \log 3.7642$. The logarithms of all numbers between 1 and 10 are less than unity. The whole number or integer part of a logarithm is called its "characteristic" and the fractional part its "mantissa." The characteristic of the logarithm of a number less than unity is negative. For example:

$$\log 0.037642 = \log (\tfrac{1}{100} \times 3.7642)$$
$$= \log 1 - \log 100 + \log 3.7642$$
$$= -2 + \log 3.7642.$$

In general, *the characteristic of a number greater than unity is positive and is one less than the number of figures to the left of the decimal, while the characteristic of a number less than unity is negative and is one greater than the number of ciphers between the decimal and the first significant figure.* A table of logarithms gives the mantissas only, the characteristics being determined by the above rule. Such a table is given below.

Antilogarithms. — If $n = \log A$, then A is the number whose logarithm is n. This may be written symbolically

$$A = \log^{-1} n.$$

A is then called the antilogarithm or inverse logarithm of n. The antilogarithm of a number (i.e., the number which has the given number for its logarithm) is found from a table of logarithms by finding the number in the margin corresponding to the decimal point of the given number in the table, and fixing the decimal point by the rule given above. Example:

$$\log^{-1} 1.6464 = 44.3.$$

Use of Logarithms. — Logarithms are used in the processes of multiplication, division, raising to powers and taking roots. For example, to find the product of two numbers take from the table the logarithms of the two numbers,

COMMON LOGARITHMS OF NUMBERS

No.	0	1	2	3	4	5	6	7
10	00000	00432	00860	01283	01703	02119	02531	02938
11	04139	04532	04922	05308	05690	06070	06446	06819
12	07918	08279	08636	08991	09342	09691	10037	10380
13	11394	11727	12057	12385	12710	13033	13354	13672
14	14613	14921	15229	15534	15836	16137	16435	16732
15	17609	17897	18184	18469	18752	19033	19312	19590
16	20412	20683	20952	21218	21484	21748	22010	22271
17	23045	23299	23552	23804	24054	24303	24551	24797
18	25527	25767	26007	26245	26481	26717	26951	27184
19	27875	28103	28330	28555	28780	29003	29225	29446
20	30103	30319	30535	30749	30963	31175	31386	31597
21	32222	32428	32633	32838	33041	33243	33445	33646
22	34242	34439	34635	34830	35024	35218	35410	35602
23	36173	36361	36548	36735	36921	37106	37291	37474
24	38021	38201	38381	38560	38739	38916	39093	39269
25	39794	39967	40140	40312	40483	40654	40824	40993
26	41497	41664	41830	41995	42160	42324	42488	42651
27	43136	43296	43456	43616	43775	43933	44090	44248
28	44716	44870	45024	45178	45331	45484	45636	45788
29	46240	46389	46538	46686	46834	46982	47129	47275
30	47712	47856	48000	48144	48287	48430	48572	48713
31	49136	49276	49415	49554	49693	49831	49968	50105
32	50515	50650	50785	50920	51054	51188	51321	51454
33	51851	51982	52113	52244	52374	52504	52633	52763
34	53148	53275	53402	53529	53655	53781	53907	54033
35	54407	54530	54654	54777	54900	55022	55145	55266
36	55630	55750	55870	55990	56110	56229	56348	56466
37	56820	56937	57054	57170	57287	57403	57518	57634
38	57978	58092	58206	58319	58433	58546	58658	58771
39	59106	59217	59328	59439	59549	59659	59769	59879
40	60206	60314	60422	60530	60638	60745	60852	60959
41	61278	61384	61489	61595	61700	61804	61909	62013
42	62325	62428	62531	62634	62736	62838	62941	63042
43	63347	63447	63548	63648	63749	63848	63948	64048
44	64345	64443	64542	64640	64738	64836	64933	65030
45	65321	65417	65513	65609	65705	65801	65896	65991
46	66276	66370	66464	66558	66651	66745	66838	66931
47	67210	67302	67394	67486	67577	67669	67760	67851
48	68124	68214	68304	68394	68484	68574	68663	68752
49	69020	69108	69196	69284	69372	69460	69548	69635
50	69897	69983	70070	70156	70243	70329	70415	70500
51	70757	70842	70927	71011	71096	71180	71265	71349
52	71600	71683	71767	71850	71933	72015	72098	72181
53	72428	72509	72591	72672	72754	72835	72916	72997
54	73239	73319	73399	73480	73559	73639	73719	73798

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COMMON LOGARITHMS OF NUMBERS

	2	3	4	5	6	7	8	9
15	74193	74272	74351	74429	74507	74585	74663	74741
96	74973	75050	75127	75204	75281	75358	75434	75511
63	75739	75815	75891	75966	76042	76117	76192	76267
17	76492	76566	76641	76715	76789	76863	76937	77011
58	77232	77305	77378	77451	77524	77597	77670	77742
87	77959	78031*	78103	78175	78247	78318	78390	78461
04	78675	78746	78816	78887	78958	79028	79098	79169
09	79379	79448	79518	79588	79657	79726	79796	79865
02	80071	80140	80208	80277	80345	80413	80482	80550
85	80753	80821	80888	80956	81023	81090	81157	81224
58	81424	81491	81557	81624	81690	81756	81822	81888
20	82085	82151	82216	82282	82347	82412	82477	82542
72	82736	82801	82866	82930	82994	83058	83123	83187
14	83378	83442	83505	83569	83632	83695	83758	83821
17	84010	84073	84136	84198	84260	84323	84385	84447
71	84633	84695	84757	84818	84880	84941	85003	85064
87	85248	85309	85369	85430	85491	85551	85612	85672
93	85853	85913	85973	86033	86093	86153	86213	86272
91	86451	86510	86569	86628	86687	86746	86805	86864
31	87040	87098	87157	87215	87273	87332	87390	87448
64	87621	87679	87737	87794	87852	87909	87966	88024
38	88195	88252	88309	88366	88422	88479	88536	88592
05	88761	88818	88874	88930	88986	89042	89098	89153
05	89320	89376	89431	89487	89542	89597	89652	89707
57	89872	89927	89982	90036	90091	90145	90200	90254
03	90417	90471	90525	90579	90633	90687	90741	90794
02	90955	91009	91062	91115	91169	91222	91275	91328
34	91487	91540	91592	91645	91698	91750	91803	91855
00	92012	92064	92116	92168	92220	92272	92324	92376
99	92531	92582	92634	92685	92737	92788	92839	92890
33	93044	93095	93146	93196	93247	93298	93348	93399
00	93550	93601	93651	93701	93751	93802	93852	93902
01	94051	94101	94151	94200	94250	94300	94349	94398
47	94546	94596	94645	94694	94743	94792	94841	94890
37	95036	95085	95133	95182	95230	95279	95327	95376
92	95520	95568	95616	95664	95712	95760	95808	95856
01	95999	96047	96094	96142	96189	96236	96284	96331
96	96473	96520	96567	96614	96661	96708	96754	96801
45	96941	96988	97034	97081	97127	97174	97220	97266
09	97405	97451	97497	97543	97589	97635	97680	97726
88	97863	97909	97954	98000	98045	98091	98136	98181
92	98317	98362	98407	98452	98497	98542	98587	98632
81	98766	98811	98855	98900	98945	98989	99033	99078
26	99211	99255	99299	99343	99387	99431	99475	99519
97	99651	99694	99738	99782	99825	99869	99913	99956

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add these logarithms, and then from the table find the number of which this is the logarithm. The position of the decimal point is fixed by the value of the mantissa in the sum of the two logarithms. By adding a whole number to a mantissa and subtracting the same number from the characteristic the mantissa of the final result can always be kept positive.

Examples. — Multiply 376.2 by 0.587:

$$\begin{aligned} \log 376.2 &= 2 + .57541 \\ \log 0.587 &= -1 + .76863 \end{aligned}$$

Adding gives $1 + 1.34404 = 2.34404$.

therefore $376.2 \times 0.587 = 220.8$.

Divide 37.62 by 587:

$$\begin{aligned} \log 37.62 &= 1 + .57541 = 1.57541 \\ \log 587 &= 2 + .76863 = 2 + .76863 \end{aligned}$$

Subtracting gives $-2 + .80678$

therefore $$\frac{37.62}{587} = 0.06409.$$

NATURAL LOGARITHMS. — (*See also Roots and Powers.*) The base of the so-called natural system of logarithms is the value of the expression $\left(1 + \frac{1}{n}\right)^n$ when n is taken equal to infinity. The numerical value of this expression is found by expanding $\left(1 + \frac{1}{n}\right)^n$ by the binomial theorem (*see Series*), and is equal to 2.718282 +. This number is usually represented by the symbol e, that is,

$$e = 2.718282 +, \text{ or } 2.718 \text{ approximately.}$$

Logarithms to this base are readily calculated by means of Taylor's series (*see Series*); also this number e enters in a very simple manner into various mathematical and physical relations (*see Equations, Differential; Transient Electric Phenomena; Hyperbolic Functions; Trigonometric Functions*).

The relation between a logarithm of any number A to any base b and the logarithm of A to any other base a is

$$\log_b A = \frac{\log_a A}{\log_a b}.$$

Hence $$\log_e A = 2.30259 \log_{10} A.$$

From this last relation the natural logarithm of any number may be found directly from the table of common logarithms.

Example. —

$$\log_e 376.2 = 2.3026 \times 2.57541 = 5.930.$$

The natural logarithm may also be taken directly from the table of exponential functions (q.v.), remembering that $\log_e A$ is the number in the margin of the table corresponding to the number equal to A in the columns of the table.

The symbol "ln" is frequently used for the natural logarithm and the symbol "log" without a subscript is usually employed as an abbreviation for the logarithm to the base 10.

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LUBRICANTS AND LUBRICATION. — (*See also Bearings; Friction.*) Ordinary lubricants may be classified as follows:

Vegetable Oils. — Commonly employed vegetable oils are linseed, cotton-seed, rape and castor. Vegetable oils decompose at comparatively low temperatures. They are used chiefly for compounding with mineral oils.

Animal Fats. — Animal fats ordinarily employed for lubrication are tallow, neat's-foot, lard, sperm, wool grease and fish oil. Like vegetable oils they decompose at comparatively low temperatures and are used chiefly for compounding with mineral oils.

Mineral Oils. — These are all petroleum products, and form the whole or the greater part of most of the lubricants employed.

Solid Lubricants. — Dry graphite, soapstone and mica are sometimes used as lubricants for slow-speed work when the bearing surface is restricted in area and the load to be carried is very large.

"Deflocculated" Graphite. — In 1906 E. G. Acheson discovered a process of producing a fine, pure, unctuous graphite, which when heated with a solution of tannin would remain suspended in water for months. The graphite thus suspended in water, known as "aquedag" has been successfully used as a lubricant (*Trans. A.I.E.E., 1907*). Acheson's "deflocculated" graphite, as the graphite in the finely divided form is called, has also been suspended in oil, the oil emulsion being known as "oildag," making an excellent lubricant.

Greases. — Compounds of oils and fats containing sufficient soap to form a more or less solid mass at ordinary temperatures are called greases. Lime soda or lead soaps are used in these compounds. For very high pressures graphite, soapstone and mica are sometimes added to the grease.

QUALIFICATIONS OF A GOOD LUBRICANT. — The generally accepted conditions of a good lubricant are as follows:

1. "Body" (i.e., viscosity) enough to prevent the surfaces to which it is applied from coming in contact with each other.
2. Freedom from corrosive acid, of either mineral or animal origin.
3. As fluid as possible consistent with sufficient "body."
4. Low coefficient of friction (as determined in a standard bearing).
5. High "flash" and burning points.
6. Freedom from all materials liable to produce oxidation or "gumming."

The examinations to be made to verify the above are both chemical and mechanical, and are usually arranged in the following order:

1. Identification of the oil, whether a simple mineral oil, or animal oil, or a mixture. 2. Density. 3. Viscosity. 4. Flash point. 5. Burning point. 6. Acidity. 7. Coefficient of friction. 8. Cold test.

Test for Fats. — Heat a small quantity of the oil in a small test tube 15 minutes with small pieces of metallic sodium or caustic potash. If fatty oil is present, a soapy mass will form at the top. (*Gebhardt.*)

Test for Tarry Matter. — Dissolve a small quantity of the oil in from 10 to 20 times its bulk of gasoline; tar and other insoluble matter will be precipitated. (*Gebhardt.*)

Specific Gravity. — This is usually made with a hydrometer, graduated according to the Baumé scale. At 60° F.

$$\text{Specific gravity} = \frac{140}{130 + \text{degrees Baumé}}.$$

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Viscosity. — Viscosity, or internal friction, is usually determined by observing the time required for a given amount of oil to flow through a standard orifice. By "specific viscosity" is meant the ratio of the time for the oil to run out to that required for an equal volume of water at 60° F. The temperature of the oil should always be observed and stated. Engine oils are usually tested for viscosity at 70° F. and cylinder oils at 212° F. (*Gebhardt.*)

Flash Point. — The flash point is determined by heating a sample of oil in a cup at the rate of 15° F. per minute until a spark will ignite the vapor; the corresponding temperature is the flash point. The flash point as thus determined depends to some extent upon the surface exposed, the size of the spark, the distance between spark and surface of oil and the dimensions of the cup. (*Gebhardt.*)

Burning Point or Fire Test. — By continuing the application of heat and noting the temperature at which the oil itself takes fire and continues to burn, the burning point is determined.

Acidity. — The presence of free acid is determined by shaking up equal quantities of oil and water and testing with litmus paper.

Cold Test. — The cold test is the temperature at which the oil will just flow.

Friction Test. — The coefficient of friction as determined from friction-testing machines gives but little information concerning the action of the oil under the widely different conditions found in practice. (*Gebhardt.*)

Properties of Vegetable and Animal Oils. — The following data are taken from Gebhardt's *Steam Power Plant Engineering.*

Kind of oil	Specific gravity		Flash test, ° F.
	Water as 1.00	Baumé	
Lard	0.9175	23	505
Sperm	0.8815	29	478
Tallow	0.9080	24.5	540
Cottonseed	0.9210	22	518
Linseed	0.9299	19	505
Castor	0.9639	15	...
Palm	0.9046	25	405
Rape-seed	0.9155	23	...

Properties of mineral oils as compounded for ordinary use are given below.

Grease Lubricants. — Tests made on an Olsen lubricant testing machine at Cornell University are reported in *Power*, Nov. 9, 1909. It was found that some of the commercial greases stood much higher pressures than the oils tested, and that the coefficients of friction at moderate loads were often as low as those of the oils. The journal of the testing machine was 3¾ inches diameter, 3½ inches long, and the babbitt bearing shoe had a projected area of 5.8 square inches. The speed was 240 revolutions per minute and each test lasted one hour, except when the bearing showed overheating. The following are the coefficients of friction obtained in the tests:

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RELATIVE VALUES OF FRICTION COEFFICIENT WITH GREASES AND OILS

Lb. per sq. in.	Mineral grease	Animal grease	Graphite grease	Mineral grease	Engine oil	Engine oil	Grease	Grease
86.2	0.024	0.023	0.04	0.023	0.019	0.015	0.020	0.025
172.4	0.021	0.023	0.05	0.018	0.04	0.022	0.015	0.022
258.6	0.021	0.023	....	0.018	0.06	0.037	0.014	0.020
344.8	0.025	0.025	....	0.019	....	....	0.017	0.020
431.0	0.050	0.035	....	0.028	....	....	0.026	0.019

APPLICATIONS OF VARIOUS TYPES OF LUBRICANTS. — The type of lubricant to use in any case depends upon:

1. The cost due to consumption of lubricant.
2. The saving in annual cost due to lessening of wear of bearings, guides and other rubbing surfaces.
3. The cost of the energy saved (as the result of decreased friction losses) due to the use of the lubricant.

For minimum annual cost the sum of the last two items should equal the first. Estimates of this kind are difficult to make, and the result is that the kind of lubricant used in any specific case is usually determined by experience.

The following table, from a paper in *Power*, December, 1905, p. 750, gives the kind of lubricant ordinarily employed for various purposes, together with their approximate characteristics. The cold test of all these oils, except oil for refrigerating machinery, is given as 30° F. Refrigerating-machinery oil should not solidify above 0° F.

METHODS OF LUBRICATION. — The commonest type of "lubricator" on engines or dynamos is the simple oil cup with sides of glass, so that the level of the oil in the cup can be seen. Any type of lubricator in which the flow of oil can be seen is known as a "sight feed." The flow of oil is regulated by a needle valve in the base of the cup.

Lubrication of Crossheads, Crank Pins, etc. — In applying oil to rubbing surfaces, both of which are in motion, various devices are used by means of which the oil cup can be kept at rest. A stationary oil cup may be used with a "wiper" on the moving member, or a "telescopic," "pendulum" or "centrifugal" oiler may be employed. Sometimes the crank, connecting rod and crossheads are inclosed in a casing the bottom of which is filled with oil so that at each revolution the end of the connecting rod splashes oil over all the parts.

Oil Rings and Chains. — The bearings of small high-speed engines and dynamos are frequently provided with rings or chains running loosely over the journal and dipping into an oil bath in the pedestal below the bearing. The rotation of the journal gives enough motion to the rings to enable them to carry up sufficient oil from the bath to keep the bearing surfaces bathed in oil.

Cylinder Lubrication. — The oil must be forced into steam cylinders against the steam pressure. This is usually accomplished by means of specially constructed cylinder cups, hydrostatic lubricators or force pumps. A brief description of the more common forms of these devices will be found in Gebhardt's *Steam Power Plant Engineering.*

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APPLICATIONS AND CHARACTERISTICS OF VARIOUS OILS

Kind of oil and application	Specific gravity, Baumé	Flash test, ° F.	Fire test, ° F.	Viscosity at 70° F. (Water = 1)
High-pressure cylinder oils: For cylinders using dry steam at from 110 to 210 lb.	25–24.5	600–610	645–660	175–205
General cylinder oil: For cylinders using dry steam at from 75 to 100 lb. Also for air compressor cylinders when the oil is made from steam-refined mineral stock and has a viscosity of 200.	26–25.5	550–585	600–630	180–190
*Wet cylinder oil** For cylinders using moist steam, especially in compound- and triple-expansion engines.	25.8–25.3	560–585	600–630	150–185
Gas-engine cylinder oil†	26.5	320	350	300
Automobile gas-engine oil‡	29.5	430	485	195
Heavy engine and machinery oils: For heavy slides and bearings, shafting and horizontal surfaces.	30.5–29.5	400	440–450	170–195
General engine and machinery oils: For high-speed dynamos and other comparatively heavy machines.	30.8–30	400–420	450–470	175–190
Fine and light machine oils: For fine work, such as printing presses, sewing machines, typewriters, spindles, etc.	32.5–30.2	400	440	110–160
Cutting oils: For cutting tools, screws, etc.	27–23	410–420	475–480	210–175
Refrigerating machine oils	30.2	200	225	165
Wet service and marine oils§	28	430	475	230
Greases: Various kinds, used in special work requiring high pressures and low velocities.	.....	....	....	.....

* May contain not over 2 to 6 per cent of refined acidless tallow oil in the high-pressure oils and not over 6 to 12 per cent in the low-pressure oils.

† Neutral mineral oil compounded with soap. The soap will not decompose at high heat, and although not a lubricant serves as a vehicle for carrying some oil.

‡ Owing to lack of body this oil will not deposit carbon on the sparking points.

§ May contain 30 to 40 per cent of pure strained lard oil.

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Oil-feed Systems. — In power plants oil is supplied continuously to the bearing surfaces of the various engines and generators by means of an oil-feed system, comprising essentially a supply tank, pump and the necessary piping. Oil filters and purifiers are also used in connection with the oiling system, to eliminate the impurities which collect in it due to dust, wear of bearings, exposure to the heat and to the atmosphere. See article on *Power Stations*.

AMOUNT OF OIL REQUIRED FOR ENGINES. — J. H. Spoor, in *Power*, Jan. 4, 1910, has made a study of a great number of records of the amount of oil used for lubricating cylinders of different engines, and has reduced them to a systematic basis, i.e., the number of pints of oil used in a 10-hour day for different areas of surface lubricated. The surface is determined in square inches by multiplying the circumference of the cylinder by the length of stroke. The results are plotted in a series of curves for different types of engines, and approximate average figures taken from these curves are given below:

PINTS OF CYLINDER OIL IN 10 HOURS

Type of Engine	Square inches lubricated								
	1000	2000	3000	4000	6000	8000	10,000	12,000	18,000
Automatic high speed	2	....	....	....	....	....	....	....	....
Simple slide valve..	0.5	....	....	....	....	....	....	....	....
Compound.....	....	2	....	3.5	4 3	5	5.5	6	6.5
Corliss:									
Average.....	0.9	1.65	2.25	3.75	....	....	....	....	....
Maximum.....	1.2	2.25	....	....	....	....	....	....	....
Minimum.....	....	1.00	....	....	....	....	....	....	....

As shown in the figures under 2000, Corliss, a certain engine may take 2¼ times as much oil as another engine of the same size. The difference may be due to smoothness of cylinder surface, kind and pressure of piston rings, quality of oil, method of introducing the lubricant, etc. Variations in speed of a given type of engine and in steam pressure do not appear to make much difference, but the small automatic high-speed engine takes more oil than any other type. Vertical marine engines are commonly run without any cylinder oil, except that used occasionally to swab the piston rods.

The amount of engine oil required will of course depend upon the number of cups on the engine and the size of the various bearings. For a 1000-h.p. Corliss engine the Vacuum Oil Company state that the amount of engine oil would not exceed twice the amount of cylinder oil required.

BIBLIOGRAPHY. — Archbutt and Deeley, *Lubrication and Lubricants;* Gill, A. H., *Short Handbook of Oil Analyses;* Hurst, G. H., *Lubricating Oils, Fats and Greases*, 3d ed.; *Graphite as a Lubricant*, Circular of Jos. Dixon Crucible Co., Jersey City, N. J.; Kent's *Mechanical Engineers' Pocket-Book;* Battle, J. R., *Lubricating Engineers' Handbook.*

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MACHINE TOOLS, ELECTRICAL OPERATION OF. — (*See also Motors, Industrial Applications of.*) When the work of equipping a machine tool with motor drive is undertaken, there are certain features which should be taken into account and properly analyzed, as the conditions of operation generally vary greatly with the product manufactured. If a tool is intended for a certain specialized kind of work, information on the following points should be given:

1. The exact class of work which the tool is to accomplish.
2. If the power required to remove the metal is not known, then a statement should be made as to the approximate feed and cutting speeds to be taken.
3. Careful analysis should be made of the time required to load and unload the machine, to determine the feasibility of employing auxiliary means other than manual labor for loading the tools.

From this information an approximate determination can be made as to the intermittency of operation of the tool, in order to decide whether an intermittently rated motor or a continuously rated motor will be required. From a knowledge of the physical shape of the work, a determination can be made as to whether an adjustable-speed motor will result in economy of time, if used on this particular class of tool. The tool builder can then decide upon the proper type of controller, and its most desirable location from an operating point of view for the workman.

If a special type of tool is not desired and it is preferable to purchase one with such characteristics that it can be used for general manufacturing, one should determine as nearly as possible the range of material or work for which it will be used in straight manufacturing operations.

TYPE OF MOTOR. — The following table will aid in the choice of the proper motor for machine tool application.

It must be kept in mind that various circumstances, such as size or roughness of work, flywheel capacity, etc., may call for radical departures in choice of motors, this list being compiled to meet average conditions.

Shunt Motors are used in the following cases: when the work is of a fairly steady nature; when considerable range of adjustment of speed is required, as on lathes and boring mills, and on group and line-shaft drives, etc.

Compound-wound Motors are used where there are sudden calls for excessive power of short duration, as on belt driven planers, punch presses, etc. When a 50 per cent shunt, 50 per cent series, field is used, a motor is obtained which will develop nearly as much torque per ampere as a series motor with the advantage that light load speed will not be greater than 150 per cent full load speed.

Series Motors should be used where speed regulation is not essential and where excessive starting torque and slow starting speeds are required, as, for instance, in moving carriages of large lathes, in raising and lowering the cross rails of planers and boring mills, and for operating cranes.

When in doubt as to the choice of compound or series motors of small horsepower, the choice might be determined by the simplicity of control in favor of the series motor. Series motors, however, should never be used when the motor can run without load, as the speed would accelerate beyond the point of safety.

Induction Motor. — The alternating-current motor of the squirrel-cage rotor type corresponds to the constant-speed, shunt, direct-current motor, but with a high-resistance rotor it approaches more closely the characteristics of a compound direct-current motor. It is understood that the variable-speed machines, checked in this list under the alternating-current squirrel-cage rotor column, have the necessary mechanical speed changes.

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MOTORS FOR MACHINE TOOLS

ool	D-C.			A-C. (See Footnotes)		
	Shunt	Comp., %	Series	×	⁂	⊕
	✓	....	....	×	..	..
eader	....	20	....	×	⁂	..
	....	20	....	×	⁂	..
s	✓	....	....	×	..	..
	✓	....	....	×	..	..
ils on boring mills						
	....	20–50	✓	..	⁂	..
	✓	....	....	×	..	..
es	....	20–50	....	×	⁂	..
	....	50	....	..	..	⊕
ls	....	20–50	....	×	⁂	..
ines	✓	....	....	×	..	..
ines	✓	....	....	×	..	..
and drilling ma-						
	✓	....	....	×	..	..
	✓	....	....	×	..	..
	✓	....	....	×	..	..
etc	✓	....	....	×	..	..
ngs	✓	....	....	×	..	..
	✓	....	....	×	..	..
op	....	20	....	..	⁂	..
iling — broach	✓	....	....	×	..	..
ciprocating	✓	20	....	×	..	..
	✓	....	....	×	..	✠
	....	....	✓	..	⁂	..
s	✓	....	....	×	..	..
ing	✓	....	....	×	..	..
	✓	....	....	×	..	..
	....	20	....	×	⁂	..
driven	....	20	....	×	..	..
sing motor	✓	....	....	×	..	..
y	✓	....	....	×	..	..
rcular	✓	....	....	×	..	..
and I beam	....	20	....	×	..	..
	....	20	....	×	..	..
	✓	....	....	×	..	..
	✓	20	....	×	..	..
	....	20	....	×	⁂	..
type	✓	....	....	×	..	..
	✓	20	..	×	⁂	..
ls or mills—indiv.	✓	....	....	×	..	..
ls or mills—group	....	20	....	×	..	..
	✓	....	....	×	..	..

otor. ⁂ Squirrel-cage rotor — high starting torque.
ction motor with external rotor resistance.
for tire lathes as it allows slowing down when cutting hard spots.
resses running at high speed can be driven by shunt motors.

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The slip-ring induction motor with external rotor resistance would be used for variable speed, but this must not be construed to mean that it corresponds to a direct-current, adjustable-speed motor, as it has the characteristics of a direct-current shunt motor with armature control.

The self-contained, rotor-resistance type would be used for line-shaft drives and for groups when of sufficient size.

Multi-speed Alternating-current Motors are those giving a number of definite speeds, usually 600 and 1200 or 600, 900, 1200 and 1800 r.p.m., and are made for both constant horse-power and constant torque. These motors would be used where alternating current only was available, or direct current limited and the speed range of the motor, together with one or two change gears, would give the required speeds.

Shaft Couplings. — In connection with the selection of motors, standard shafts and shaft extensions should be chosen so that spare parts and interchanges may be made with the least cost and time. A number of standard shafts and shaft extensions are shown in the sketches in Fig. 1.

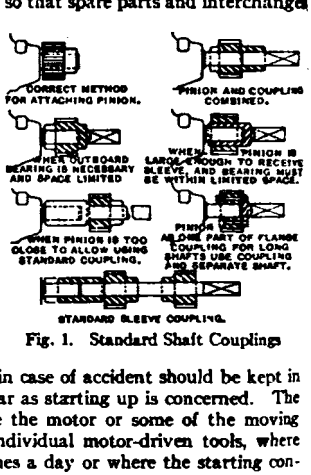


Fig. 1. Standard Shaft Couplings

CONTROL EQUIPMENT. — The choice of control, whether it be for old or new tools, in the majority of cases is fully as important as that of the motor. In selecting the control it is necessary to consider the nature of the work, the accessibility of the controller to the operator, the method of attaching it to the tool and in some cases its relative position to other tools; for instance, an open-type starting rheostat should not be exposed to danger of short-circuit from flying chips.

When installing controllers, accessibility in case of accident should be kept in mind, even though of little importance as far as starting up is concerned. The starting apparatus should be placed where the motor or some of the moving parts can be seen by the operator. On individual motor-driven tools, where the motor is started and stopped many times a day or where the starting conditions are of a severe nature, or where tools are edged along, drum-type controllers with extra heavy starting resistance should be used. For adjustable speed motors, using the drum-type control, the field control should be through fingers making contact on segments of the controller drum and not by sliding contacts on a dial. Motors above 40 or 50 horse-power under these severe conditions are best operated by a master controller which operates contactors for cutting out steps of starting resistance, and if adjustable speed, the field control should be taken care of by fingers making contact on segments of the drum. This class of starting apparatus will stand any quantity of abuse and, by the addition of a simple current limit relay device, becomes practically a fool-proof protection for the motor. There are cases where it might be advantageous to use master controllers and contactors even with smaller motors. The controlling apparatus as well as the motor in the case of individual drives should be attached directly to the tool when possible. This arrangement allows moving the tool by simply disconnecting the leads and connecting them in the new position. In case of portable tools this, of course, is an absolute necessity.

Upon the convenient arrangement of the control depends, to a considerable degree, the output of the tool. The importance of the arrangement from the standpoint of the operator cannot be ignored, since the output of a tool will be

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materially increased when an operator can start and stop the tool and obtain at all times maximum cutting speeds by simply turning a handle. The controller must be placed in a safe position and should be accessible for repairs, which very often means that some arrangement is necessary to bring the operating handle within easy access of the operator.

The convenience of control, which bears directly on production, is ignored in the majority of tools where the control is of the greatest importance. A familiar illustration of the convenience of control is the arrangement so commonly seen on lathes, whereby the operating handle travels with the tool carriage and allows the operator at all times a complete control of his tool.

APPLICATION OF REVERSING MOTORS. — One of the most interesting motor applications is the use of reversing motors for machine tools. The large increase in production due to this form of drive on planers is generally appreciated, but the application of the reversing motor drive in its various forms (which is almost unlimited) is not so well understood. This reversing drive is applicable not only to planers, new and old, but to screw, worm and rack-driven slotters, keyseaters, turret lathes, wire and tube drawing machinery, grinder tables, lapping machines and to boring mills, when machining projections which are short in comparison with the total travel of the mill or when machining surfaces where projections prevent a complete revolution.

The motors recommended for this service are of the commutating pole type with a speed range usually of from 300 to 1200 r.p.m. for the small sizes and 250 to 1000 r.p.m. for the larger sizes. Other speeds can be obtained when required. The speeds given allow the motor, in the majority of cases, to be coupled direct to the driving shaft of the machine.

Starting, stopping and reversing are accomplished in remarkably short periods of time. It is considered the best practice to bring the motor to rest by means of dynamic braking.

On all reversing motor equipments, an emergency brake must be provided so the motor will be brought to rest quickly, when the voltage fails. Undervoltage protection should always be used.

Reversing Planers. — These equipments should provide quick reversals, the motor being brought to rest before each reversal, preferably by dynamic braking. This method will insure the motor, and consequently, the planer, coming to rest at practically the same point, for the various conditions encountered. This is especially important when planing up to a shoulder or in a pocket, where any overtravel would damage the work or the machine.

It is advisable to use an equipment so interlocked that it is impossible to connect the panel to the power supply with the master switch in a running position. If this feature is not used, an unexpected start is liable to result. "Jogging" by means of a portable push button is desirable for setting up work.

The "cutting" and "returning" speeds should be independently adjustable, and thirty-five or more cutting speeds provided.

Example. — In Fig. 2 curves *A*, *B* and *C* are for motor No. 2 and show the ampere input of a 10 horse-power, 1250 r.p.m. motor driving a 36-inch modern type planer through shifting belts. *A* is the return stroke of the planer table at a speed of 68 feet per minute; *C*, the cutting stroke, without cut, at 33.3 feet per minute; *B*, the same cycle but with a cut slightly less than 10 horse-power. The lost time on the cutting stroke, due to the belt slipping, is plainly seen, the cutting speed falling off from 33.3 feet to 29.4 feet or 13 per cent. Curves *E*, *F* and *G* are made on the same machine when driven by motor No. 1, a 10-horse-power, 250 to 1000 r.p.m. reversing motor, direct connected. These curves are superimposed on the above curves for comparative purposes. No attempt was made in this set of curves to duplicate the slow cutting or return speeds of the

belt-driven machines as the comparison would have shown power only. *E* is the return stroke of the planer table at a speed of 88.7 feet

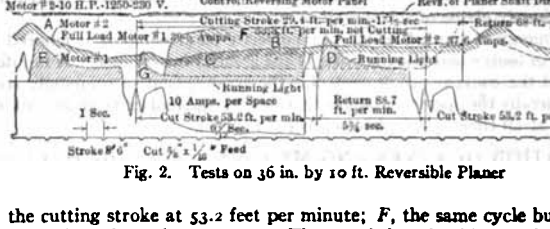


Fig. 2. Tests on 36 in. by 10 ft. Reversible Planer

G, the cutting stroke at 53.2 feet per minute; *F*, the same cycle bu of approximately 13 horse-power. The speed drop in this case is down only. For comparison the speed of motor No. 1, curve *F*, w the most economical speed under the conditions which the test was loss in time of the belt drive as compared with the direct-connecte motor drive (the depth of cut and feed being the same in both cas cent.

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MAGNETIC PROPERTIES OF IRON AND OTHER METALS.

—(*See also Electricity and Magnetism, Principles of; Magnetic Testing.*) For the definitions of magnetizing force and flux density see *Electricity and Magnetism, Principles of;* for the relations of the various units in which these quantities are expressed see *Units and Conversion Factors.*

Hysteresis Loop — Residual Magnetism and Coercive Force. — When a magnetic substance which is not magnetized initially is placed in a magnetic field the intensity of which is increased from O to H_m, the flux density produced

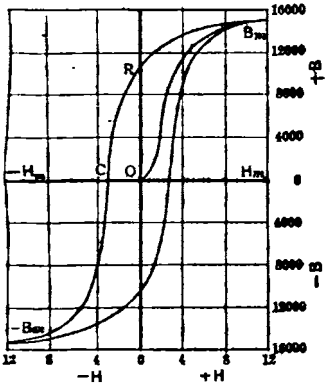


Fig. 1.

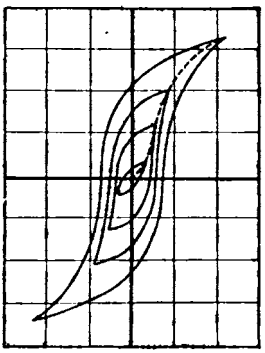


Fig. 2.

in the magnetic substance increases in the manner shown by the curve OB_m in Fig. 1. If the magnetizing force is then decreased to a value H the flux density does not return to the value corresponding to this value of H on the ascending curve, but decreases less rapidly than it increased. This phenomenon is known as "magnetic hysteresis."

When the magnetizing force is reduced to zero the flux density in general has a considerable value (OR in Fig. 1); this value of B is called the "remanent" or "residual" magnetism. To reduce the flux density to zero the magnetizing force must be reversed and increased in the reversed direction to a value OC, called the "coercive force." As the magnetizing force is still further increased in the reversed direction to a value numerically equal to the positive maximum, and then decreased to zero, reversed, and increased again to H_m, the flux density passes through the cycle of values represented by the closed loop. This closed loop is called the "hysteresis loop."

If the iron (or other magnetic substance) is not originally unmagnetized, this hysteresis loop will be shifted above or below the axis of H, but after a number of reversals of the magnetizing force between given positive and negative values, the loop will become practically symmetrical with this axis, particularly if the iron is continually jarred. In the armatures of electrical machines and the cores of transformers, in which the field intensity reverses a large number of times every second, and the iron is continually jarred, the relation between flux density and field intensity after a short interval of time is represented by a symmetrical loop of the form shown in Fig. 1.

The area inclosed by the hysteresis loop depends upon the maximum value of the flux density reached during the cycle, but the general shape remains

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about the same. Fig. 2 shows a series of loops corresponding to various values of the maximum flux density. The area of the loop is also different for various kinds of iron or steel. $\frac{1}{4\pi}$ times the area of this loop when B and H are plotted to scale is equal to the ergs of heat developed in the iron per cubic centimeter per cycle. (*See section on Hysteresis Loss, below.*)

Permanent Magnets — Retentiveness. — An examination of this hysteresis loop also makes clear how a bar of steel may be permanently magnetized by placing it in a magnetic field. For, when the bar is removed from the field it retains a flux density approximately equal to the residual magnetism *OR*. In the case of a cast-iron or steel bar, properly hardened, the bar thus magnetized may be handled with comparative roughness without reducing to any considerable extent the strength of its poles, but in the case of a soft-iron bar even the slightest jar will cause it to lose its magnetism almost entirely. The property possessed by a magnetic substance of retaining its magnetization is called its "retentiveness." See also article on *Magnets, Permanent.*

B-H Curves. — Starting with a sample of iron completely demagnetized, and gradually increasing the magnetizing force, the flux density increases in the manner indicated by the middle curve from *O* to *B* in Fig. 1. This curve is called the "rising *B–H* curve." The curve showing the relation between the maximum flux density and the maximum magnetizing force for successive hysteresis loops, i.e., the dotted curve in Fig. 2, is similar in shape to this rising *B–H* curve, and is called the "alternating *B–H* curve." Except for the lower values of the flux density the rising and alternating *B–H* curves are practically identical. For engineering purposes, the alternating characteristic is the more important, and may be conveniently referred to as the "normal" *B–H* curve.

Permeability. — The magnetic permeability μ of a substance corresponding to any degree of magnetization is usually defined as the quotient of the flux density B by the magnetizing force H, that is

$$\mu = \frac{B}{H}.$$

On account of the hysteresis effect, however, this quotient may have any value within wide limits depending upon how the magnetization is produced. Consequently a more restricted definition of permeability is required in the case of highly magnetic substances like iron and steel. For such substances the normal permeability for any value of the flux density is taken as the ratio of $\frac{B}{H}$ corresponding to this flux density on the normal *B–H* curve.

The relation between permeability and magnetizing force or flux density is a complex one. As the flux density increases, μ reaches a maximum at a relatively low flux density and then decreases ultimately to unity when the magnetizing force reaches a value so large that the intensity of magnetization J is negligible in comparison with H. This limiting condition, however, is never reached in practice.

Reluctivity. — Magnetic reluctivity is defined as the reciprocal of magnetic permeability, viz.,

$$\text{Reluctivity} = \rho = \frac{1}{\mu} = \frac{H}{B}.$$

Typical reluctivity curves are given in Fig. 6, corresponding to the *B–H* curves in Figs. 3 to 5.

Intensity of Magnetization. — The difference between the flux density B

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in a magnetic substance corresponding to a given magnetizing force H and the flux density (numerically equal to H) which this same magnetizing force H would produce in free space, divided by 4π, is called the intensity of magnetization, viz.,

$$J = \frac{B - H}{4\pi}.$$

Susceptibility. — The quotient of the intensity of magnetization J divided by the magnetizing force H is called the magnetic susceptibility κ corresponding to this magnetizing force; viz.,

$$\kappa = \frac{J}{H} \quad \text{whence} \quad \mu = 1 + 4\pi\kappa.$$

Magnetic Saturation. — Experiment shows that up to the highest values of the magnetizing force which have yet been produced, the normal flux density B always increases with an increase in the magnetizing force H. However, such experiments indicate that the difference between the flux density B and the magnetizing force H, that is, the difference $(B-H)$, approaches a definite maximum limit, dependent solely upon the nature of the material under test. In other words, for any given magnetic substance there is a definite limit to the intensity of magnetization $\left(J = \frac{B - H}{4\pi}\right)$ which can be established in it. When this limiting value of the intensity of magnetization is reached, the substance is said to be "magnetically saturated."

The difference $(B-H)$, when B and H are both expressed in c.g.s. electromagnetic units, may be conveniently designated as the "metallic" component of the flux density corresponding to a given magnetizing force H, since it is equal to the excess of the resultant flux density over the flux density which this same magnetizing force would produce in free space. The maximum, or saturation, value of this metallic flux density is about 20,000 gausses for soft iron and steel, 15,000 gausses for cast iron, 12,000 gausses for cobalt, and 6000 gausses for nickel. To increase the flux density beyond these values requires an increase in the magnetizing force equal to the increase in flux density desired.

An inspection of the reluctivity curves in Fig. 6 shows that for values of the magnetizing force greater than about 40 ampere-turns per inch (or 20 gilberts per centimeter), the relation between reluctivity and magnetizing force is approximately a straight line one. Due to the fact that there is a definite magnetic saturation point, the reluctivity curves actually have a slight downward droop. If instead of the reluctivity $\rho = \frac{H}{B}$, the ratio $\frac{H}{B - H}$ is plotted against the magnetizing force, it is found that for very high values of H, this ratio bears an exact linear relation to the magnetizing force H, viz., that

$$\frac{H}{B - H} = \alpha + \sigma H \qquad (5)$$

where α and σ are constants for any given material. Steinmetz calls the constant α the "coefficient of magnetic hardness" and the constant σ the "coefficient of magnetic saturation."

FACTORS AFFECTING THE PERMEABILITY AND HYSTERESIS LOSS. — The normal permeability and the hysteresis loss (the latter is proportional to the area of the hysteresis loop) depend to a very great extent upon the physical structure and chemical constitution of the sample and the heat treatment to which it has been subjected. It has also been recently discovered (*Pender and Jones, Phys. Rev., 1913*) that when sheet steel is annealed in an alternating magnetic field, the permeability is increased in certain cases as much

as 50 per cent, but there is no appreciable change in the hysteresis loss. The B–H curves of two samples taken from the same lot of material may even differ considerably. The permeability and hysteresis loss also depend to a slight extent upon whether the sheets are magnetized in the direction of rolling, or transverse thereto, being higher in the latter case.

Temperature and Aging. — Permeability and hysteresis also depend upon the temperature of the sample at the time the observations are taken, though the variation due to ordinary changes of temperature is slight. For very high temperatures, however, all magnetic substances become practically non-magnetic. This temperature corresponds to the major recalescence point, which is about 750° C. for steel of the quality used in armature and transformer punchings. When steel is kept continuously at a moderately high temperature (100° C.), the hysteresis loop also gradually increases in size, and therefore the energy loss in the magnetic circuits of electric machines due to hysteresis increases with time. This effect is called "aging." There is practically no aging of silicon steel.

Chemical Composition of "Electrical" Sheet Steel. — Sheet-steel manufacturers make a special grade of sheet for electrical purposes, which they sell under various trade names. Such steel is always low in carbon content and, except silicon in the so-called silicon steels, all impurities are reduced to small amounts. Silicon steel, i.e., steel containing about 3 per cent silicon is also extensively used, particularly for the magnetic circuit of transformers. The permeability of this steel is somewhat lower, in the useful range of flux densities, than that of ordinary electrical steel, but the area of the hysteresis loop, and therefore the hysteresis loss, is from 40 per cent to 60 per cent less; the specific resistance of silicon steel is also about 3 times greater than that of ordinary electrical steel, resulting in a reduction of about 70 per cent in the eddy current loss (*see curves below*). Aluminium has much the same effect as silicon, but the aluminium alloy is not so easily rolled.

The following are typical chemical analyses of the two kinds of electrical steel, but it should be understood that considerable variations in the proportions of the various constituents occur in practice.

	Ordinary electrical steel *	Silicon steel
	Per cent	Per cent
Silicon	0.01	3.46
Phosphorus	0.08	0.04
Manganese	0.50	0.13
Sulphur	0.03	0.02
Carbon	0.06	0.06

* Parshall & Hobart, Electric Machine Design.

Of a large number of electrical steels analyzed by the Bureau of Standards (*Lloyd and Fisher, Trans. A.I.E.E., 1909, Vol. 28, p. 463*) none showed more than the slightest trace of vanadium.

Annealing of Sheet Steel. — Sheet steel as it comes from the rolling mill may be greatly improved in magnetic properties by proper annealing. The chief requirement seems to be that the steel be brought to a temperature about 100° C. above the major recalescence point, i.e., to a temperature of about

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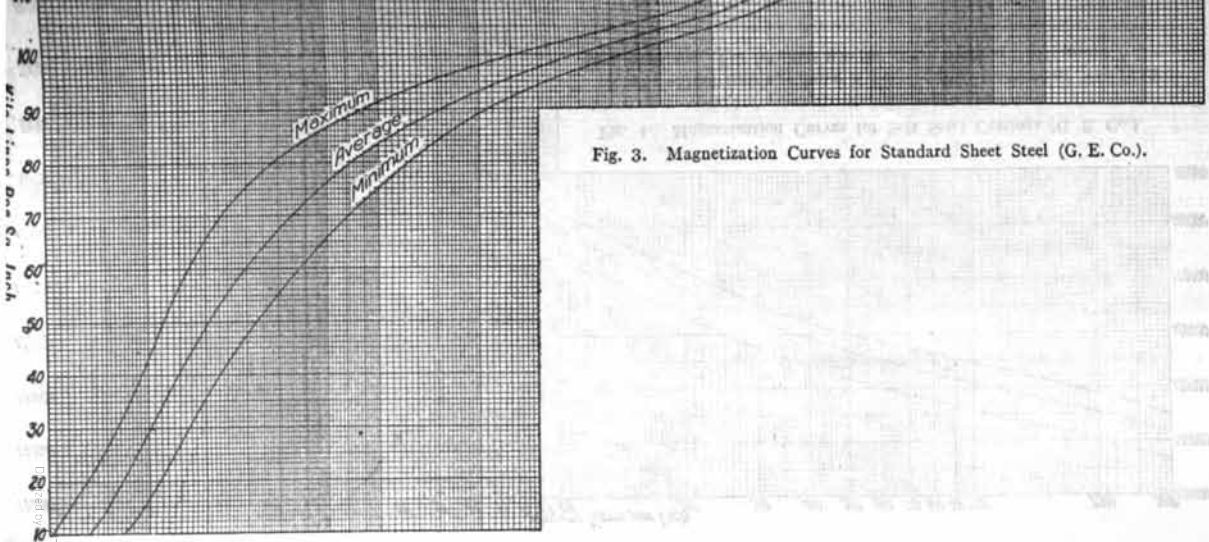


Fig. 3. Magnetization Curves for Standard Sheet Steel (G. E. Co.).

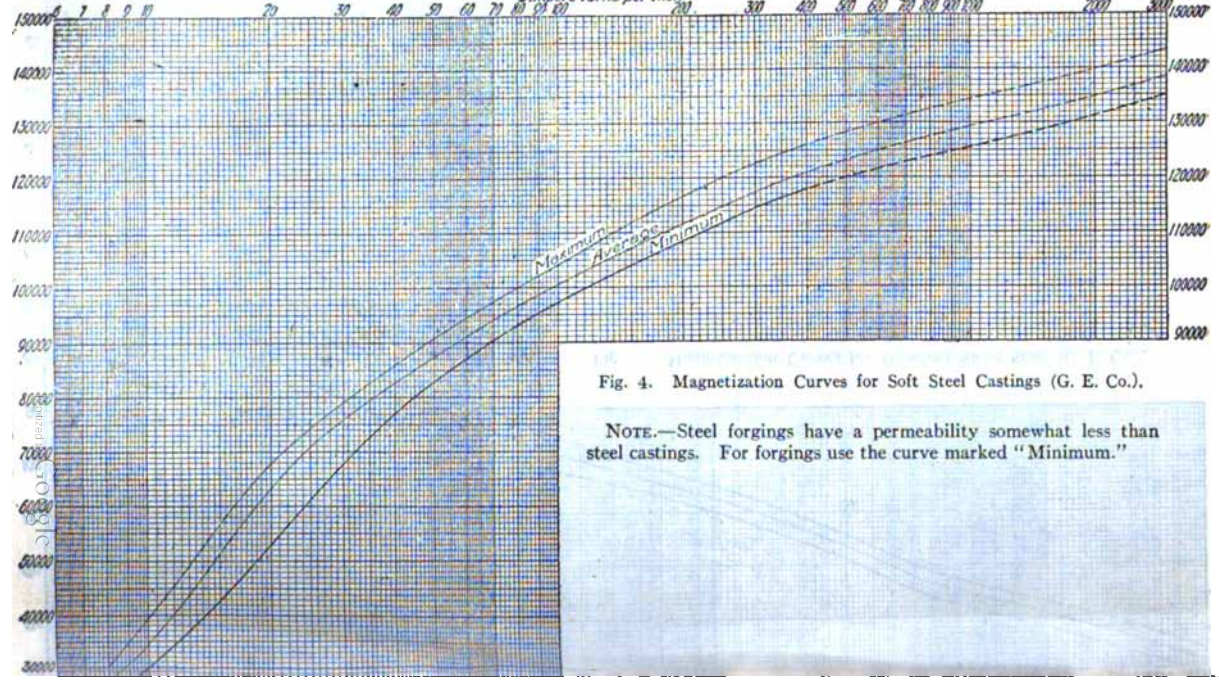


Fig. 4. Magnetization Curves for Soft Steel Castings (G. E. Co.).

NOTE.—Steel forgings have a permeability somewhat less than steel castings. For forgings use the curve marked "Minimum."

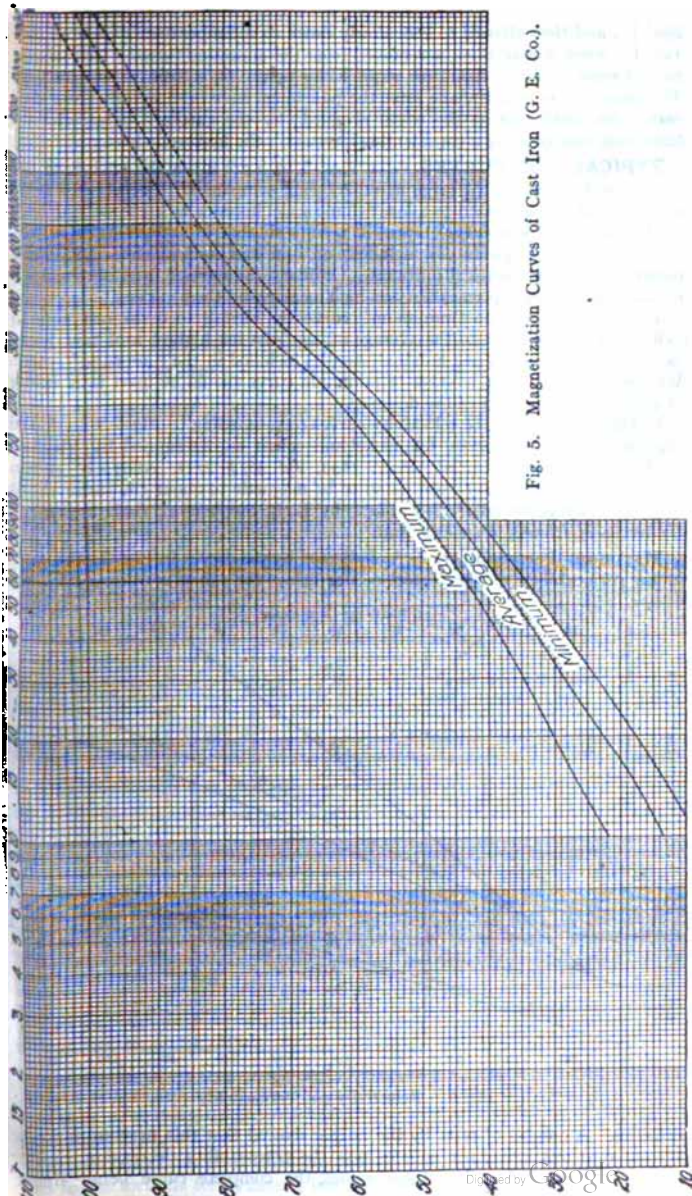


Fig. 5. Magnetization Curves of Cast Iron (G. E. Co.).

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850° C., and then allowed to cool slowly down to a temperature of from 100 to 150° C., when it may then be removed from the annealing furnace and allowed to cool more rapidly. The time required for annealing is from 12 to 36 hours. The annealing is usually done after the punchings have been made, thus eliminating the hardening at the edges produced by the cutting; otherwise this hardening may produce a considerable increase in the hysteresis loss.

TYPICAL *B-H* CURVES. — In Figs. 3 to 5 are given the standard *B-H* curves used by one of the large manufacturing companies. The abscissas (H) of these curves are plotted to a logarithmic scale, in order to increase the range of the curves. These curves represent results obtainable under ordinary commercial conditions (joints not included) on iron and steel of the composition found suitable for electrical purposes. Ordinary commercial iron or steel will not, as a rule, have a permeability as high as given by these curves.

The "maximum" and "minimum" curves in Figs. 3 to 5 do not refer to individual samples, but to the average of, say, the ten highest and ten lowest samples respectively in one hundred samples included in the "average" curve. Whether the maximum, average or minimum curve should be used is a matter of judgment on the part of the designer.

In Fig. 6 are given the reluctivity curves corresponding to Figs. 3 to 5, and also the reluctivity curves for nickel and cobalt as determined by Fleming, Ashton and Tomlinson (*Phil. Mag., 1899, Vol. 48, p. 271*). Alloys of certain non-magnetic metals have been found to be magnetic to about the same extent as nickel; see paper on *Heusler Alloys* by E. B. Stephenson, *Bull. 47 (1911), University of Illinois, Eng. Exp. Stat.*

Maximum Permeability. — As indicated by the curves in Fig. 3, the maximum permeability of sheet steel occurs below the range of commercial flux

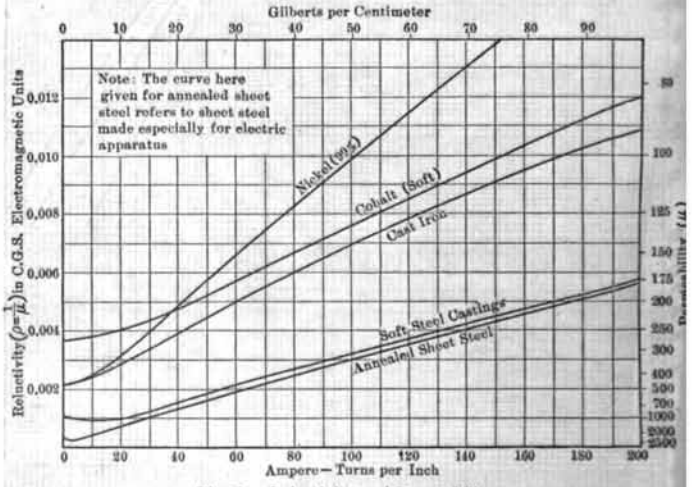


Fig. 6. Reluctivity and Permeability

densities. A number of tests by the author showed that this maximum occurs at from 6 to 10 kilolines per square inch, the permeability decreasing rapidly with flux densities less than these values, the complete curve being similar

ves shown in Fig. 6. The author has obtained a maximum ut 9000 c.g.s. units with ordinary electrical sheet steel, and oo c.g.s. units with silicon steel carefully annealed in small ing magnetic field (*Pender and Jones, Phys. Rev., 1913*). A h as 72,000 has been obtained by Yensen for pure iron heat- n (*Elec. Rev., London, 80, p. 539, 1917*). These exceptionally , however, are not obtained in practice under commercial ling.

S. — When a varying magnetic field is established in a e a certain amount of heat is developed due (1) to hys- the electric currents induced in the conducting mass. The re called eddy currents, and the total amount of energy ult of hysteresis and eddy currents is known as the core-

re-loss = hysteresis loss + eddy-current loss.

onent. — As already noted, the hysteresis loss is propor- of the hysteresis loop. Steinmetz (*Elec. Eng., 1890; Trans. ol. 9, p. 3*) found from a series of tests on a large number of ea of the hysteresis loop for a given sample is approximately 1.6 power of the maximum flux density corresponding to the

fficient. — If the magnetic field throughout the iron is *uni-* resis exponent is assumed constant and equal to 1.6, then the xpressed by the formula

$$P_h = KVfB^{1.6} \quad \text{or} \quad P_h = KWfB^{1.6},$$

e of iron,
ncy of alternating field, in cycles per second,
ium flux density,
or mass of the iron.

e factor K depends upon the units in which the other quan- l. If V is in cubic centimeters, B in gausses, f in cycles per rgs per second the formula is usually written

$$P_h = \eta VfB^{1.6}.$$

ergs per cycle per cubic centimeter is $\eta B^{1.6}$. The factor η metz's hysteresis coefficient and the quality of iron or steel steresis is frequently expressed in terms of this constant.

efficient η is not absolutely constant, even for a given sample, ny heterogeneity in the material of the sample, as, for example, ount of scale on the sheets of which the sample may be com- h heterogeneity the value of η increases with the flux density, rease depending upon the degree of heterogeneity. See Ball, *of Magnetic Laws for Steel and Other Materials, Journal of the April, 1916.*

oss is also sometimes stated as the watts per pound at 10,000 cles. Let w_1 = hysteresis loss in watts per pound at 10,000 cles. Then the corresponding value of η is:

vity = d	Specific Gravity = 7.7	Specific Gravity = 7.5
d	$\eta = 0.0013\, w_1$	$\eta = 0.00110\, w_1$.

e hysteresis loss only, excluding the eddy-current loss, which

able gives the value of K in terms of η when the various quan- la for hysteresis loss are in the units stated.

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FORMULA FOR CALCULATING HYSTERESIS LOS

$$P_h = KVfB^{1.6}$$

Power, P_h	Volume, V	Frequency, f	Flux density, B
Ergs per sec.	Cu. cm.	Cycles per sec.	Gausses
Watts	Cu. cm.	Cycles per sec.	Kilogausses
Watts	Cu. in.	Cycles per sec.	Kilogausses
Watts	Cu. in.	Cycles per sec.	Kilolines per sq. in.

$$P_h = KWfB^{1.6}$$

Power, P_h	Weight, W	Frequency, f	Flux density, B
Ergs per sec.	Grams	Cycles per sec.	Gausses
Watts	Kilograms	Cycles per sec.	Kilogausses
Watts	Pounds	Cycles per sec.	Kilogausses
Watts	Pounds	Cycles per sec.	Kilolines per sq. in.

d = specific gravity = 7.7 for ordinary electrical sheets = 7.5 for si

Hysteresis Loss for Various Substances. — The hysteresis lo and steel and other magnetic metals depends to so great extent chemical composition, physical structure, heat treatment, etc., th

VALUES OF HYSTERESIS COEFFICIENT

η = ergs per cycle per cubic centimeter for B = 1 gauss

w_1 = watts per pound at 60 cycles for B = 10,000 gausses

Metal	Values of η		Values
	From	To	From
Silicon steel, annealed sheets	0.0006	0.0015	0.55
Ordinary electrical sheets, annealed	0.00095	0.004	0.84
Soft cast steel	0.003	0.012	2.7
Cast iron	0.011	0.016	10
Forged steel	0.015	0.025	13
Hard cast steel	.....	0.028	....
Cobalt	0.012	.....	11
Nickel	0.013	0.040	12

values have no significance. The preceding table is intended to give the range of the value of the hysteresis coefficient for iron and steel used in electrical machinery; figures for nickel and cobalt are also included.

The extreme low values of η can seldom be uniformly realized in practice. One of the large manufacturing companies uses for design purposes the values $\eta = 0.00145$ for silicon steel and $\eta = 0.0033$ for ordinary electrical sheets, these values allowing a considerable margin for variations in the quality of the steel. For close design the particular quality of steel to be used should be carefully tested (*see Magnetic Testing*) and the test results used.

In Fig. 7 are plotted hysteresis loss curves for various values of η assuming the $B^{1.6}$ law.

Eddy-Current Loss. — When an alternating magnetic field is established in a conducting material alternating currents are set up in it due to the alter-

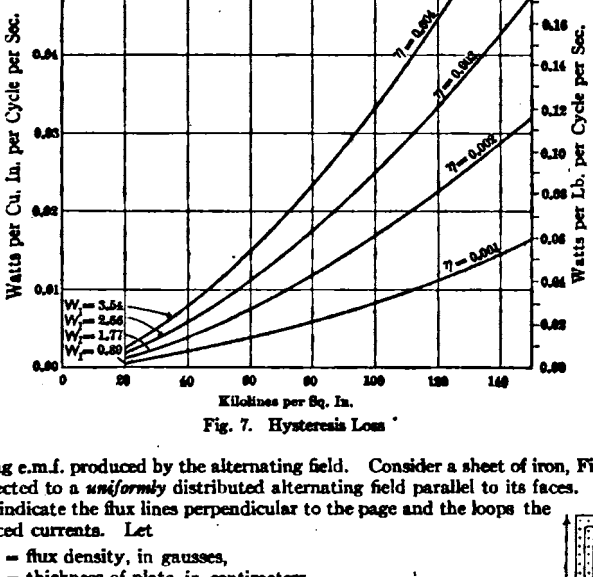


Fig. 7. Hysteresis Loss

nating e.m.f. produced by the alternating field. Consider a sheet of iron, Fig. 8, subjected to a *uniformly* distributed alternating field parallel to its faces. The dots indicate the flux lines perpendicular to the page and the loops the induced currents. Let

B = flux density, in gausses,
x = thickness of plate, in centimeters,
ρ = specific resistance of plate, in abohms per cm-cube,
$\frac{dB}{dt}$ = rate of change of flux density with time, gausses per second.

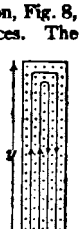


Fig. 8.

Then the *instantaneous* power loss per cubic centimeter of the sheet, when the thickness x is very small (1 per cent or less) compared with the width of the plate, is

$$p = \frac{x^2}{12\rho}\left(\frac{dB}{dt}\right)^2.$$

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The *average* power loss per cubic centimeter for a complete cycle of variation of the flux, in ergs per second, is

$$P_e = \frac{x^2}{12\rho} \times \left(\text{root-mean-square value of } \frac{dB}{dt}\right)^2.$$

It should be noted that this average loss depends upon the form factor (*see Alternating Currents*) of the rate of change of flux density, the latter being proportional to the counter e.m.f. induced by the varying field of the magnetizing coil.

If the induced voltage and therefore the flux density varies according to a sine function of the time, i.e., if $B = B_m \sin(2\pi ft)$, where B_m is the maximum value of the flux density, f the frequency, and t the time, then the average power loss due to eddy currents per cubic centimeter is

$$P_e = \frac{(\pi x f B_m)^2}{6\rho}.$$

If the voltage wave has a form-factor h, the loss for the *same* B_m is greater than this by the factor $\left(\frac{h}{1.11}\right)^2$; see below.

The corresponding formula for the eddy-current loss per unit volume in a wire or cylinder of radius r, magnetized *parallel* to its axis, to a *uniform* flux density over its cross section is

$$P_e = \frac{(\pi r f B_m)^2}{4\rho}.$$

Eddy-current Coefficient. — In practice the field in the sheets is seldom perfectly uniform, and eddy currents flow from one sheet to the other, unless they are insulated from each other; consequently the eddy-current loss in a core made up of a bunch of sheets is usually greater than that given by the above formula. The eddy-current loss in a laminated core is therefore usually expressed by the formula

$$P_e = K_1 V (xfB)^2,$$

or

$$P_e = K_1 W (xfB)^2,$$

where V and W are the volume and weight respectively of the core and B is the maximum flux density. The coefficient K_1 is determined from actual tests on a suitable sample (*see Magnetic Testing*).

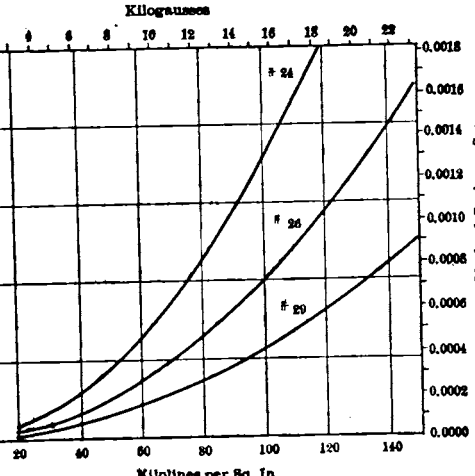
The coefficient K_1 (aside from its dependence upon the units in which the various quantities are measured) depends upon the specific resistance of the iron, the wave shape of the induced voltage, the distribution of flux in the sheets, the degree to which the sheets are insulated from each other, and upon the shape of the magnetic circuit in so far as this affects the distribution of flux. The results of the tests by Lloyd and Fisher also indicate that K_1 depends upon the value of B, or, in other words, that the eddy-current loss does not vary directly as the square of the maximum flux density, all other conditions being the same. At high frequencies, above 100 cycles per second, the loss also increases less rapidly than the square of the frequency, due to the increase in the effective resistance of the sheets as the result of an action similar to the skin effect (q.v.) in a wire carrying a rapidly alternating current.

When the loss P_e is expressed in watts, V in cubic centimeters, f in cycles per second, x in centimeters and B in gausses, the coefficient K_1 may be represented by the symbol ϵ, and the formula for eddy-current loss becomes

$$P_e = \epsilon V (xfB)^2.$$

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t loss is frequently stated as the watts per pound at 10,000
les for a thickness of sheet corresponding to No. 29 on the
= 0.0141 inch = 0.0358 centimeter). Let w_2 = eddy-current



9. Eddy-current Loss in Ordinary Electrical Sheet Steel

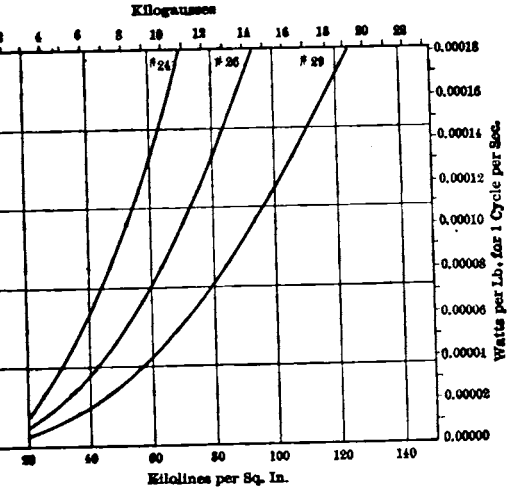


Fig. 10. Eddy-current Loss in Silicon Sheet Steel

r pound at 10,000 gausses and 60 cycles for sheets 0.0141 inch
ne corresponding value of ϵ is:

vity = d	Specific Gravity = 7.6	Specific Gravity = 7.5
$78\, w_2 d$	$\epsilon = 0.000368\, w_2$	$\epsilon = 0.000359\, w_2$

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FORMULA FOR CALCULATING EDDY-CURRENT LOSS*

$$P_e = K_1 V (xfB)^2$$

Power, P_e	Volume, V	Thickness of sheets, x	Frequency, f	Flux density, B
Ergs per sec.	Cu. cm.	Cm.	Cycles per sec.	Gausses
Watts	Cu. cm.	Cm.	Cycles per sec.	Kilogausses
Watts	Cu. in.	In.	Cycles per sec.	Kilogausses
Watts	Cu. in.	In.	Cycles per sec.	Kilolines per sq. in.

$$P_e = K_1 W (xfB)^2$$

Power, P_e	Weight, W	Thickness of sheets, x	Frequency, f	Flux Density, B
Ergs per sec.	Grams	Cm.	Cycles per sec.	Gausses
Watts	Kilograms	Cm.	Cycles per sec.	Kilogausses
Watts	Pounds	In.	Cycles per sec.	Kilogausses
Watts	Pounds	In.	Cycles per sec.	Kilolines per sq. in.

d = specific gravity = 7.7 for ordinary electrical sheets = 7.5 for silicon-st

Eddy-current Loss in Sheet Steel. — The eddy-current coeffi various makes of ordinary electrical sheets is subject to much the sa ation as the hysteresis coefficient, and the same is true for various silicon steel. The values given in the following table are for unifo distribution of flux and sinusoidal time variation.

VALUES OF EDDY-CURRENT COEFFICIENT †

ϵ = ergs per sec. per cu. cm. for 1 cycle per sec., thickness of 1 cm B = 1 gauss.

w_2 = watts per lb. at 60 cycles, thickness of 0.0141 in., and B gausses.

Kinds of sheets	Values of ϵ			Values of w		
	From	To	Average	From	To	A
Silicon steel.....	0.000043	0.000098	0.000065	0.12	0.27	
Ordinary electrical..	0.00012	0.00025	0.00022	0.34	0.70	

* These formulas are based on the assumption that the flux-time wave is s When this is not the case the total eddy-current loss is the sum of the losses several harmonics (including the fundamental) in the flux-time wave woul separately.

† From tests by L. T. Robinson, *Trans. A. I. E. E.*, *1911*, *Vol. 30*, *p. 741* and Fisher, *Bull. Bur. Stds.*, *1909*, *Vol. 5*, *p. 453*. The "average" values given by Mr. Robinson for "standard" and "alloyed iron" respectively.

Eddy-current-loss curves for ordinary electrical sheets are plotted in Fig. 9, and for silicon steel in Fig. 10, these being based on Robinson's values of w_1 and the formula given above, *which assumes uniform distribution of flux in the sheets and a sine-wave variation with time.* The numbers on the curves are the gage numbers of the sheets, viz.,

No. 29 gage = 0.0141 inch thick,
No. 26 gage = 0.0188 inch thick,
No. 24 gage = 0.0250 inch thick.

See *Gages, Sheet Metal.*

Effect of Wave Form on Core-Loss. — Experiments by M. G. Lloyd (*Bull. Bur. Stds., 1908, Vol. 5, p. 381*) show that for a given maximum flux density in the core the hysteresis loss is practically independent of the wave form of the counter induced e.m.f. in the exciting coil, provided the voltage wave does not pass through zero more than twice per cycle On the other hand, the eddy-current loss for a given maximum flux density depends upon the magnitudes of the harmonics which may be present in the voltage wave.

Effect of Direction of Grain in Silicon Steel. — According to Chubb and Spooner (*Elec. J., 13, p. 303, 1916*), whenever it is possible to avoid it, silicon sheet-steel should not be used with the lines of force perpendicular to the direction in which the sheets have been rolled, since the magnetic properties under these conditions are not at their best.

EXCITING CURRENT ANGLE OF HYSTERETIC ADVANCE. — For a given wave shape of the impressed e.m.f., the wave shape of the exciting current (neglecting eddy currents) is determined by the shape of the hysteresis loop, since the exciting current is proportional to the magnetizing force H. Curve I in Fig. 11 shows the wave shape of the exciting current for a sine wave impressed e.m.f. calculated from hysteresis loop in Fig. 2 for a maximum flux density of 10,000 gausses.

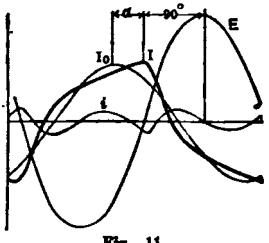


Fig. 11.

The sine curve I_0 is the fundamental of this wave (*see Wave Analysis*), and the curve i is the difference between I and I_0 and consists chiefly of the third harmonic.

The curve E is the sine wave of induced voltage. The flux curve would be a sine curve shifted 90° to the left (ahead of E). The angle α by which the fundamental of the current wave leads the flux wave is called by Steinmetz the "angle of hysteretic advance of phase."

For flux densities below the knee of the B–H curve the effective value of the fundamental current wave I_0 differs but slightly from the effective value of the actual current wave.

In the above discussion the effect of eddy currents is neglected. The effect of these is to increase the exciting current by a component of the same shape as, and in phase with, the impressed e.m.f., thus causing an increase in the effective value of the exciting current and an increase in the angle by which the exciting current leads the flux.

Magnetizing and In-phase Components of Exciting Current. — Let

P_0 = total core-loss,
E = back e.m.f. induced in the exciting coil,
I = exciting current,

$\cos \phi = P_0/EI$.

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Then $I \sin \phi$ is called the magnetizing component of the exciting cu
$I \cos \phi$ the in-phase (or energy) component. For magnetizations
knee of the B–H curve

$$\phi = 90 - \alpha',$$

where α' is the total angle of advance of the exciting current ahead c
due to both hysteresis and eddy-current losses.

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Lloyd, M. G., *Dependence of Magnetic Hysteresis upon Wave Form*,
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Oct., 1915; also *Bibliography* in article on *Magnetic Testing*.

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MAGNETIC TESTING. — (*See also Electricity and Magnetism, Principles of; Magnetic Properties of Iron and Other Metals.*) The ordinary magnetic tests of iron and other substances are: (1) The determination of the normal *B–H* curves and hysteresis loop, and (2) The determination of the core-losses, i.e., hysteresis and eddy-current losses. The following is a brief table of contents of this article:

DETERMINATION OF THE NORMAL *B–H* CURVES AND HYSTERESIS LOOP. — Under certain conditions, noted below, the magnetizing force H may be calculated in terms of the number of turns per unit length and the current. The flux density B may be measured in any one of three ways: (1) By winding on the sample a secondary or "test" coil and connecting in series with it a ballistic galvanometer or equivalent device (e.g., a fluxmeter, q.v.) and noting the deflection of this instrument when the current in the primary or "magnetizing" coil is changed in value or reversed; (2) by measuring the mechanical force required to separate one end of the sample from a yoke which, with the sample, forms a closed magnetic circuit; and (3) by measuring the change in resistance of a spiral of bismuth inserted in an air gap between two parts of the sample or between the sample and a yoke. (4) In addition the permeability of two samples may be compared by a device known as a permeability bridge, in which the detector is a magnetometer or compass. These four methods may be designated respectively as the ballistic, traction, bismuth spiral and bridge methods respectively. The first is best suited for precision measurements, the last three for rapid shop tests where great accuracy is not demanded.

Magnetic Circuit of Testing Apparatus. — The simplest form of circuit is a straight bar, which is placed inside a solenoid or helix, the flux returning through the air. With this type of circuit, however, unless the bar and coil are very long, the demagnetizing action of the magnetic poles formed at the ends and along the sides of the bar render it impossible to calculate with accuracy the resultant magnetizing force in the bar. If the sample is made in the form of a closed iron ring, the mean magnetizing force over the cross-section of the metal may be calculated, but unless the radial thickness of the metal is small compared with the radius of the ring, the magnetizing force will be appreciably greater near the inner edge than near the outer edge, and as the permeability is a function of the magnetizing force, an appreciable error may be introduced. Also, the difficulty of winding the coils on a ring makes its use objectionable.

Bar and Yoke. — As a compromise, the sample is usually made in the form of a rod (or bunch of straight strips, in the case of sheet steel) which is fitted into a massive yoke of low reluctance which completes the magnetic circuit. The magnetizing coil is wound on the sample only. As a first approximation, in case the joints between sample and yoke are well made, the reluctance of the yoke and joints may be neglected, and the magnetizing force per unit length of the sample taken as the total magneto-motive force divided by the length of the sample. Methods have been devised for correcting the effect of the yoke and joints as described below.

Demagnetizing the Sample. — After the sample has been mounted ready for test (inserted in the yoke, if a bar and yoke method is employed) the circuit is thoroughly demagnetized by an alternating magnetizing force, preferably of about 1 period per second, which is gradually reduced from an initial intensity which establishes an induction well beyond the point of maximum induction to be measured to a final value somewhat lower than the lowest induction to be measured.

Ordinary Ballistic Method. — The connections are shown in Fig. 1. A ring sample is here shown, but this may be replaced by a straight sample

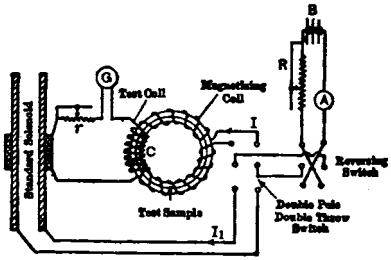


Fig. 1. Connections for Ballistic Method of Measuring Permeability

or by a straight bar in a yoke, Fig. 2. The test coil on the sample, the ballistic galvanometer G, the secondary coil of the standard solenoid and a resistance r are all connected permanently in series. This

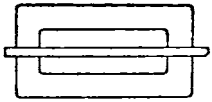


Fig. 2. Bar and Yoke

resistance is adjusted so that the galvanometer shows a suitable deflection when the current in the magnetizing coil of the test sample is reversed. The galvanometer is then calibrated (*see Galvanometers*), keeping this resistance unchanged. A double-pole double-throw switch is provided for connecting the battery circuit at will to the magnetizing coil on the test sample or to the primary coil of the standard solenoid. The sample should be in place when the galvanometer is checked, as the hysteresis and eddy-current losses due to the variable current in the primary during the test have the same effect as an increase in the resistance of the galvanometer circuit. (*See Burrows, C. W., Bull. Bur. Standards, 1909, Vol. 6, p. 31.*)

Precautions. — For a high degree of precision the sample should be placed with its axis perpendicular to the earth's field, the apparatus should be protected from mechanical vibration, and should be sufficiently remote from any strong magnets (such as the permanent magnets in ammeters and voltmeters) in order not to be affected by their magnetic fields.

Calibration of Galvanometer. — Let

N_1 = number of turns in primary of standard solenoid *per centimeter length* (axial),
n_1 = total number of turns in secondary coil of standard solenoid,
n = total number of turns in secondary coil on test sample,
A_1 = mean cross-section, in square centimeters of primary coil of standard solenoid if secondary is on the outside; if the secondary is inside the primary A_1 is the mean cross-section of the secondary,
A = cross-section in square centimeters of the test sample,
a = mean cross-section in square centimeters of the magnetizing coil on test sample if the test coil is on the outside; if the test coil is on the inside a is the mean cross-section of the test coil,
I_1 = current established through primary of solenoid,
D = deflection of galvanometer when this current is reversed,
B = flux density in test sample corresponding to a deflection D when the current through the magnetizing coil on the sample is reversed,
H = magnetizing force in sample corresponding to the flux density B.

The flux in maxwells established by the current I_1 through the primary of the solenoid is then $0.4\pi N_1 I_1 A_1$, and the number of linkages of this flux with the secondary of the standard solenoid, i.e., with the galvanometer circuit, is $0.4\pi n_1 N_1 A_1 I_1$. When the double-throw switch is thrown to connect the battery to the magnetizing coil on the test sample, establishing in this coil a current I and a flux density B, the number of linkages between the flux in the test sample

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and the galvanometer circuit will be $BnA + Hn(a - A)$. If these two linkages are equal, as they will be if the galvanometer shows the same deflection D when I is reversed through the magnetizing coil on the test sample as when I_1 is reversed in the primary of the solenoid, then

$$B = \frac{0.4\pi n_1 N_1 A_1}{nA} I_1 - \frac{a - A}{A} H. \qquad (1)$$

Or, putting

$$K = \frac{0.4\pi n_1 N_1 A_1}{nA},$$

which is a constant for a given solenoid and sample, then

$$B = KI_1 - \frac{a - A}{A} H. \qquad (2)$$

The correction term $\left(\frac{a - A}{A}\right) H$ is usually negligible except for very low values of the flux density.

Hence, by sending various currents I_1 through the primary of the solenoid, reversing these currents and noting the deflection D, a curve may be plotted showing the relation between B ($= KI_1$) and D. Then, when a given current is reversed through the magnetizing coil on the test sample and the deflection D noted, the flux density corresponding to this current may be read directly from the curve. This curve will be practically a straight line unless the damping of the galvanometer is excessive.

The calibration curve holds only for a constant total resistance in the galvanometer circuit (*see Galvanometers*). If it is necessary to change this resistance in order to alter the sensibility of the galvanometer a new calibration curve must be obtained.

Calculation of Magnetizing Force. — Let

N = number of magnetizing turns per centimeter of mean circumference (*see Fig. 1*). If a straight sample with or without a yoke is used, N is taken as the total number of magnetizing turns divided by the free length of the sample in inches.

I = current in magnetizing coil in amperes.

Then the magnetizing force in gilberts per centimeter is

$$H = 0.4\pi NI. \qquad (3)$$

This formula represents the *average* magnetizing force over the section of the ring, if a ring sample is used. If a straight sample is used, the formula is approximate only, due to the reluctance of the return circuit through the air or yoke.

Determination of Normal B–H Curve by Ballistic Method. — The sample is first demagnetized as described above, then the lowest magnetizing force to be used is applied and reversed many times until the iron is brought to a cyclic magnetic state, that is, until the reversal of the magnetizing force reverses the direction of magnetization without changing its magnitude. The number of reversals required to establish a cyclic condition in soft steel ranges from about 10 at high flux densities to several hundred at low flux densities. In general the harder the steel the fewer the number of reversals required. The galvanometer deflection is then noted, and the corresponding value of B taken from the calibration curve and H calculated from the formula given above. As a check, it is well to carry the iron through the demagnetizing process again, reduce to a cyclic state, and redetermine the point.

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Higher points on the curve may be obtained in a similar manner, but it is not necessary to demagnetize the sample between successive points unless it accidentally becomes magnetized above the point being determined.

Determination of Hysteresis Loop by the Ballistic Method. — The sample is first demagnetized and then the maximum magnetizing force (corresponding to the tip of the loop) is applied and a cyclic condition established as described in the preceding paragraph. By suddenly inserting an additional resistance in the magnetizing circuit, e.g., by moving the slider on the resistance R so that less of this resistance is short-circuited, the magnetizing force is reduced to any desired value, and the change in flux density corresponding to this change in magnetizing force is determined by noting the galvanometer deflection. If the calibration curve of the galvanometer has been obtained by the method of reversals, as described above, the change in flux density is twice the value of B as read from the calibration curve, since the actual change in flux corresponding to any ordinate of the calibration curve is twice this ordinate.

The next point on the hysteresis loop is determined in the same manner, first bringing the iron to a cyclic state under the maximum magnetizing force corresponding to the tip of the loop. Data with negative values of the magnetizing force are obtained by reversing the currents in addition to making the adjustments already described. The points on the hysteresis curve may be taken in any order.

In this method of obtaining hysteresis data, the measured quantity is the change in induction when the magnetization is changed at one step from a maximum to any other given point on the hysteresis loop. This method is comparatively free from the irregularities due to the slow creep that occurs when a magnetizing force is applied slowly or changed by small steps. It is also free from irregularities due to variations in the size of step in the "step-by-step" method, in which the magnetizing force is changed from one value to the next lower without restoring it each time to the maximum value. (*See Burrows, Bull. Bur. Standards, 1909, Vol. 6, p. 1.*)

Zero Ballistic Methods for Determining Flux Density. — By using an independent battery circuit to energize the primary of the standard solenoid and establishing the currents I_1 and I at the same time and reversing them simultaneously, it is possible by having the relative directions of these currents right, so to adjust I_1 that for a given value of I the net discharge through the galvanometer is zero, and no deflection occurs. Under this condition B may be calculated directly from equation (1) or (2) above.

Instead of using a standard solenoid with fixed coils, an adjustable mutual inductance, previously calibrated, may be used, and a constant current maintained through its primary, the adjustment being effected by moving the secondary. Let

M = mutual inductance of standard, in henries,
I = current in amperes, in primary of mutual inductance,
n = total number of turns in test coil on sample,
A = cross-section of sample in square centimeters,
B = flux density in sample for balance.

Then

$$B = 10^8 \frac{MI}{nA} = K_1 M,$$

where $K_1 = \frac{10^8 I}{nA}$ = a constant for a given test coil and sample and given current in the primary of the mutual inductance.

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The design of a standard mutual inductance suitable for this purpose is described in detail by Burrows, *Bull. Bur. Stds., 1909, Vol. 6, p. 31.*

Burrows' Compensated Double-Yoke Method. — This method, described in detail in Vol. 6 of the Bulletins of the Bureau of Standards (*Reprint No. 117*), is the standard method used by the Bureau of Standards and has also been adopted as the standard method of testing permeability by the American Society for Testing Materials, see *Proc. Am. Soc. Test. Mat., 1912.* The following description of the method is taken from Burrows' paper.

Fig. 3 shows the relative positions of the magnetizing and test coils when double yokes and double rods are used. The lower rod is the one under test.

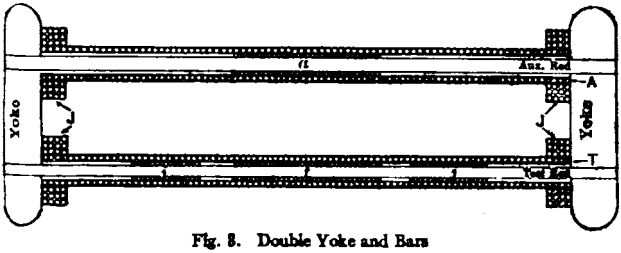


Fig. 3. Double Yoke and Bars

The upper rod is an auxiliary rod of approximately the same magnetic properties as the test specimen. *T* and *A* are the two main magnetizing coils, one wound over each rod. Over the four joints are wound four short coils *J*, each about 1.5 centimeters long. These are connected in series and used as a single coil. *t* and *a* are the two test coils surrounding test and auxiliary specimen respectively. *j* is the end test coil distributed with one-half over each end of the test rod.

Test Samples. — When rods are to be tested these should preferably be of square cross-section, ⅜ by ⅜ inch (0.9525 cm.) and 30 cm. long. With rods of square cross-section it is possible to make a more perfect joint between the rods and yokes. Sheet steel is tested by making up two equal bundles of strips 3 centimeters wide by 50 centimeters in length, having a total weight of 5 kilograms (*Stand. Spec. of Am. Soc. Test. Mat., June, 1912*). Each bundle will be about 2.25 centimeters thick. One bundle takes the place of the test rod, the other takes the place of the auxiliary rod.

Yokes. — The yokes are of soft iron, provided with suitable clamps for holding the sample firmly and making a good magnetic joint. When sheet steel is being tested, the yokes may be made of short strips of the material 3 centimeters wide, the magnetic circuit in this case being a rectangle made up of strips, the joints at the four corners being alternately butt and lap in successive layers.

Magnetizing Coils. — No. 18 A. W. G. double-cotton-covered copper wire is a convenient size. A coil made of ten layers of this wire will stand continuously a current of 1.7 amperes, corresponding to a magnetizing force of $H = 171$ gilberts per centimeter. For short periods twice this current may be safely employed, giving a magnetizing force of about 350 gilberts per centimeter. The length and diameter of the coils will depend upon the dimensions of the test sample (see above). If the coils are made of round cross-section the hollow core on which they are wound should have a shallow screw thread, 8 threads to the centimeter, cut on the outside. The first layer is wound in this thread, and succeeding layers wound in the same direction between adjacent wires in the previous layer. The various layers are then connected in series. The mag-

netizing force at the center of such a coil of ten layers, assuming perfect compensation for the rest of the magnetic circuit, is

$$H = 0.4\pi \times 8 \times 10 I = 100.53 I,$$

where I is the current in the coil.

Test Coils. — The test coils are made of fine wire (enameled or silk covered) wound on thin cores of paper, cloth or slotted metal. Coils t and a are placed over the middle portions of the test rod and auxiliary rod, respectively. Over the two ends of the test rod are placed the two halves of a third test coil j. These three test coils have the same number of turns and are spread over a considerable length of rod, so as to prevent any irregularities which may exist in the iron from exerting a preponderating influence. If the test coils are placed inside the magnetizing coils the correction for the flux between the rod and the coil will be small.

Connections for Permeability Test. — Fig. 4 shows diagrammatically the full scheme of electric circuits both primary and secondary. The coils T, J, A, t, j and a are the same as those of the same letters in Fig. 3. The coils M and m are the primary and secondary of the variable mutual inductance (or standard solenoid) used to balance the e.m.f. induced in the test coil.

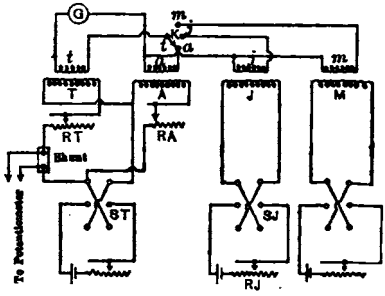


Fig. 4. Connections for Burrows' Method of Testing Permeability

Compensation. — Compensation is secured when the flux across every section of the iron circuit is the same, i.e., when there is no leakage. This condition may be closely realized by adjusting the currents in the three magnetizing coils separately.

The switches ST and SJ are reversed repeatedly, and the resistance RA and RJ adjusted until the three test coils, t, j and a, indicate the same change in flux when the magnetizing currents are simultaneously reversed, i.e., switches ST and SJ reversed simultaneously. With the key K on the point t–a, the equality of flux in the test and auxiliary rods is secured first by adjusting RA until the galvanometer shows no deflection on reversing ST. Then with the key K on the point t–j the flux near the magnetic joints is adjusted to uniformity.

Measurement of Induction. — To measure the induction K is moved to the point t–m. A reversal of the magnetizing forces produces an impulsive electromotive force acting on the galvanometer, which may be measured as a deflection or may be compensated for by reversing simultaneously a suitable current through a variable mutual inductance, or standard solenoid M.

Measurement of Magnetizing Force. — For accurate work the current should be measured by means of a potentiometer (*see Potentiometers*). If the shunt used for measuring the current has a resistance of 1.0053 ohms and the magnetizing coil T 80 turns per centimeter, then

$$H = 100 V,$$

where V is the fall of potential across this shunt.

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STANDARD INDUCTION TESTS OF THE A.S.T.M. (1921 Edition). — The normal magnetic induction is the induction produced by a magnetizing force in a given piece of magnetic material which has been previously demagnetized and then subjected to many reversals of the given magnetizing force.

Both the induction B and the magnetizing force H shall be expressed in terms of the C. G. S. electromagnetic unit (gauss).

Sheet Metal. — The standard normal induction data for sheet material shall consist of the magnetizing forces corresponding to inductions of 2000 4000, 6000, 8000, 10,000, 12,000, 14,000, 16,000, 18,000, 20,000 gausses, or such as may be obtained without exceeding a magnetizing force of 200 gausses.

The following details are to be observed:

The permeability sample for sheet material shall consist of an even number of strips cut parallel to the direction of rolling, and even number of strips cut perpendicular to that direction selected from material sampled as for core loss.

The sample shall weigh not less than 1 nor more than 2 kg.

The magnetic circuit shall be a rectangle having the test material for one pair of opposite sides, and the same or different material for the other pair, which may be shorter. The joints at each corner are alternately butt and lap, or may be clamped on the edges.

The magneto-motive force is applied in two sections. The main magnetizing coils shall consist of two equal uniformly-wound solenoids surrounding the test material. The compensating coils shall consist of four short coils, each having the same number of turns wound closely over the ends of the magnetizing coils.

The test coil surrounds the middle portion of each bundle of test material. Four other test coils each of half the number of turns are placed over the four positions of the test material, approximately midway between the yokes and the center. The two center test coils are joined in series and the four end test coils are joined in series. The corresponding ballistic deflections, due to these two sets of test coils, are measures of the magnetic fluxes through the underlying portions of the magnetic circuit. By connecting the two test coils so that the induced electromotive force opposes that of the four coils, and adjusting the current through the compensating magnetizing coils so that there is no resulting ballistic deflection, an approximate uniformity of flux is secured through the greater portion of the test material, and the induction may be measured ballistically in the regular manner. The magnetizing force when the flux is adjusted to uniformity is that calculated from the uniform winding of the main magnetizing solenoids.

The cross-section of the magnetic circuit is determined as in the standard core-loss test.

Rods. — The standard test for rods for use in electromagnets shall consist of the magnetizing forces corresponding to induction of 2000, 4000, 6000, 8000, 10,000, 12,000, 14,000, 16,000, 18,000, 20,000 gausses, or such as may be obtained without exceeding a magnetizing force of 200 gausses.

The standard data for material intended for permanent magnets shall consist of the normal induction (B), the normal residual induction (B_r), and the normal coercive force (H_c) corresponding to a magnetizing force of 200 gausses.

Standard magnetic data shall be determined by the Burrows compensated double-yoke method. (For further details see *A.S.T.M. Standards.*)

Permeability Bridge. — A double-bar and yoke arrangement, such as shown in Fig. 3, may be ured without compensating or test coils to obtain a fairly

accurate measure of the permeability of a sample, provided the *B–H* curve of one of the rods is known. A small magnetic needle or compass placed in the air space between the two rods is used as a detector of magnetic leakage from one rod to the other. The currents in the two magnetizing coils are adjusted until the needle shows no deflection when the currents in the two coils are reversed. The total flux in each rod will then be the same. The magnetizing forces in the two rods are then calculated from the currents in the magnetizing coils (*equation 3 above*) and the flux from the *B–H* curve of the standard sample.

PERMEAMETERS FOR SHOP TESTS. — A great number of approximate methods have been devised for the rapid testing of permeability in shop work, where a high degree of precision is not required. Some of these are briefly described below.

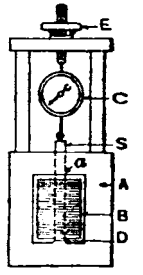


Fig. 8. Thompson Permeameter

Thompson Permeameter (Fig. 5). — In this instrument the flux density is measured in terms of the force required to separate a rod *S* from a yoke *A*, when the magnetic circuit formed by the rod and yoke is magnetized by a current in the coil *B*. The handle *E* is turned until the sample is pulled away from the yoke and reading on the balance taken at the instant of break.

Let

I = amperes in magnetizing coil,
N = number of turns in magnetizing coil,
l = "equivalent" length of magnetic circuit in inches = distance from *a* to *D* plus from 10 to 20 per cent to allow for reluctance of yoke and joints,
P = pull in pounds as read by balance,
A = cross-section of rod *S* in square inches.

Then the magnetizing force is

$$H = \frac{0.4\pi NI}{2.54\,l},$$

and the flux density is, within the accuracy of measurement by the instrument,

$$B = 1320\sqrt{\frac{P}{A}}.$$

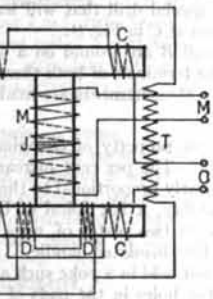
There are several errors in the instrument, however, notably the unavoidable air gap between the sample and the top of the yoke and the contact at *D*, which makes the instrument unsuitable for the accurate determination of the absolute values of the qualities of iron and steel. It is, however, extremely useful for the comparison of samples where exact absolute values are not required. More nearly absolute values can be obtained by properly calibrating the instrument by using a standard sample the permeability of which at various flux densities has been measured by a more accurate method.

Fahy Permeameter. — This apparatus (Fig. 6) is H-shaped with test coils *ST* spanning the free ends of the *H* and a magnetizing coil *M* wound on the cross-piece. *D* and *D'* are also test coils. *SDD'T* have the same number of turns and are connected in series and in such a manner that the integrated e.m.f.'s induced in *S* and *D'* when a magnetizing current is reversed in *M* are in the same direction but in opposition to those simultaneously induced in *D* and *T*. The permeameter is initially adjusted so that when the coils *S* and *T* encircle air the differential effect of the coils *D* and *D'* is zero. In use, *S* encircles a standard bar bridging the gap on the left and *T* the test-bar bridging the gap on the right. In the cross-bar is an air-gap *J*, designed to create a demagnetizing force within

which is adjustable to suit requirements. Magnetomotive pplied in the compensating coils C and the currents in M and tly adjustable. When current is flowing in both M and C uit has its m.m.f. increased and that of the other circuit is equal amount.

g the current in the compensating coils the difference in fluxes oils D' and T can be made equal to the difference in fluxes When these flux differences are equal, the leakage flux through is in parallel with the path of the coil T is equal to the leakage th in parallel with S. Since these two paths are symmetrical e flux, the same difference of magnetic potential exists between H has a relatively large number of turns. It is wound on the d may be used to measure the difference of magnetic potential hence the mean magnetizing force, which will be that obtain- of T in which the test specimen lies.

consistency of repetition, effect of length of test specimen, ts, effect of iron in the vicinity, position of specimen on the rain effect the instrument represents a distinct advance on meameters in common use. Normal induction measurements errors no greater than 5 per cent of the magnetizing force ven induction. Commercial materials are seldom uniform t better precision than 5 per cent. The instrument is also measurement of sheet materials. For a complete description and its use see *Bull. Bur. Stands., 14, p 267, 1917.*



Fahy's Permeameter

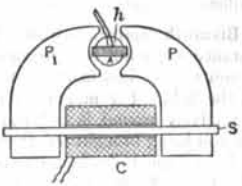


Fig. 7. Koepsel Permeameter

eameter (Fig. 7). — The magnetic circuit consists of the heavy soft-iron pole pieces P and P_1, with a gap and soft- lar to the gap and core in the voltmeter). A small coil h is gap and connected to an auxiliary current supply. The sample current passing through the magnetizing coil C. The flux magnetic circuit causes the coil h to deflect an amount pro- flux, for a constant strength of auxiliary current. The de- ed by a pointer, attached to the coil h, swinging over a scale to read directly in flux densities. The calibration of the not hold for wide variations in the permeability of the samples depends upon this permeability. Also the magnetizing force d only approximately. These difficulties can be overcome placing compensating coils on the yokes P and P_1 and sending

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sufficient current through these to compensate for the leakage. For detailed description see *Bull. Bur. Stands., 11, p. 101, 1914.*

Esterline Permeameter. — This instrument is similar to the Koepsel apparatus except that the moving coil and core (*h* and *A* in Fig. 7) are replaced by a small direct-current armature. The apparatus then becomes a small separately-excited dynamo. The armature is driven by an auxiliary motor at a constant speed. The voltage across the armature is then directly proportional to the total flux cutting the armature conductors. Leakage is avoided by the use of compensating coils on the pole pieces. The current in these compensating coils is adjusted until a small compass placed near the magnetic circuit of the apparatus shows no deflection when the magnetizing and compensating currents are simultaneously reversed. The apparatus is described in detail in *Proc. Am. Soc. Test. Mat., 1906, Vol. 6, p. 320.*

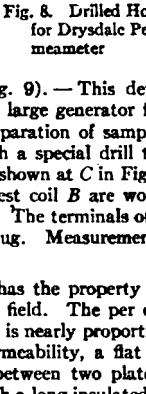


Fig. 8. Drilled Hole for Drysdale Permeameter

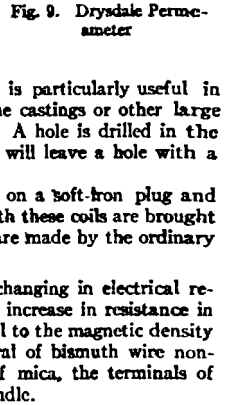


Fig. 9. Drysdale Permeameter

Drysdale Permeameter (Fig. 9). — This device is particularly useful in determining the permeability of large generator frame castings or other large masses of metal without the preparation of samples. A hole is drilled in the casting at any point desired with a special drill that will leave a hole with a core in the center similar to that shown at *C* in Fig. 8.

A magnetizing coil *A* and a test coil *B* are wound on a soft-iron plug and inserted into this hole as shown. The terminals of both these coils are brought out through small holes in the plug. Measurements are made by the ordinary ballistic method.

Bismuth Spiral. — Bismuth has the property of changing in electrical resistance when put in a magnetic field. The per cent increase in resistance in bismuth when in a magnetic field is nearly proportional to the magnetic density of the field. For measuring permeability, a flat spiral of bismuth wire non-inductively wound is fastened between two plates of mica, the terminals of the coil being brought out through a long insulated handle.

The sample is made in two pieces and held in a yoke such as shown in Fig. 2. The two rods are inserted through the holes in the ends of the yoke and are pushed in until only a small air gap is left between their opposing ends. The bismuth spiral is inserted in this gap. The resistance of the spiral is measured with a Wheatstone's bridge and the flux density determined from a curve furnished with the spiral giving the variation in resistance with varying density. The calculated value of the magnetizing force must be corrected for the reluctance of the yoke and air gap.

CORE-LOSS MEASUREMENTS. — A great number of methods have been suggested for determining the core-loss in a sample of iron or steel when subjected to an alternating field. These methods may be classified as: (1) hysteresis loop method; (2) wattmeter method; (3) mechanical torque methods. Of these the wattmeter method, when a properly constructed magnetic circuit is employed, gives the most reliable results. The hysteresis loop method is tedious and gives no knowledge of the eddy-current loss. The mechanical torque methods necessitate an air gap in the magnetic circuit with a resulting induction in the specimen which is far from uniform; these latter methods, however, are frequently used where high degree of accuracy may be sacrificed

to speed in testing, e.g., in comparative shop tests.

Hysteresis Loss from Hysteresis Loop.—The hysteresis loop may be determined by any of the methods described above. The loop is plotted on cross-section paper and integrated. Plot the magnetizing force, in gilberts per centimeter, to a scale of h gilberts per centimeter equal to 1 inch and the flux density to a scale of b gausses equal to 1 inch. Then if A is the area of the loop in square inches, the hysteresis loss, in ergs per cycle per cubic centimeter of iron, is

$$W = \frac{hbA}{4\pi}.$$

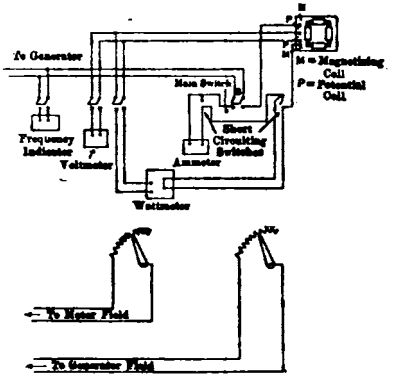


Fig. 10. Connections for Core-loss Tests

Principle of Wattmeter Method of Determining Core-Loss. — Fig. 10 is a complete diagram of connections. The principle of this method is as follows: The sample to be tested is inserted in a magnetizing coil of a known number of turns, under* which is wound a secondary coil having either the same number of turns or a multiple thereof. The primary coil is connected in series with a source of alternating e.m.f. (which can be adjusted without changing its wave form) and the current coil of a wattmeter. The potential coil of the wattmeter is connected to the secondary coil on the test sample. A voltmeter is also connected across this secondary coil.

Let

N_1 = number of primary turns,
N_2 = number of secondary turns,
A = cross-section of sample in square centimeters,
f = frequency in cycles per second,
k = form factor of secondary voltage,
B = maximum flux density in sample, assumed constant throughout its length,
V = reading of voltmeter,
P = reading of wattmeter,
$R = r + \frac{R_1 R_2}{R_1 + R_2}$, where r is the resistance of the secondary coil, R_1 the resistance of the voltmeter and R_2 the resistance of the potential coil of wattmeter.

The resistance R should be sufficiently large so that the heat developed (V^2/R) in the secondary circuit is small compared to the core-loss, and the resistance r of the secondary coil should also be small compared with R. Then if the instruments are calibrated to read correctly and P and V are read simultaneously, the total core-loss is, assuming r negligible compared with R,

$$P_c = \frac{N_1}{N_2} P - \frac{V^2}{R},$$

and the maximum flux density is

$$B = \frac{10^8 V}{4kfAN_2}.$$

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* The two windings may also be "sandwiched."

Test Specimen with Single Coil. — The core-loss test can also be made with a single coil (the magnetizing coil) on the sample with the voltmeter and potential circuit of the wattmeter connected to the terminals of this coil. In this case, however, the voltage read by the voltmeter must be corrected for the resistance drop in the magnetizing coil, and the wattmeter reading for the rI^2 loss in this coil. The two-coil method also has the advantage that the wattmeter reading can be made any multiple of the actual loss by using a proper ratio of N_2/N_1, thus enabling one to measure small losses with greater accuracy.

Control of Impressed E.M.F. — The e.m.f. impressed across the terminals of the magnetizing coil should have a sine wave form for all values of the maximum flux density at which tests are to be made. To secure this condition it is necessary that the e.m.f. of the generator supplying the current have a sine wave form, and that the resistance and reactance of both the generator and the circuit between the generator and the test sample be as small as possible, as the magnetizing current, having a distorted wave form due to hysteresis (*see Magnetic Properties of Iron*), will introduce a voltage drop having a non-sine form, thus distorting the impressed voltage wave.

The impressed voltage should therefore be controlled through the field of a generator having a large capacity compared to the power taken by the test sample, or instead of varying the field a transformer with suitable taps may be used, provided the resistance and leakage reactance of the transformer are small. In either case, the generator should give a sine wave at all field excitations within the range used. If this condition cannot be realized the hysteresis and eddy-current losses should be separated by measuring the total loss at two frequencies and the total loss then corrected for form factor (see below).

Form of Specimen for Wattmeter Test. — The specimen may have one of three forms: (1) It may be in the form of straight strips, the flux lines returning through the air; (2) straight strips may be used with a yoke; and (3) the specimen may be arranged to form a closed magnetic circuit in itself.

The first form gives a distribution of flux which is far from uniform. It is possible, however, by determining the flux distribution in the sample by means of an exploring coil to correct the observed losses for this flux variation (*see Robinson, L. T., Trans. A.I.E.E., 1911, Vol. 30, p. 741*).

The second form gives a more uniform flux, but it is necessary to distinguish between the energy supplied to the specimen and that supplied to the yoke. This can only be done satisfactorily by knowing the constants of the yoke, and only then by having the distribution of flux uniform, a condition difficult to secure.

Consequently, for accurate measurements the third form is the most reliable, although for factory use the first or second may prove more convenient where accuracy can be sacrificed for other considerations. The material used should be cut in a form such that only a small part of it is contiguous to a cut edge since all methods of cutting have a hardening effect upon the material bordering upon the cut. This means that the strip, whether straight or in ring form, should not be too narrow. This condition may be dispensed with if all specimens are annealed under definite conditions after cutting to size, and prior to testing.

Two general forms of magnetic circuit are available. The material may be stamped into rings (as in the Esterline apparatus), or the circuit may be built up from straight strips as in the Epstein apparatus. Leakage is most effectually avoided by using rings. With this form of specimen, however, the flux density will not be uniform unless rings of very great diameter are employed, and in the latter case there is a very great waste of material. The non-uniformity of flux existing in rings of small diameter, even when uniformly wound, and the errors resulting therefrom, are discussed by Loyd, M. G., *Bull. Bur. Stds., 1909, Vol. 5, p. 435*. The use of rings is thus restricted to cases where the

d after stamping, and the radial width of the ring should be nparison to its diameter. When rings are employed, the each specimen separately with a magnetizing coil may be se of the apparatus of Esterline (*see p. 925*) or Möllinger *N. 22, p. 379*).

ethod.—This method has been adopted as the standard in the American Society for Testing Materials in this country. mercial testing by both the General Electric and Westing- The method is clearly described in the standard specifica- ore-loss tests given in the following paragraph.

Standard Core-loss Tests. (1921 Edition.)—The power ctrical sheet steel when subjected to an alternating magnet- s the core-loss. The standard core-loss is the total power in each kilogram of material at a temperature of 25° C., when rmonically-varying induction having a maximum of 10,000 quency of 60 cycles per second, when measured as specified sented by the symbol $W_{10/60}$.

cient is the percentage change in the standard core-loss after at 100° C. for 600 hours.

re-loss shall be measured under the following conditions:

rcuit consists of 10 kilograms (22 pounds) of the test material, ear into strips 50 centimeters (19 11/16 inches) long and 3 centi- s) wide, half parallel and half at right angles to the direction p into four equal bundles, two containing material parallel material at right angles to the direction of rolling, and finally sides of a square with butt joints and opposite sides consisting the same manner. No insulation other than the natural rial (except in the case of scale-free material) shall be used ns, but the corner joints shall be separated by tough paper 004 inch) thick.*

g winding shall consist of four solenoids surrounding the magnetic circuit and joined in series. A secondary coil shall ing the voltmeter and the potential coil of the wattmeter. shall be wound on a form of any non-magnetic non-conducting owing dimensions:

ection	4 by 4 cm.
wall	not over 0.3 cm.
h	42 cm.

ing on each solenoid shall consist of 150 turns of copper wire over the 42-centimeter length. The total resistance of the ng shall be between 0.3 and 0.5 ohm. The secondary wind-

this paper is to prevent the exposed end of the laminations being s between those in the adjacent side of the other part of the sample ormation of eddy currents at the corners which may not be confined e laminations if the paper is not used. The certainty of the measure- proved by a small but definite amount over the results which are e paper in the joints. This improvement is of course accomplished me increase of leakage flux at the corners and consequently greater lute uniformity of flux distribution along the length of the sample, mposed upon wattmeter are more severe as the general power factor distribution over a section of the sample is more uniform with the lt is a definite gain in accuracy.

(*L. T. Robinson.*)

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ing of 150 turns of copper wire on each solenoid shall be similarly wound beneath the primary winding. Its resistance shall not exceed 1 ohm.

A voltmeter and the voltage coil of a wattmeter shall be connected in parallel to the terminals of the secondary winding of the apparatus. The current coil of the wattmeter shall be connected in series with the primary winding.

A sine-wave electromotive force shall be applied to the primary winding and adjusted until the voltage of the secondary circuit is given by the equation,

$$E = \frac{4fNnBM}{4lD\,10^8},$$

in which

f	= form factor of primary e.m.f.	= 1.11 for sine wave,
N	= number of secondary turns	= 600,
n	= number of cycles per second	= 60,
B	= maximum induction	= 10,000
M	= total mass in grams	= 10,000,
l	= length of strips in centimeters	= 50,
D	= specific gravity	= 7.5 for high-resistance steel
		= 7.7 for low-resistance steel,
E	= 106.6 volts for high-resistance steel for sine voltage	
	= 103.8 volts for low-resistance steel for sine voltage.	

A specific gravity of 7.5 is assumed for all steels having a resistance of over 2 ohms per metergram, and 7.7 for all steels having a resistance of less than 2 ohms per metergram. These steels are designated as high- and low-resistance steels, respectively.

The wattmeter gives the power consumed in the iron and the secondary circuit. The loss in the secondary circuit is given in terms of the total resistance and voltage. Subtracting this correction term from the total power gives the net power consumed in the steel as hysteresis and eddy-current loss. Dividing this value by ten gives the core-loss in watts per kilogram.

Sampling. — The core loss material shall be cut from two or more sheets taken at random from the shipment. The strips should be distributed symmetrically over the sheet, as nearly as may be practicable. It is recommended that a test sample shall represent not more than 5000 kg. (11,000 pounds).

The Procedure. — 1. Cut the test material into strips 3 by 50 centimeters as indicated under *Sampling*.

2. Place on the balance a pile of strips weighing 2.5 kilograms. Add a second pile of the same kind, bringing the weight up to 5 kilograms. In each case the weight is taken to the nearest strip. Add in succession two piles of 2.5 kilograms each, of the other kind of strips, bringing the weight up to 7.5 kilograms and 10 kilograms respectively.

3. Secure each bundle by string or tape (not wire) and insert in the apparatus as indicated.

4. Apply the alternating voltage to the primary coil and tap the joints together until the current has a minimum value, as shown by an ammeter in series. Then clamp the corners firmly by some suitable device.

5. Shunt the ammeter and adjust the primary current until the voltmeter indicates the proper value. This adjustment may be made by an auto-transformer by varying the field of the alternator, or by both, but not by the insertion of resistance or inductance in the primary circuit. Simultaneously the frequency must be adjusted to 60 cycles.

6. Read the wattmeter.

7. Calculations. Subtract from the wattmeter reading the instrument losses, which will be constant for any set of instruments and voltage, and divide by 10. The result is the standard core-loss.

Bureau of Standards' Method. — (*Bull. Bur. Stds., 1909, Vol. 5, p. 453; Trans. A.I.E.E., 1909, Vol. 28, p. 439.*) This is a modification of the Epstein method. It differs from the latter in the use of a smaller test specimen, from 1.5 to 2 kilograms (about 4 pounds) of strips 25.4 by 5 centimeters (10 by 2 inches), and in the use of a different form of joint between the four bundles of strips. In other respects it is essentially the same as the Epstein method.

Fig. 11 shows the arrangement of the joint. At the corners of the square, short pieces of test material are bent at right angles and interleaved between the strips of adjacent bundles, as shown in the figure. There are as many of

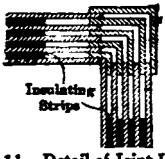


Fig. 11. Detail of Joint Used by N. B. S.

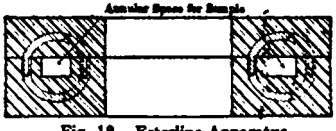


Fig. 12. Esterline Apparatus

these corner pieces as there are test pieces, and they are graduated in length so as to give a uniform lap of about 2 millimeters. A special clamp is tightened over these laps, so as to give a good magnetic joint. The object of these corner pieces is to reduce the leakage and thereby obtain a more nearly uniform flux throughout the sample. The loss in these corner pieces is small and can be calculated to a sufficient degree of accuracy and allowed for.

Esterline Apparatus For Testing Iron Rings (Fig. 12). — This apparatus is designed for testing rings made up of punchings from sheet steel. It is essentially a solenoid made in the form of a doughnut, but divided into two halves. The sample is inserted by lifting off the top half; the top half is then replaced and the teeth formed by the projecting ends of each upper half-turn fit into little sockets formed at the ends of the corresponding lower half-turn. (*Esterline, J. W., Proc. Am. Soc. Test. Mat., 1906, Vol. 6, p. 320.*)

Ewing Hysteresis Tester. — Strips ⅝ by 3 inches are cut from the sheets to be tested and a bundle of about 7 is used in each test. This sample is rotated at a relatively low speed (to avoid eddy currents) between the poles of a permanent magnet, the magnet being pivoted at the center of rotation and carrying a pointer that deflects over a scale, the deflection depending on the hysteresis loss in the sample. Two standard samples of known hysteresis properties are furnished with the instrument, so that the scale may be calibrated from time to time.

The Blondel Hysteresis Tester. — This apparatus is similar in principle to the Ewing hysteresis tester, but the magnet is revolved instead of the sample. The samples are made in the form of rings which are mounted on a pivoted spindle between the poles of a U-shaped permanent magnet. When the magnet is revolved the sample tends to follow it but is restrained by a spiral spring, and therefore it turns only through an angle such that the torque due to the hysteresis loss is balanced by the opposing torque of the spring.

The Holden-Esterline Core-loss Tester. — This instrument is similar to the Blondel hysteresis tester previously described but an electromagnet is substituted for the permanent magnet and this magnet is driven by a motor at the required frequency. The spring is arranged with a torsion head and pointer that is set to zero when the instrument is not in use.

The angle of torsion necessary to bring the sample back to its zero position

when the instrument is operating is read on a scale calibrated directly in watts loss. The speed of rotation being high the eddy-current losses are appreciable, and therefore the instrument reads the combined loss due to hysteresis and eddy currents at the frequency corresponding to the speed of rotation.

SEPARATION OF HYSTERESIS AND EDDY-CURRENT LOSSES. —When the counter e.m.f. induced in the winding on any magnetic core is sinusoidal, the eddy-current and hysteresis losses may be separated by making measurements of the total loss at two frequencies f_1 and f_2, at voltages E_1 and E_2, respectively proportional to these frequencies. Let the values of the total core-loss at these two frequencies be P_1 and P_2. Since the voltages are taken proportional to the frequencies and the voltage is sinusoidal, the maximum flux density will be the same in the two measurements. Let P_e be the eddy-current loss at the frequency f_1 and P_h the hysteresis loss at this frequency. Then the following relations hold:

$$P_1 = P_e + P_h, \qquad P_2 = \left(\frac{f_2}{f_1}\right)^2 P_e + \left(\frac{f_2}{f_1}\right) P_h.$$

Putting $a = \dfrac{f_2}{f_1}$ and solving for P_e and P_h, gives

$$P_e = \frac{a P_1 - P_2}{a\ (1 - a)}, \qquad P_h = \frac{P_2 - a^2 P_1}{a\ (1 - a)}.$$

IRON-LOSS VOLTMETER. — As pointed out in the article on *Magnetic Properties of Iron*, the core-loss depends upon the form of the impressed voltage wave. The dotted curves *A*, *B* and *C* in Fig. 13 show the variation in core-loss with form factor when the eddy-current loss is 14 per cent, 20 per cent and 30 per cent of the total loss. The loss corresponding to a sine-wave voltage (form factor 1.11) is taken as 100 per cent.

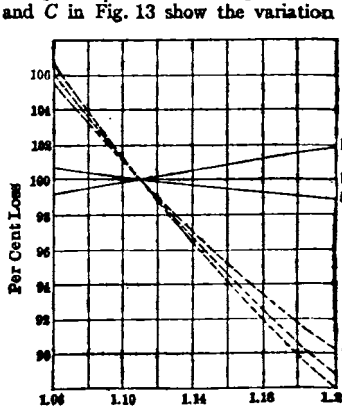


Fig. 13.

In making commercial tests on transformers it is frequently inconvenient to obtain a sine-wave voltage, and it is also equally inconvenient to obtain the form factor of the actual voltage available and the relative value of the eddy-current loss. Yet, for comparative purposes, the core-loss should be referred to a standard sine-wave form. The iron-loss voltmeter, devised by L. W. Chubb (*Trans. A.I.E.E., 1909, Vol. 28, p. 417*) is an instrument designed to read, when connected to a circuit in which the voltage has *any wave form whatever*, the value of the sine-wave voltage which would produce the same total loss as produced by the actual voltage. The meter is calibrated for one frequency only, usually 60 cycles per second. When such an instrument is connected across the transformer and the voltage adjusted until the instrument reads the rated voltage of the transformer, the core-loss read by a wattmeter connected in the usual manner will be the core-loss corresponding to a sine-wave voltage having an effective value equal to the voltage

s voltmeter, irrespective of what the reading of an ordinary
d across the line may be.

voltmeter is essentially an ordinary wattmeter, the current
nnected in series with a winding on a small laminated iron
nents in series being connected directly across the line. The
the wattmeter is also connected across the line to the same
ne first or series circuit. The meter therefore has but two
flection of the moving element of such a meter, when con-
upply mains, is proportional to the total power absorbed by
iron core. Neglecting the small resistance loss in the series
e, by adjusting the resistance in the potential circuit and the
n the iron ring, to make the equivalent eddy-current loss in
cluding the resistance loss in the potential circuit as an
since it depends on the effective value of the voltage in the
ddy-current loss in the sample) any desired proportion of the
djustments are so made that at about 0.6 full-scale deflection
y-current loss on a pure sine-wave voltage at 60 cycles is
otal, this being the average proportion of the hysteresis loss
mercial 60-cycle transformers.

is then calibrated to read directly in volts by connecting it
ordinary alternating-current voltmeter on a pure sine-wave
ired frequency.

e hysteresis loss in the transformer under test is different
on-loss voltmeter, a slight error will be introduced. Curves
show the error when the eddy-current loss in the transformer
0 per cent respectively, instead of 20 per cent.

eed only approximate the normal values; the final core loss
voltage indicated by the iron-loss voltmeter will be the same
ed on a sine wave of normal frequency and voltage.

Form Factor. — Chubb also gives a method of obtaining
1 from a wave of any shape. This is shown in Fig. 14. *T*
under test,
ttmeter, V_1
eter, V_2 an
neter, *R* a
L a vari-
an alumi-
condenser
oltage less
d across it.
R the read-

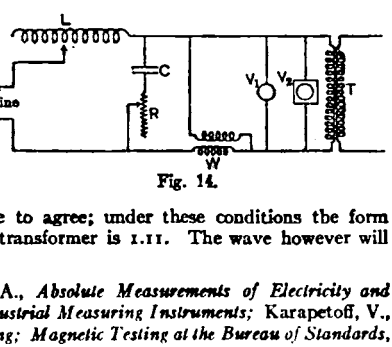


Fig. 14.

may be made to agree; under these conditions the form
e across the transformer is 1.11. The wave however will
a sine wave.

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MAGNETS, PERMANENT. — (*See also Magnetic Properties of Iron and Other Metals; Magnetic Testing.*) A permanent magnet is a piece of iron or steel which has been magnetized and which retains a relatively large part of its magnetism when the external magnetizing force is removed. The simplest form of permanent magnet is the bar magnet, used principally for experimental and instructional purposes and in the compass and certain types of galvanometers, etc. U-type permanent magnets are largely used in electrical measuring instruments and in the construction of magnetos.

The materials used for permanent magnets are (1) cast iron, (2) carbon-steel (0.15 to 0.3 per cent carbon), and (3) alloy steel containing carbon together with tungsten, molybdenum, chromium, or vanadium.

Cast iron magnets are used principally where weight is not objectionable.

Prior to 1914 high grade permanent magnets were made almost universally of alloy steel containing principally carbon, tungsten and chromium, and in which the percentage of manganese, sulphur and phosphorus was kept within the lowest practical limits. Since that date, chromium alloys have been produced from which it is possible to make magnets equal to those made of tungsten steel.

While the chromium alloys do not permit of as wide a range in manufacturing and heat-treating conditions as tungsten steels, with proper and uniform conditions the product shows greater uniformity than that made of tungsten steel.

Carbon-steel magnets have about 75 per cent of the strength of tungsten steel magnets of the same size.

Permanent magnets are usually made by cutting and forming the raw material, and hardening it by heating to a temperature, dependent upon the nature of the steel, usually in the neighborhood of 900° C., and cooling quickly by plunging into cold water or brine, and magnetizing.

Residual Induction and Coercive Force. — The two magnetic qualities of fundamental importance in a permanent magnet are (1) the residual induction of magnet and (2) its coercive force or retentivity. By residual induction is meant the flux density which exists in the material when the external magnetizing force is reduced to zero. By the coercive force or retentivity is meant the external magnetizing force required to reduce the induction to zero.

The total magnetic strength of a magnet having a given residual flux per unit area is proportional to its cross-sectional area, and the ability of a magnet of given retentivity to hold its magnetism is proportional to its length; that is, the length of the bar from which it is made. For any magnetic circuit considered there is a cross-section and length of permanent magnet which will give the maximum flux with the requisite stability, using a minimum of magnet steel.

Values of Residual Induction and Coercive Force. — In the *Physical Review* for Dec., 1920 (p. 496), Honda and Saito give data on "K.S." magnet steel, a cobalt-tungsten-chromium steel having the composition:

C.....	0.4 to 0.8 per cent
Co.....	30 to 40 per cent
W.....	5 to 9 per cent
Cr.....	1.5 to 3 per cent

For samples 20 cm. long and 0.5 cm. diameter (dimensional ratio of 40), heated to 950° C. and quenched in heavy oil, and then magnetized in a field of 1500 gilberts per centimeter, the residual induction ranged from 7800 to 11,500, depending upon the composition of the sample. The coercive force ranged from 257 to 226 gilberts per centimeter. This coercive force is stated by Honda and Saito to be about three times greater than that of the best tungsten steel, and the residual induction to be also greater than that of tungsten steel.

The data given by Honda and Saito also show that for dimensional ratios greater than about 18, the residual induction is independent of the value of the dimensional ratio, whereas for smaller dimensional ratios the residual induction is approximately proportional to this ratio, the relation being

$$B = 650\frac{l}{d},$$

where B is the residual induction, l the length, and d the diameter of the specimen. For a dimensional ratio of 15, K. S. magnet steel is about 1.8 times stronger than that of tungsten steel.

Effect of Air Gap. — The useful flux of a permanent magnet operating across an air-gap is always less than the flux which the magnet would give with no air-gap between its poles, or when magnetically "short circuited." On account of the very high reluctance, or magnetic resistance, of air the residual magnetism of a magnet of a given length is lessened as the air path between the poles is increased. This must be given careful consideration in the design of apparatus embodying the use of permanent magnets.

Since the introduction of an air gap between the poles of a permanent magnet has the effect of partially demagnetizing it, and the extent of the demagnetizing depends upon the relative length of the magnet and the air gap, it is important that the ratio of length of the magnet to the length of the air gap be such that the magnet will not be demagnetized by the air gap to the point where magnetization becomes unstable.

In some types of apparatus, such as magnetos, the magnet is opposed by a coil of wire carrying current. In designing permanent magnets for machines of this type it is important to take into account the effects of both air gap and coil.

Magnetization. — The process of magnetizing should be such as to fully saturate the magnet uniformally throughout its entire length. This can best be done by having the proper shaped and size coils to slip over each leg of the magnet, in the case of U-shaped magnets, completing the magnetic circuit by placing a keeper over the magnet gap and passing current through the coils.

The magnetizing apparatus should be so arranged that the magnet can be slipped out of the magnetizing coils and a soft iron keeper put on it before removing the keeper that was put on to complete the magnetic circuit while magnetizing.

U-shaped magnets magnetized by a very common but incorrect method, that of placing the magnets on the poles of a large electromagnet, will have large losses due to a large portion of the flux circulating around the magnet in paths that are not useful.

Aging and Magnetic Treatment. — One of the main conditions to be met by permanent magnets used in most electrical measuring instruments is that the magnet be stable and not subject to change with time, otherwise the instrument will go out of calibration. To secure this condition requires (1) a physical treatment of the steel after quenching, which makes further changes in its structure, molecular condition or magnetic qualities improbable, and (2) a magnetic treatment which will make changes in its magnetization under the condition of ordinary operation improbable.

When a magnet is hardened it undergoes rapid structural changes and for a time after quenching there is a change in condition taking place, rapid at first, and gradually decreasing until the physical properties become stable. This stability of the structural state of the steel can be hastened by physical treatment which usually consists in boiling the magnet in water for about 40 hours. This is called aging or maturing.

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The magnetic treatment of the permanent magnet is usually carried out as follows: After the magnetic circuit on which the permanent magnet is to operate is completely assembled, a demagnetizing force is applied which removes a portion of the flux. It is next subjected to a magnetizing force and then to a demagnetizing force. This has the effect of reducing the residual induction somewhat, but makes the magnet more stable.

Magnet Meter.— The magnet meter provides a simple and effective method for the commercial testing of permanent magnets. This instrument consists of an ordinary millivoltmeter with the permanent magnet removed and having soft iron extensions which are attached to the pole pieces of the meter and extend through the meter case. The moving coil of this meter is connected in series with a battery, rheostat and milliammeter.

A magnet of standard strength is placed against the soft iron extensions of the meter pole pieces and the current through the magnet meter coil adjusted, by means of the rheostat, until the pointer of the instrument deflects to some arbitrary point on the scale. The standard magnet is now replaced with the magnet to be tested. With the current kept the same as in the first test the deflection of the instrument is noted.

BIBLIOGRAPHY. — A considerable portion of the material in this article is taken from a pamphlet on *Permanent Magnets* published by the Esterline Co., Indianapolis. See also Kelly, F. C., *Permanent Magnets*, G. E. Rev., 20, p. 569, 1917; Thompson, S. P., *Magnetism of Permanent Magnets*, Inst. Elec. Eng. J. 50, p. 80, 1913 (contains complete bibliography up to 1913); Honda and Saito, *Phys. Rev.*, Dec., 1920; Morgan, J. D., *Testing Magneto Magnets*, Engin., 103, p. 559, 1917.

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D MINIMA. — (*See also Derivatives; Series, Mathematical.*)
tion of a variable x, then y will be a maximum or minimum
which satisfies

$$\frac{dy}{dx} = 0 \qquad (1)$$

t zero. If the second derivative $\frac{d^2y}{dx^2}$ is positive for this value
esponding value of y is a minimum; if this second derivative
rresponding value of y is a maximum.

lso zero for the value of x which satisfies (1), the corresponding
maximum or minimum unless $\frac{d^3y}{dx^3}$ is also zero and $\frac{d^4y}{dx^4}$ is not
= 0, y is a minimum if $\frac{d^4y}{dx^4}$ is positive and a maximum if $\frac{d^4y}{dx^4}$ is
$\frac{d^4y}{dx^4}$ is also zero, similar relations must hold for the fifth and
etc.

— Find the maximum and minimum values of

$$y = 2x^3 - 9x^2 + 12x - 3,$$

$$\frac{dy}{dx} = 6x^2 - 18x + 12 = 0,$$

$$\frac{d^2y}{dx^2} = 12x - 18,$$

num or minimum for $x^2 - 3x + 2 = 0$, that is, for $x = 2$, or
$\frac{d^2y}{dx^2}$ is positive; for $x = 1$, $\frac{d^2y}{dx^2}$ is negative; hence the maxi-
2 and occurs for $x = 1$, while the minimum value of y is 1 and

[W. A. Del Mar.]

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MECHANICS, PRINCIPLES OF. — (*See also Structures, Simple; Units and Conversion Factors.*) In this article are given the definitions of the more commonly-used mechanical quantities together with a statement of the quantitative laws in accord with which displacements and motion of matter (including deformations) take place. The interrelations of the various units employed for measuring any particular quantity are given in the article on *Units and Conversion Factors.*

DEFINITIONS. — The various terms relating to the displacement and motion of matter and to forces producing these displacements and motions are the following:

Scalar and Vector Quantities. — A mechanical quantity which is not directed in space, e.g., mass, energy, etc., is called a scalar quantity. A mechanical quantity which has a space direction as well as magnitude, e.g., velocity, force, etc., is called a vector quantity. A scalar quantity may be positive or negative, that is, has two "senses," but to specify a vector quantity like force it is necessary to specify not only its magnitude but its direction with respect to one or more fixed lines of reference or axes. Scalar quantities may be treated as ordinary algebraic quantities, and added and subtracted in the usual way. Vector quantities must be added and subtracted *vectorially*, as described in the article on *Vectors.*

Linear Displacement (l). — When a particle P moves from a point A to any other point B, the distance, measured along a straight line, from A to B is called the linear displacement of the point P.* Any unit of length may be used as a unit of displacement; see *Units and Conversion Factors.*

Angular Displacement (θ). — Let a particle P move from a point A to some other point B, and let OX be any arbitrarily-chosen line, or axis. Draw planes through A and OX and through B and OX. Then the angle between the planes AOX and BOX is called the angular displacement of P about OX.* Angular displacement may be measured in degrees, radians or turns; see *Angles* and *Units and Conversion Factors.*

Linear Velocity (v) **and Speed** (s). — The linear velocity or speed of a particle P is the rate of increase with time of the linear displacement of P, i.e.

$$v = \frac{dl}{dt} \qquad \text{or} \qquad s = \frac{dl}{dt}, \tag{1}$$

where dl is the linear displacement in time dt.
Any unit of length per any unit of time may be used as a unit of velocity or speed; see *Units and Conversion Factors.*

Angular Velocity or Speed (ω). — The angular velocity or speed of a particle about a given axis X is the rate of increase with time of its angular displacement about this axis, i.e,

$$\omega = \frac{d\theta}{dt}, \tag{2}$$

where $d\theta$ is the angular displacement in time dt. Any unit of angle per any unit of time may be used as a unit of angular speed; see *Units and Conversion Factors.*

* The positions of A and B (and of OX also in the case of angular displacement) must be referred to some system of coördinates; when the system of coördinates moves, the displacement as above defined is the displacement *relative to* this system of coördinates.

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Linear Acceleration (a). — The linear acceleration of a particle P is the rate of increase with time of the linear velocity of P, i.e.,

$$a = \frac{dv}{dt} = \frac{d^2l}{dt^2}, \tag{3}$$

where dv is the increase of linear velocity in time dt. Any unit of velocity per any unit of time may be used as a unit of acceleration, e.g., centimeters per second per second, miles per hour per hour, etc.; see *Units and Conversion Factors*.

Acceleration Due to Gravity (g). **Gravitational Acceleration Constant** (g_0). — At any given place on the earth a body falling freely in a vacuum has a constant linear acceleration, independent of its size, shape or material. This acceleration is called the acceleration due to gravity (g), and the particular value of this acceleration at 45 degrees latitude and sea level is called the gravitational acceleration constant (g_0). The value of g_0 as adopted by international agreement * is

$$g_0 = 980.665 \text{ cm. per sec. per sec.}$$
$$g_0 = 32.1739 \text{ ft. per sec. per sec.}$$

The value of g for any other location varies but slightly from this value, being at sea level approximately 0.3 per cent less at the equator, 0.3 per cent greater at the poles, and decreasing at the rate of about 0.01 per cent per 1000 feet increase in elevation. See *Landolt-Bornstein's Tables*.

Angular Acceleration (α). — The angular acceleration of a particle P about an axis X is the rate of increase with time of the angular velocity of P about X, i.e.,

$$\alpha = \frac{d\omega}{dt} = \frac{d^2\theta}{dt^2}, \tag{4}$$

where $d\omega$ is the increase in angular velocity in time dt. Any unit of angular velocity per any unit of time may be used as a unit of acceleration, e.g., degrees per second per second, turns per second per second, etc.; see *Units and Conversion Factors*.

Mass or Weight. * — Two bodies are said to have equal masses or weights,† irrespective of their volume, shape or chemical composition, if, when they are suspended simultaneously in a vacuum, one from each end of an equal-armed balance, there is no tipping of the beam of the balance from its original position. This criterion for the equality of two masses holds only in case the bodies and the balance are neither electrically charged nor magnetized, both bodies are supported at the same distance from the earth, and the equilibrium of the balance is not affected by the presence of any other bodies (except the earth) in the vicinity. This is an entirely arbitrary definition, but mass as thus defined is found to be a fundamental property of a body irrespective of its shape, physical state or relation to other bodies. The units of mass or weight and their interrelations are given in the article on *Units and Conversion Factors*.

Density (δ) **and Specific Gravity.** — The density of a uniform substance is defined as the mass of the substance per unit volume. When the substance

* *Troisième Conf. Gen. des Poids et Mes., 1901, p. 66.* See Note 5, p. 3 of this book.

† The term weight is also used for the force exerted by the earth on a portion of matter; in this sense weight is not independent of the relation of the given portion of matter to other bodies, and the term mass is therefore preferable when referring to quantity of matter, since it has not acquired a double meaning. However, engineers almost invariably use the word weight instead of mass for quantity of matter. See the article on *Units and Conversion Factors* for a further discussion of this point.

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is not uniform, its density at any point is defined as the mass of an infinitesimally small volume taken about the point divided by this volume; i.e., calling dv the volume and dm the mass of this volume, the density is

$$\delta = \frac{dm}{dv}. \tag{5}$$

In the c.g.s. system the standard unit of density is the gram per cubic centimeter, but any other unit of mass per any unit of volume may be used in either the metric or English system; see *Units and Conversion Factors*. For values of the density of various materials see article on *Weights of Materials*.

The specific gravity of a substance is defined as the ratio of the weight of a given volume of that substance to the weight of an equal volume of water or air. Water is used as the standard of reference for solids and liquids, and air at 0° C. and 760 mm. mercury pressure as the standard of reference for gases. Strictly, the temperature of the water also should be specified, but this is not always done. The variation in the weight of a given volume of water with temperature is slight and for many purposes negligible. When 4° C. is taken as the standard water temperature the specific gravity of a substance is numerically equal to its density in grams per cubic centimeter to within 25 parts in 1,000,000, a difference which is very much less than the degree of precision of ordinary measurements of density.

Surface and Lineal Densities. — Density as defined above is the *volume* density of a body. It is sometimes convenient to use factors which represent the mass or weight of a substance (or other physical quantity) per unit of surface or per unit of length, e.g., the weight per square foot of a plate or the weight per foot of a wire.

Center of Mass, Center of Gravity, or Center of Inertia. — A body of mass M which has any size or shape may be considered as made up of a number of small particles of masses m_1, m_2, m_3, etc., such that $m_1 + m_2 + m_3 + \cdots = M$. These particles may be considered as small as desired, that is, each particle may be considered so small that it occupies but a point in space. Choose any three mutually perpendicular planes, fixed with respect to one another, and represent by x_1, y_1 and z_1 the perpendicular distances of the particle m_1 from these planes respectively, and by x_2, y_2 and z_2 the perpendicular distances of the particle m_2 from these three planes respectively, and so on for the other particles. Then the point whose distances from these three planes are respectively

$$X = \frac{m_1x_1 + m_2x_2 + m_3x_3 + \cdots}{M}$$
$$Y = \frac{m_1y_1 + m_2y_2 + m_3y_3 + \cdots}{M} \tag{6}$$
$$Z = \frac{m_1z_1 + m_2z_2 + m_3z_3 + \cdots}{M}$$

is defined as the center of mass, or center of gravity, or center of inertia, of the body. The name center of gravity arises from the fact that the vertical forces acting on all the various particles of a body, due to the pull of the earth, may be considered equivalent to a single force, equal to the sum of these individual forces, applied to the body at this point. The center of mass of a perfectly rigid body is a fixed point with respect to every point in the body; it may, however, lie either within or without the body.

Equations (6) may also be written in terms of the calculus, thus:

$$X = \int \frac{\delta x\, dv}{M}, \quad Y = \int \frac{\delta y\, dv}{M}, \quad Z = \int \frac{\delta z\, dv}{M}, \tag{6a}$$

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where dv represents an elementary volume of the body at any point, x, y and z the distances of this point from the three planes of reference, δ the density of the body at this point, and M the total mass of the body. When the density is uniform throughout,

$$X = \int \frac{x\,dv}{V}, \quad Y = \int \frac{y\,dv}{V}, \quad Z = \int \frac{z\,dv}{V},$$

where V is the total volume of the body.

Centroid or Center of Gravity of a Plane Section. — This is defined as the point whose coördinates in the plane of the section are

$$X = \int \frac{x\,dA}{A} \quad \text{and} \quad Y = \int \frac{y\,dA}{A} \tag{6b}$$

referred to any two fixed mutually perpendicular lines in this plane, A being the total area of the section and dA any elementary area of the section. Physically, the center of gravity of a plane section may be defined as the center of gravity of a thin plate having the same shape as that of the section and of uniform thickness and specific gravity. See article on *Structures, Simple*, for the position of center of gravity for various plane sections.

Center of Gravity of Cylinders and Prisms. — The center of gravity of a cylinder or prism with parallel end surfaces and of *any* shaped cross-section, solid or hollow, is the centroid of that cross-section of the cylinder or prism which is halfway between the two ends, provided the cylinder has a uniform density throughout.

Moment of Inertia (I). — Consider any axis of reference X and any particle of mass m at a distance r from this axis; then the product mr^2 is called the moment of inertia of the particle m about the axis X. The moment of inertia of an extended body or system of bodies about any axis is

$$I = m_1r_1^2 + m_2r_2^2 + m_3r_3^2 + \ldots, \tag{7}$$

the summation including products mr^2 for all the particles of the body or system of bodies, r being the distance of the particle from the axis. This may also be written in the notation of the calculus as

$$I = \int r^2\,dm, \tag{7a}$$

where dm represents the mass of any particle and r is the distance from the axis. In case the body has a uniform density δ throughout this may also be written

$$I = \delta \int r^2\,dv, \tag{7b}$$

where dv represents an elementary volume of the body.

Units of Moment of Inertia of Bodies. — The moment of inertia of a body is of the nature of, or has the "dimensions" of, (length)^2 × (mass). When the mass is expressed in pounds and the distance r in feet then the moment of inertia may be said to be expressed in (foot)^2-pounds, and similarly for any other units of mass and length. In applying the formulas below the same set of units must be used throughout. See *Units and Conversion Factors*.

Moment of Inertia of a Plane Section. — The moment of inertia of a plane section about any axis is defined by the relation

$$I = \int r^2\,dA, \tag{7c}$$

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where dA represents any elementary area of this section and r the distance of this elementary area from the axis. When the axis is chosen *perpendicular* to the plane of the section *through its center of gravity* the moment of inertia about this axis is called the "polar" moment of inertia. Physically, the moment of inertia of a plane section about any axis may be defined as the moment of inertia about this same axis of a thin plate having the same shape as that of the section and having unit mass per unit of area.

The unit of moment of inertia of a plane surface has the dimensions of length to the fourth power.

Let X and Y be two mutually perpendicular axes in the plane of the section *passing through its center of gravity* and let Z be the axis through the center of gravity perpendicular to this plane and therefore also perpendicular to X and Y; let I_x and I_y be the moments of inertia of the plane section about X and Y respectively, and I_z be the polar moment of inertia of the section. Then

$$I_z = I_x + I_y. \tag{7d}$$

Values of I_x and I_y for various plane figures are given in the article on *Structures, Simple.*

Let X be any axis in the plane of a section, X_0 an axis through the center of gravity of the section parallel to X, s the distance between the two parallel axes X and X_0, I_0 the moment of inertia of the section about X_0, and A the area of the section. Then the moment of inertia of the section about X is

$$I_x = I_0 + s^2A. \tag{7e}$$

Principal Axes and Principal Moments of a Plane Section. — For every plane surface there are two rectangular axes passing through its center of gravity and lying in the surface, such that about one of these axes the moment of inertia is less, and about the other greater, than that about any other axis in the given surface. These two axes are called the *principal axes* and the moments the *principal moments of inertia.* If the plane figure has an axis of symmetry, this axis is one of the principal axes; e.g., a rectangle has two axes of symmetry, one parallel to each side, hence each of these axes is a principal axis. In the case of a circle any axis may be considered a principal axis. The principal axes for various sections are given in the article on *Structures, Simple.*

Moment of Inertia of Cylinders and Prisms. — Let the cylinder or prism be of any cross-section whatever, solid or hollow; let its density be δ constant throughout; let the length of its own axis between the parallel end surfaces be l; and let I_s be the moment of inertia of the cross-section of the cylinder or prism about any axis X parallel to the length l; then the moment of inertia of the entire cylinder or prism about this axis X is

$$I_c = \delta l I_s. \tag{7f}$$

The density δ must be referred to a volume unit based upon the same unit of length as that in which the dimensions of the cylinder or prism are expressed. For example, if I_s is expressed in centimeters-to-the-fourth-power, δ must be expressed in mass per cubic centimeter, and l must be expressed in centimeters; if δ is in grams per cubic centimeter, then the moment of inertia is in (centimeter)^2-grams.

Radius of Gyration (ρ). — The radius of gyration of a body about any axis is defined by the relation

$$I = M\rho^2 \quad \text{or} \quad \rho = \sqrt{\frac{I}{M}}, \tag{8}$$

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where M is the mass of the body and I its moment of inertia about the given axis. When the body has a uniform density throughout the radius of gyration may also be written

$$\rho = \sqrt{\frac{\int r^2 dv}{V}}, \tag{8a}$$

where V is the volume of the body. Radius of gyration is of the same nature as length and is therefore expressed in the same units as length.

Radius of Gyration of Plane Section. — The radius of gyration of a plane section about any axis is defined by the relation

$$\rho = \sqrt{\frac{\int r^2 dA}{A}}, \tag{8b}$$

where A is the total area of the section, dA an elementary area of this section and r the distance of dA from the axis. Values of ρ_x and ρ_y for various sections are given in the article on *Structures, Simple.*

From formula (7d) it follows that if ρ_x and ρ_y represent the radii of gyration of a plane section about two mutually perpendicular axes *passing through the center of gravity* of the section, then the radius of gyration ρ_z of this section about an axis through its center of gravity *perpendicular* to the plane of the section is

$$\rho_z = \sqrt{\rho_x^2 + \rho_y^2}. \tag{8c}$$

For example, for a circular section $\rho_x = \rho_y = \frac{d}{4}$, where d is the diameter of the section. Hence the polar radius of gyration about a perpendicular axis through the center of the circle is $\rho_z = \frac{\sqrt{2}}{4} d$.

From formula (7e) it also follows that if ρ_0 is the radius of gyration about any axis X_0, then the radius of gyration about a *parallel* axis X at a distance x from X_0 is

$$\rho_x = \sqrt{\rho_0^2 + x^2}. \tag{8d}$$

Radius of Gyration of Cylinders and Prisms. — The radius of gyration of a cylinder or prism about any axis X parallel to its own axis is the same as the radius of gyration about the axis X of any plane section of the cylinder or prism, provided the end surfaces are parallel and the density is uniform throughout. This relation holds for a prism or cylinder of any shape of cross-section, whether solid or hollow.

Linear Momentum (mv). — When the *center of mass* of a body of mass m is moving with a linear velocity v with respect to any point P, the product mv is called the linear momentum of the body with respect to this point. Units of linear momentum are of the same nature or dimensions as the units of power; see *Units and Conversion Factors.*

Experience shows that in any system of bodies composed of two bodies or groups of bodies A and B, any change in the linear momentum of the first body or group of bodies A with respect to the center of mass of the system is accompanied by an equal and opposite change in the linear momentum of the second body or group of bodies B with respect to the center of mass of the system, and vice versa. This fact of experience is known as the ***Principle of the Conservation of Linear Momentum.***

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Angular Momentum ($I\omega$). — When a body has a moment of inertia I about any axis X and is rotating about this axis with an angular velocity ω with respect to any point P, the product $I\omega$ is called the angular momentum of the body about this axis with respect to the given point. Units of angular momentum are of the same nature or dimensions as those of linear momentum and of power; see *Units and Conversion Factors*.

Experience shows that in any system of bodies composed of two bodies or groups of bodies A and B, any change in the angular momentum of the first body or group of bodies A about any axis X is accompanied by an equal and opposite change in the angular momentum of the second body or group of bodies B about this same axis, and vice versa. This fact of experience is known as the *Principle of the Conservation of Angular Momentum*.

Force (f). — In general terms a force is that which produces or tends to produce a change in the state of rest or motion of a body, or "a force is pull or a push." The nature of force is not thoroughly understood, but the effects of a force, e.g., change in motion, the extension or compression of a spring, etc., are readily measured. From the principle of the conservation of linear momentum stated above it follows that any change in the motion of a body or portion of a body A is always accompanied by a change in the motion of some other body or portion of the same or of some other body B. Hence the body A is said to exert a force on the body B, and vice versa.

In a system composed of but two bodies A and B, uninfluenced by the presence of any other bodies, the measure of the force produced on the body A by the body B may be taken as the rate of change with time of the linear momentum of A with respect to the center of mass of the system formed by A and B. The measure of the force produced on B by A is similarly defined. From the principle of the conservation of linear momentum it then follows that the force produced on A by B is equal and opposite to the force produced on B by A, or "action and reaction are equal and opposite."

Stated in a formula the above definition is that the mutual force between any two bodies A and B whose motion is uninfluenced by any other forces is

$$f = m_1 a_1 = -m_2 a_2, \tag{9}$$

where m_1 and m_2 are the masses of A and B respectively, and a_1 and a_2 are the accelerations of the centers of mass of A and B respectively with respect to the center of mass of the system formed by A and B together.

Force of Gravitation. — For example, consider the case of a mass m at any point above the earth. The earth exerts a force on m and m exerts an equal and opposite force on the earth, and if there are no other forces acting m will move toward the joint center of mass of the earth and the body m, and similarly the earth will move toward this same point. However, as the earth has a mass many times that of any body at or near its surface, the center of mass of the system formed by m and the earth is practically that of the earth itself, and the motion of the earth with respect to this point is inappreciable. Hence the force exerted by the earth on the mass m is, within the limits of error of observation,

$$f = mg, \tag{9a}$$

where g is the acceleration of the center of mass of m with respect to the center of the earth, or with respect to any point fixed with respect to the surface of the earth in the vertical line through the center of mass of m.

Units of Force. — The rational unit of force is that force which will give unit linear acceleration to unit mass; this unit of force is called the "absolute" unit of force. When the mass is expressed in grams and the acceleration in centimeters per second per second, the corresponding absolute unit

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of force is called the "dyne;" when the mass is expressed in pounds and the acceleration in feet per second per second, the corresponding absolute unit of force is called the "poundal."

The relation expressed by equation (9a), however, suggests another unit of force which for many purposes is very convenient, and in fact is the unit ordinarily used by engineers. This unit, called the "gravitational" unit of force, is the force exerted by the earth on unit mass; since the value of this force in terms of the absolute unit varies with latitude and elevation, it is also necessary to specify a definite place of measurement of this unit force, or better a *definite* value of the acceleration g, which shall be used in evaluating this force in terms of the absolute unit. The value of g adopted by international agreement is $g = 980.665$ cm. per sec. per sec. $= 32.1739$ ft. per sec. per sec., which (see Note 5 at top of p. 3 of this book) is equal to the acceleration due to gravity at 45 degrees latitude and sea-level; see also above under *Acceleration*. Unfortunately the gravitational units of force are given the same names as the units of mass to which they refer; for example a force of 1 pound is the pull exerted by the earth on a mass of 1 pound at 45 degrees latitude and sea-level. This double use of names often leads to confusion unless one keeps clearly in mind the definitions of unit mass and unit force. See *Units and Conversion Factors*.

When the force acting on a body is expressed in absolute units, the relation between force, mass and linear acceleration is

$$f = ma \quad \text{absolute units.} \tag{9b}$$

When the force is expressed in gravitational units, the relation between force, mass and linear acceleration is

$$f = \frac{m}{g_0} \cdot a \quad \text{gravitational units,} \tag{9c}$$

where g_0 stands for the numerical factor 32.1739 when f is in pounds, m in pounds and a in feet per second per second; similarly when f is expressed in grams, m in grams and a in centimeters per second per second g_0 stands for 980.665.

Measurements of Force. — One seldom has to deal with a simple system of but two bodies, and consequently the above definitions of the measure of a force can seldom be applied to an actual measurement. The value of these definitions is that they fix the unit of force. Forces are measured by balancing the pull of an unknown force against a known force (e.g., gravity or the reacting force of a spring), the principles involved being deduced from the fundamental principle of the conservation of linear and angular momentum when applied to bodies in equilibrium; see the section on *Conditions for Equilibrium* below.

Weight and Force. — The word weight, as already noted, is used to designate both mass and force. A weight of 10 pounds, say, as ordinarily used in reference to "how much" of a substance, means that the piece of matter in question has a mass of 10 pounds. A weight of 10 pounds used in reference to the pull produced by the earth on a piece of matter means that this pull is a force of 10 pounds. From the above definitions it follows that, neglecting the slight variation with latitude and elevation, the *numerical* values of weight used in the two senses are equal, provided mass is expressed in absolute units and force in gravitational units, i.e., a mass of 10 pounds also weighs 10 pounds, but weighs 321.739 *poundals;* see above under *Units of Force*.

Point of Application and Line of Action of a Force. — Any particle or point of a body which is acted upon directly by some external force (e.g.,

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a string attached to the body at this point) is said to be the point of application of this external force. A line drawn through this point in the direction of the force is called the line of action of the force. In general, whenever a solid body is acted upon by any number of external forces applied at various points the motion produced is the same as that which could be produced by *not more than two* single external forces. When the points of application of these two resultant forces coincide, then the actual motion produced is the same as that which would be produced by a *single* force acting at that point.

Impulse of a Force. — The impulse of a force is defined as the time integral of the force, i.e., if a force f is applied for a time t, then the impulse is $\int_0^t f\,dt$, account being taken of both the variation of the magnitude and direction of the force during the given time interval. The total change in the linear momentum of a body in any time t is equal to the impulse of the resultant force acting on it during this time. The conception of the impulse of a force is useful in dealing with suddenly applied forces which continue but a short time.

Concurrent and Coplanar Forces. — When the lines of action of all the external forces acting on a body meet in a point these forces are said to form a concurrent system of forces. When all the external forces acting on a body lie in the same plane they are said to form a coplanar system of forces.

Pressure (p). — The perpendicular component of the force per unit area exerted on any surface is called the pressure on that surface. Let df be the perpendicular or normal component of the force acting on an area dA, then the pressure at dA is

$$p = \frac{df}{dA}. \tag{10}$$

The term pressure is sometimes used as a synonym for force and what is here defined as pressure is called the "intensity of pressure." The rational unit of pressure is force per unit area, e.g., dynes per sq. cm. or pounds per sq. in., but a number of other arbitrary units are employed, such as, one inch of water column, one millimeter of mercury column, one atmosphere, etc. A dyne per square inch is also a barie. A standard atmosphere is the pressure that will support a column of mercury 76 centimeters = 29.9212 inches high at 0° C. at a place where g = 980.665 centimeters per second per second; using Thiesen and Scheel's determination of the density of mercury at 0° C. as 13.59545 grams per cubic centimeter (*Zeitsch. f. Instrkde., 1898, Vol. 18, p. 138*) a standard atmosphere is equivalent to 14.6964 pounds per square inch. See *Units and Conversion Factors*.

Absolute Pressure. — The atmosphere exerts a pressure (ranging from about 29 to 30 inches of mercury, depending upon the weather conditions and elevation) upon every surface with which it is in contact. The total pressure on a surface including that applied by any artificial means and that of the atmosphere is called the absolute pressure on the surface.

Torque or Moment of a Force (T). — Consider any axis X and any force acting at a point P at a perpendicular distance r from this axis; let f be the *component* of this force perpendicular to the plane through X and P. Then the product

$$T = rf \tag{11}$$

is called the moment of the force, or the torque due to this force, about the axis X. The distance r is called the "lever arm" or simply the "arm" of the force about this axis. Both absolute and gravitational units of torque are

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used, the units being of the same nature or dimensions as the units of energy (see below), but the two words in the compound names of the energy units are usually reversed. For example the foot-pound is an energy unit but the corresponding unit of torque is called the pound-foot. The conversion factors, however, are identical; see *Units and Conversion Factors*. Torque is also frequently expressed as "torque at unit radius," e.g., a torque of so-many pounds at 1 foot radius is a common expression; a more exact expression for the measure of torque would be "force at unit radius."

Torques about the same axis can be added algebraically, and torques about several axes meeting in a point can be added vectorially.

Couples. — Two equal and opposite parallel forces which are not concurrent (i.e., do not act along the same line) are said to form a couple, and the strength of the couple is defined as the product of either force by the perpendicular distance between their lines of action. The torque produced by a couple about any axis perpendicular to the plane of the two forces is equal to the strength of the couple.

Torque and Angular Acceleration. — The relation between torque, moment of inertia and angular acceleration is the same as that between force, mass and linear acceleration, i.e.,

$$T = I\alpha, \qquad \text{absolute units,} \tag{12}$$

where T is the torque in absolute units, I the moment of inertia and α the angular acceleration, all about the same axis. When the torque is expressed in gravitational units the relation is

$$T = \frac{I}{g_0}\alpha, \qquad \text{gravitational units,} \tag{12a}$$

where g_0 is a number numerically equal to 32.1739 when T is expressed in pound-feet, I in (foot)^2-pounds and α in radians per second per second; similarly for the centimeter-gram-second units $g_0 = 980.665$.

Work and Energy. — When the point at which a force is applied to a body A moves* with respect to the agent producing the force, in such a manner that the force has a component in the direction of the displacement of its application point, the force is said to do work; the body B exerting the force on A is also said to do mechanical work on the body A. As a measure of the mechanical work dW done by the force f, when its point of application moves a distance dl with respect to the body producing the force, is taken the product of the displacement dl by the component of the force f in the direction of this displacement, i.e.,

$$dW = (f \cos\theta)\, dl, \tag{13}$$

where θ is the angle between the direction of the force and the direction of the displacement. For a finite displacement the mechanical work done is

$$W = \int_0^l f(\cos\theta)\, dl. \tag{13a}$$

When mechanical work is done on a body a change in the state of motion or in some other condition of the body is always produced. Like changes can also be produced by other means. For example, when two bodies are rubbed together rapidly, mechanical work is done on them by the agent which produces the force which moves one over the other against the opposing force due to friction. As a result, the temperature of the bodies is raised. The

* Either as a result of the motion of the body A as a whole or in consequence of the motion of that part of A to which the force is applied.

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temperature of the two bodies may also be raised by placing them near or in contact with a hotter body, without there being any appreciable amount of *mechanical* work done. In general, any change produced in a body or system of bodies by any means whatever, which change can also be produced directly by doing mechanical work on that body or system, or indirectly by doing mechanical work on some other body or system, is said to be due to a transfer of "energy" *to* that body or system; or work * is said to be done on that body or system, irrespective of the means whereby the change is produced.

As a measure of the gain in energy corresponding to any change in a body or system of bodies is taken the amount of mechanical work which would have to be done by a mechanical force to produce this change and no other. For example, water can be heated by stirring it rapidly with a paddle driven by some external force; the total mechanical work done by this force can be expressed in terms of the value of the force, the number of revolutions of the paddle and the diameter of the pulley attached to the paddle, and the mass of the water and the resultant temperature rise can be measured. By making proper corrections for the work done against the various frictional forces other than the opposing force due to the stirring of the water itself and for the loss of energy by radiation, the amount of work required to raise the temperature of a pound of water, say, one degree Fahrenheit can be determined. By this means a very convenient secondary unit of energy can be expressed in terms of the unit of mechanical work, and the secondary unit can be used for expressing the amount of energy involved in various heat effects. See *Heat and Thermal Properties*.

Whenever a change takes place in a body or system of bodies which is the *reverse* of the change which can be produced in it by doing work *on* it, the body or system is said to *lose* energy, or energy is said to be transferred *from* it, or it is said *to do* work. As a measure of the amount of energy lost by the body or system when a given change takes place in it is taken the amount of work which would have to be done on it to restore it to its original condition.

Units of Work and Energy. — The fundamental unit of mechanical work in the c.g.s. system is the work done by a force of 1 dyne when its point of application is displaced (with respect to the agent producing the force) a distance of 1 centimeter in the direction of the force; this unit is called the "erg." The "joule" is equal to 10^7 ergs, by definition. The fundamental unit of mechanical work in the English gravitational system is the foot-pound, which is the work done by a force of 1 pound when its point of application is displaced a distance of 1 foot in the direction of the force; or 1 foot-pound is the work required to raise a mass of 1 pound a distance of 1 foot at a place where the acceleration due to gravity is 980.665 cm. per sec. per sec. or 32.1739 ft. per sec. per sec. Energy is expressed in the same units as mechanical work and in addition various heat units, such as the British thermal unit, the large and small calories, etc., are used; see *Heat and Thermal Properties*. For the relations among the various units see *Units and Conversion Factors*.

Principle of the Conservation of Energy. — Experience indicates that the amount of energy, as above defined, which can be transferred from a body or system of bodies to which no energy is added, is limited; i.e., the energy "possessed by" or "associated with" any body or system of bodies is *finite* in amount. As a rule, only a relatively small portion of the energy

* The word "work" is used by some writers to signify mechanical work only, but the term is a very convenient one to use in referring to the transfer of energy by other means as well, i.e., any change resulting in a transfer of energy to a body may be said to result from the doing of "work" on the body, whether the change is produced by mechanical, electrical or other means.

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associated with a body or system can be transferred to another body or system. Experience also justifies the assumption that whenever one body or system of bodies *gains* energy, some other body or system *loses* an *exactly equal amount* of energy. In every instance where this assumption can be tested directly it is found to hold, and every deduction from it has been found to be in accord with experimental fact. Hence this assumption is accepted as a fundamental principle of nature.

Kinetic Energy. — Work is required to set a body in motion, for while its motion is changing it is accelerating and therefore a force must be exerted upon it. From the definitions of acceleration, force and work given above it follows immediately that the work required to change the *linear* velocity of a body from v_0 to v_1 is

$$W_l = \frac{1}{2} m (v_1^2 - v_0^2) \qquad \text{absolute units,}$$

or

$$W_l = \frac{1}{2} \frac{m}{g_0} (v_1^2 - v_0^2) \qquad \text{gravitational units,}$$

where m is the mass of the body and g_0 is the gravitational constant. Similarly, the work required to change the angular velocity of a rigid body about a given axis from ω_0 to ω_1 is

$$W_r = \frac{1}{2} I (\omega_1^2 - \omega_0^2) \qquad \text{absolute units,}$$

or

$$W_r = \frac{1}{2} \frac{I}{g_0} (\omega_1^2 - \omega_0^2) \qquad \text{gravitational units,}$$

where I is the moment of inertia of the body about this axis and g_0 the gravitational constant. The expression

$$\frac{1}{2} m v^2 \qquad \text{or} \qquad \frac{1}{2} \frac{m}{g_0} v^2 \tag{14}$$

is called the "kinetic energy of translation" of the body, and the expression

$$\frac{1}{2} I \omega^2 \qquad \text{or} \qquad \frac{1}{2} \frac{I}{g_0} \omega^2 \tag{14a}$$

is called the "kinetic energy of rotation" of the body, both referred to the point with respect to which the velocities are measured.

Total Kinetic Energy of a System of Bodies. — The total kinetic energy of a moving system of bodies is equal to (1) the kinetic energy of the entire system moving with a velocity equal to the velocity of the center of mass of the system plus (2) the sum of the kinetic energies, rotational and translational, of each constituent body of the system due to the relative motion of this constituent body with respect to the center of mass of the whole system. For example, the total kinetic energy of a railway car is

$$W = \frac{1}{2} M v^2 + \frac{1}{2} \Sigma I \omega^2 \qquad \text{absolute units,} \tag{14b}$$

$$W = \frac{1}{2} \frac{M}{g_0} v^2 + \frac{1}{2 g_0} \Sigma I \omega^2 \qquad \text{gravitational units,} \tag{14c}$$

where M is the entire mass of the car with full equipment, I the moment of inertia, ω the angular velocity of any rotating part and the summation sign Σ indicates the sum of the products $I\omega^2$ for all the rotating parts. See also *Railways, Energy Requirements for.*

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Potential Energy. — The energy possessed by a body in virtue of its position with respect to the earth is usually called potential energy. More generally the term potential energy is used to designate any form of energy other than kinetic energy. In absolute units the increase in the potential energy of a body when it is raised a vertical distance h is mgh; in gravitational units the increase in potential energy is mh.

Power. — By power is meant the time rate of doing work or the time rate of change of energy. Let dW be the work done in time dt, then the power is

$$P = \frac{dW}{dt}. \tag{15}$$

The power produced by a force f or a torque T can also be expressed as

$$P = fv \qquad \text{or} \qquad P = T\omega, \tag{15a}$$

where v is the linear velocity of the point of application of the force and ω is the angular velocity of the point of application of the torque. The rational unit of power is the unit of work done or of energy transferred per unit time, such as 1 erg per second, 1 joule per second, 1 foot-pound per second, 1 British thermal unit per second, and the like. 1 joule per second is called the watt, which is also equal to the power corresponding to 1 ampere and a potential difference of 1 volt (*see Units, Practical Electrical*). The horse-power (English and American) is defined* as the power corresponding to 550 foot-pounds per second or 33,000 foot-pounds per minute. The metric horse-power, also called cheval-vapeur, force de cheval, Pferde-kraft, is defined as 75 kilogram-meters per second. The boiler horse-power is defined in the article on *Boilers, Steam*. The interrelations of the various units of power are given in the article on *Units and Conversion Factors*.

CONDITIONS FOR EQUILIBRIUM. — A body or system of bodies is said to be in equilibrium with respect to any external body (e.g., the earth) when (1) there is no change in the motion of the center of mass of the system with respect to this external body and (2) when there is no change in the total angular momentum of the body or system about any axis fixed with respect to this external body. These two conditions require (1) that the resultant of all the external forces† acting on the body or system be zero and (2) that the resultant of all the moments of these external forces, or torques, about any axis acting on the body or system be zero. These two conditions are most conveniently expressed by choosing three mutually perpendicular axes fixed with reference to the body of reference (e.g., the earth) and resolving all the forces into components F_x, F_y and F_z parallel to these three axes and calculating the moments or torques T_x, T_y and T_z of each of these forces about these three axes; then, using the symbol Σ to indicate the algebraic summation of the individual x, y or z components,

$$\left.\begin{array}{ll} \Sigma F_x = 0 & \Sigma T_x = 0 \\ \Sigma F_y = 0 & \Sigma T_y = 0 \\ \Sigma F_z = 0 & \Sigma T_z = 0 \end{array}\right\} \tag{16}$$

* The Bureau of Standards recommends the adoption of 746 watts as the definition of a horse-power. The older definition given above makes a horse-power 745.701 watts, using the standard value of g_0 given above, namely, 980.665 cm. per sec. per sec. and the legal values of the foot and the pound (*see Units and Conversion Factors*). As this older definition is the one generally employed by all classes of engineers, it seems preferable to the author to retain it. See *Circular No. 34 of the Bureau of Standards* and discussions in the various technical journals during 1912 and 1913.

† i.e., forces any one of which would, if acting alone, produce a motion of the body or system or of some part of it with respect to the reference body.

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These two sets of conditions constitute the basis of the entire subject of statics Certain elementary applications are given in the article on *Structures, Simple.*

Stability. — When a body or system of bodies is in equilibrium and the state is such that when the body or system is displaced slightly it returns of itself to its original condition, the equilibrium is said to be stable; if when displaced slightly the body or system moves farther from its original condition, the equilibrium is said to be unstable; if when displaced slightly it remains in that condition, the equilibrium is said to be stable. The condition for stability may be expressed in a number of ways, viz.: (1) when the potential energy of the system with respect to the body of reference (e.g., the earth) is a minimum the equilibrium is stable; (2) when the forces acting are all gravitational the equilibrium is stable when the center of mass is in the lowest possible position; or (3) when the body or system rests on a number of points, the equilibrium is stable only when the resultant of all the forces acting on the body including its own weight, but excluding the supporting forces, cuts the smallest polygon which can be drawn including all the points of support.

MOTION OF A PARTICLE. — By a particle of matter is meant a portion of matter so small that it may be considered as occupying but a point in space. Let m be the mass of the particle, v its linear velocity at any instant with respect to any arbitrarily chosen set of axes of reference, dv the increase in its velocity in time dt (including both change in direction as well as in magnitude), and let F be the resultant of all the external forces, in absolute units,* acting on the particle. Then the motion of the particle is completely specified by the equation

$$F = m\frac{dv}{dt},$$

where dv is taken to include the change in *direction* as well as the magnitude of the velocity. To take into account the variation of the direction of v as well as the variation in its magnitude, the resultant force F and the velocities may be resolved into components along the three axes, in which case this equation breaks up into the three equations

$$F_x = m\frac{dv_x}{dt}, \quad F_y = m\frac{dv_y}{dt}, \quad F_z = m\frac{dv_z}{dt}.$$

Since the velocity along any axis is equal to the time rate of displacement along that axis, $v_x = \frac{dx}{dt}$, $v_y = \frac{dy}{dt}$, and $v_z = \frac{dz}{dt}$, whence these equations may also be written

$$\frac{d^2x}{dt^2} = \frac{F_x}{m}, \quad \frac{d^2y}{dt^2} = \frac{F_y}{m}, \quad \frac{d^2z}{dt^2} = \frac{F_z}{m}. \tag{17}$$

Hence when the forces can be expressed in terms of the coördinates of the point which the particle occupies at each instant, the displacements and velocities can be determined by solving these equations. Note that $\frac{F_x}{m}$, $\frac{F_y}{m}$ and $\frac{F_z}{m}$ are the accelerations a_x, a_y and a_z along the three axes.

Rectilinear Motion. — The simplest case is that of a particle acted upon by a force F which remains constant in direction. One of the axes, say the

* When F is expressed in gravitational units replace m by $\frac{m}{g_0}$, where g_0 is the gravitational constant.

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X axis, may be taken parallel to the line of action of the force, in which case equations (17) reduce to the single equation

$$\frac{d^2x}{dt^2} = \frac{F}{m}, \tag{17a}$$

and there is no acceleration along either of the other axes; i.e., the particle moves along the line of action of the force. If the force is also constant in magnitude, $\frac{F}{m} = a$, a constant. In this case the solution of (17a) is (*see Equations*):

$$\left.\begin{aligned} x - x_0 &= \tfrac{1}{2} a (t - t_0)^2 + v_0 (t - t_0), \\ v - v_0 &= a (t - t_0), \end{aligned}\right\} \tag{17b}$$

where $t - t_0$ represents any interval of time, $x - x_0$ the displacement of the particle during this interval and $v - v_0$ the change in velocity of the particle during this interval. The displacement $x - x_0$ may also be written

$$x - x_0 = \frac{v^2 - v_0^2}{2a}. \tag{17c}$$

Curvilinear Motion; Motion in a Circle. — Consider the special case of a particle moving in a circle of radius r with a constant tangential or peripheral velocity v. Choose the Z axis perpendicular to the plane of the circle. Let θ be the angle (measured counter-clockwise) which a line drawn from the center of the circle to the particle makes at any instant with the X axis, then $(90 - \theta)$ is the angle which this line makes with the Y axis at this instant. At any instant, then,

$$v_x = -v \sin\theta \qquad \text{and} \qquad v_y = v \cos\theta$$

and these components are not constant since θ changes with time. The corresponding accelerations along the two axes are

$$a_x = -v \cos\theta \frac{d\theta}{dt} \qquad \text{and} \qquad a_y = -v \sin\theta \frac{d\theta}{dt},$$

both of which components are *toward* the center of the circle. But $\frac{d\theta}{dt}$ is the angular velocity of the particle about the Z axis, and this is equal to the peripheral velocity divided by the radius, or $\frac{d\theta}{dt} = \frac{v}{r}$. Whence

$$a_x = -\frac{v^2}{r}\cos\theta \qquad \text{and} \qquad a_y = -\frac{v^2}{r}\sin\theta,$$

and therefore the resultant acceleration has the numerical value

$$a = \sqrt{a_x^2 + a_y^2} = \frac{v^2}{r} \tag{17d}$$

and is *toward* the center of the circle. Hence to cause a particle to rotate in a circle a force equal to $\frac{mv^2}{r}$ must be applied to it in the direction *toward* the center, and the particle in turn pulls away from the center with an equal and opposite force which produces a tension outward along the radius in whatever (e.g., a string) holds the particle to the center. The tendency of the particle to pull outward from the center is called the centrifugal force, and its value

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is $\frac{mv^2}{r}$; the equal inward pull required to make the particle move in the circular orbit is called the centripetal force.

Simple Harmonic Motion. — (*See also Wave Analysis.*) By simple harmonic motion is meant a motion such that the acceleration of the moving particle or point at each instant is proportional to, but in the opposite direction from, the displacement. Such motion may be either rectilinear or a rotation about a fixed axis. Rectilinear simple harmonic motion may also be defined, see Fig. 1, as the motion of the projection P on a given diameter YY', of a point Q which moves with a constant angular velocity ω around a circle of radius A. The motion of the bob of a simple pendulum, the position of the end of a piston rod, etc., are examples of simple rectilinear harmonic motion (very nearly).

Referring to the circle diagram in Fig. 1, P_0 represents the projection of the moving point Q at time $t = 0$. The angle made by OQ at any instant with

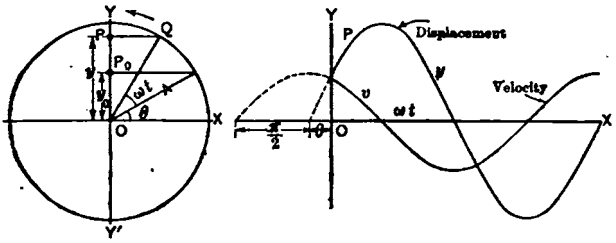


Fig. 1. Harmonic Motion

OX is then $(\omega t + \theta)$. The linear velocity of Q is $A\omega$, and the *component* of this velocity at any instant *along* OY, i.e., the velocity of P, is

$$v = \frac{dy}{dt} = A\omega \cos(\omega t + \theta). \tag{18}$$

Whence the displacement y of P from O is, by integration,

$$y = A \sin(\omega t + \theta), \tag{18a}$$

and the acceleration along OY is, by differentiation,

$$a = \frac{d^2y}{dt^2} = -\omega^2 A \sin(\omega t + \theta), \tag{18b}$$

whence $a = -\omega^2 y$, which agrees with the first definition of harmonic motion.

Period and Frequency. — The period of any kind of an oscillation is defined as the time (usually in seconds) taken for the oscillating point to pass through a complete cycle of values back again to the starting point. The frequency is the number of complete cycles per unit time (usually per second). In the case of a harmonic oscillation the period is

$$T = \frac{2\pi}{\omega} \tag{18c}$$

and the frequency is

$$f = \frac{\omega}{2\pi}. \tag{18d}$$

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Amplitude. — The "sine curves" to the right of the circle diagram show the variation with time of the displacement and the velocity (along OV) of the projected point P. Displacement and velocity are plotted along the Y axis and ωt, which is proportional to time, is plotted along the X axis. These curves bear a definite relation to each other and to the "origin" of time, i.e., to the point O. The maximum ordinate of each curve is called the "amplitude" of the curve. The amplitude of the displacement curve is A, the radius of the circle; the amplitude of the velocity curve is ωA.

Phase. — The distance expressed in angular measure, from the origin to the point at which the curve first crosses the X axis in the *rising* direction is called the "phase angle" of the curve. The phase angle is taken positive when it is measured to the *left* from the origin, and negative when measured to the right.* The phase angle of the displacement curve is θ, and the phase angle of the velocity curve in the above case is $\frac{\pi}{2}+\theta$.

Difference in Phase. — The difference in the phase angles of two sine curves of the same frequency is called the "difference in phase" between the two curves; the difference in phase between the displacement curve and the velocity curve in the above case is $\frac{\pi}{2}$ radians or 90 degrees. The curve which has the larger (algebraically) phase angle is said to "lead" the other curve, and the one with smaller (algebraically) phase angle is said to "lag behind" the other one. In the above example the velocity curve leads the displacement curve. Note that the curve to the left is the leading curve.

ROTATION OF A SOLID BODY. — When a solid body moves in such a manner that one straight line through the body remains fixed with respect to any given set of axes of reference, its motion is called simple rotation with respect to these axes. For such motion the external forces must be equivalent to two equal and opposite forces which have a moment only about the axis of rotation. Let T be the value of this moment or torque, I the moment of inertia of the body about this axis and $d\omega$ the increase in the angular velocity about this axis in time dt (the same for each point of the body), then the motion is completely specified by the equation

$$\left.\begin{aligned} T &= I\frac{d\omega}{dt} && \text{(for } T \text{ in absolute units)} \\ \text{or} \quad T &= \frac{I}{g_0}\frac{d\omega}{dt} && \text{(for } T \text{ in gravitational units).} \end{aligned}\right\} \tag{19}$$

For constant torque and therefore constant angular acceleration, i.e., for $\frac{d\omega}{dt}=\alpha=$ constant, the change in angular velocity in the interval of time (t_2-t_1) is

$$\omega_2-\omega_1=\alpha\,(t_2-t_1), \tag{19a}$$

and the angle turned through in the interval (t_2-t_1) is

$$\theta_2-\theta_1=\frac{1}{2}(\omega_2+\omega_1)(t_2-t_1)=\frac{\omega_2^2-\omega_1^2}{2\alpha}. \tag{19b}$$

THREE-DIMENSIONAL MOTION. — The motion of a solid body may in the most general case be expressed in terms of a translation of its center and a rotation of the body around an axis through its center of mass. The motion

* The opposite convention is used by some writers, in which case the equation for the sine curve is $y=A\sin(\omega t-\theta)$.

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of the center of mass produced by any number of external forces is the same as would be produced by a single force, equal to the vector sum of the actual forces, acting on a single particle occupying the position of the center of mass in the actual body and having a mass equal to the entire mass of this body. The rotation can be determined by considering the center of mass as fixed and the actual forces then applied. That is, the translation of the center of mass and the rotation about the axis through it can be considered independently of each other; the actual motion is then the resultant of these two types of motion. See *American Civil Engineers' Pocket Book* for a brief treatment of this subject.

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MENSURATION. — (*See also Angles; Equations; Trigonometry*) term mensuration is used in this article to include the relations betw areas and volumes of geometric figures and their linear dimensions.

Triangle. —

$$\text{Area} = \tfrac{1}{2}\,(\text{base}) \times (\text{perpendicular height})$$
$$= \sqrt{s\,(s-a)\,(s-b)\,(s-c)},$$

where a, b and c are the lengths of the three sides respectively, and $s = \tfrac{1}{2}(a$

Trapezoid. —

$$\text{Area} = \left(\frac{a+b}{2}\right) d,$$

where a and b are the lengths of the parallel sides respectively, and distance apart.

Parallelogram. —

$$\text{Area} = (\text{base}) \times (\text{perpendicular height}).$$

Parabola. —

$$\text{Area} = \tfrac{2}{3}\,(\text{area of circumscribing triangle}).$$

Cycloid. —

$$\text{Area} = \tfrac{3}{4}\pi \times (\text{altitude})^2,$$

the altitude being the diameter of the rolling circle.

Circle. —

$$\text{Circumference} = 2\pi r = \pi d,$$

$$\text{Area} = \pi r^2 = \frac{\pi}{4} d^2,$$

where r is the radius and d the diameter.

$$\text{Area of segment} = \frac{r^2}{2}\,(\theta - \sin\theta),$$

where θ is the angle in radians (*see Angles*) subtended by the arc of the If n is the height of the segment, measured along the radius perpend the chord,

$$\text{Area of segment} = \pi r^2 M - A\,(r - n),$$

where

$$A = \sqrt{n\,(2r - n)} \quad \text{and} \quad M = \frac{1}{180} \sin^{-1}\left(\frac{A}{r}\right).$$

Ellipse. —

$$\text{Area} = \pi ab,$$

where a and b are the principal semi-axes.

Prism with Parallel Sides and Parallel Ends. —

Volume = (area of end) × (Perpendicular Distance between End

Right Circular Cylinder. —

$$\text{Volume} = \frac{\pi}{4} d^2 l,$$

where d is the diameter, and l the length.

Total surface of right cylinder $= \pi d\,(l + \tfrac{1}{2} d)$.

Right Circular Cone. —

Volume = ⅓ (area of base) × (height),
= ⅓ (volume of circumscribing cylinder),

where r is the radius of base and h the height of the cone.

Area of curved surface of a right circular cone = $\pi r \sqrt{h^2 + r^2}$.

Right Pyramid. —

Volume = ⅓ (area of base) × (height),

Volume of frustum of pyramid = ⅓ (height) $(A + a + \sqrt{aA})$,

where A and a are the areas of the ends respectively.

Sphere. —

r = radius,

Area of surface = $4\pi r^2$
= ⅔ (total area of circumscribing cylinder).

Area of the surface of a zone of a sphere = area of zone of the same height as this zone projected on to a cylinder.

Volume = $\frac{4}{3}\pi r^3$
= ⅔ (volume of circumscribing cylinder).

Volume of a frustum of a sphere = $\pi r^2 (k \mp h) - \frac{\pi}{3}(h^3 \mp k^3)$, where k is the distance of its outer face from center and h the distance of its inner face from the center, the negative signs in the brackets to be used if both faces are on the same side of the center and the positive signs if on opposite sides of the center.

Ellipsoid. —

Volume = $\frac{4}{3}\pi abc$,

where a, b and c are the three principal semi-axes respectively.

Paraboloid. —

Volume of a paraboloid of revolution equals one half that of the circumscribing cylinder.

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MOTOR-CONVERTERS. — (*See also Converters, Synchronous; Motors, Induction; Standardization Rules.*) A motor-converter is a combination of an induction motor and synchronous converter, with the secondary of the motor and the armature of the converter mounted upon the same shaft and connected together electrically without slip rings. The induction motor receives all the a-c. power, transforms a part of it into mechanical power delivered to the shaft, and also acts as a transformer delivering the rest of the power in electrical form at a lower frequency from its secondary to the armature of the converter. It operates like two induction motors in "concatenation" or "cascade." The object is to obtain the steadiness of a 30-cycle converter on a 60-cycle circuit.

The speed of a motor converter depends upon the supply frequency and varies inversely as the sum of the number of poles in both machines. Thus if a combination of a 6-pole motor and 6-pole converter be operated from a 60-cycle circuit the speed of the armature will be 600 r.p.m. The primary of the induction motor will operate at 60 cycles but the secondary will supply the armature of the converter with 30 cycles. Thus the converter may be built with the good design constants of a 30-cycle machine.

This combination is larger than a converter but smaller than a motor-generator set and its efficiency is lower than that of a converter. It is used somewhat in Europe but not much in the United States.

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MOTOR-GENERATORS. — (*See also Converters, Synchronous; Frequency Changers; Generators; Motor; Standardization Rules.*) A motor-generator set is a combination of a motor and a generator having separate fields and armatures but mounted on the same shaft with common base and bearings. Combinations of various types of motors and generators are used; some of the more important combinations and their applications are described below.

Frequency Changers. — See separate article on *Frequency Changers.*

Direct-current Motor Driving Direct-current Generator. — These sets are used when it is desired to convert low-voltage direct current into high voltage direct current, or vice versa; they are used in preference to a dynamotor (q.v.) when good regulation is desired in the secondary circuit.

Direct-current Motor Driving Alternating-current Generator. — These sets are used for converting direct into alternating current. See also the section on *Inverted Synchronous Converters* in the article on *Converters, Synchronous.*

Induction Motor Driving Direct-current Generator. — The induction motor may be wound for potentials as high as 13,000 volts and the transformation from alternating current at this voltage to direct current may be made without the use of transformers. Since the induction motor has a decreasing speed with increasing load the direct-current generator must be compounded to give good regulation; with proper compounding excellent regulation may be obtained. The induction-motor-generator set is sometimes used in preference to a synchronous converter when the service requires specially good regulation. However, the efficiency of such a set (about 85 per cent at rated load) is less than that of a synchronous converter, even if no transformers are required by the motor-generator set. The motor-generator set also occupies from 50 per cent to 80 per cent more floor space, weighs from 30 per cent to 50 per cent more, and costs from 25 per cent to 50 per cent more than a synchronous converter, in spite of the fact that they are designed to operate at the highest practicable speeds.

Costs and Speeds of Induction-motor-generator Sets. — Very roughly the prices and suitable speeds are (in 1922) as follows:

Kw. capacity	R.p.m.	Cost per kw.
200	750	$33
500	500	24
1000	300	19

These prices are about 50 per cent higher than pre-war prices.

Synchronous Motor Driving Direct-current Generator. — This combination is preferable in many instances to the preceding, because it operates at constant speed and because the field of the synchronous motor may be adjusted to make use of line compounding or to compensate for low power factor in other apparatus on the circuit (*see Motors, Synchronous*). Provision must be made for the direct-current excitation for the synchronous motor. If the direct-current generator is wound for too high a potential a special exciter must be provided. Since there is no load on the set at starting the synchronous motor may be started in the usual manner.

SPECIFICATION FOR MOTOR-GENERATORS. — The following memoranda are intended to assist in writing specifications. See also articles on *Specifications; Motors;* and *Generators.*

General description and use of machine. Motor: see specifications in articles on *Motors*. Generator: see specifications in articles on *Generators*. Whether or not motor and generator are to be on common bed-plate. Exciter for generator field. Limiting over-all dimensions.

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MOTORS, ALTERNATING-CURRENT COMMUTATOR. — (*See also Motors, Direct-current; Motors, Polyphase-induction; Motors, Single-phase Induction; Standardization Rules.*) There are several different types of alternating-current commutator motors designed to operate on single-phase circuits, but they differ chiefly in the electrical connections employed. They may be divided into two general classes, series motors and repulsion motors. While these motors differ in their connections and in slight details in their characteristics, they all have the general characteristics of the d-c. series motor, that is, increasing torque with decreasing speed and a high efficiency over a considerable range of speed. Alternating-current commutator motors with shunt motor characteristics are also used to a limited extent abroad.

GENERAL CHARACTERISTICS. — The torque of any a-c. commutator motor is constant in direction, but pulsating in value, and its average value

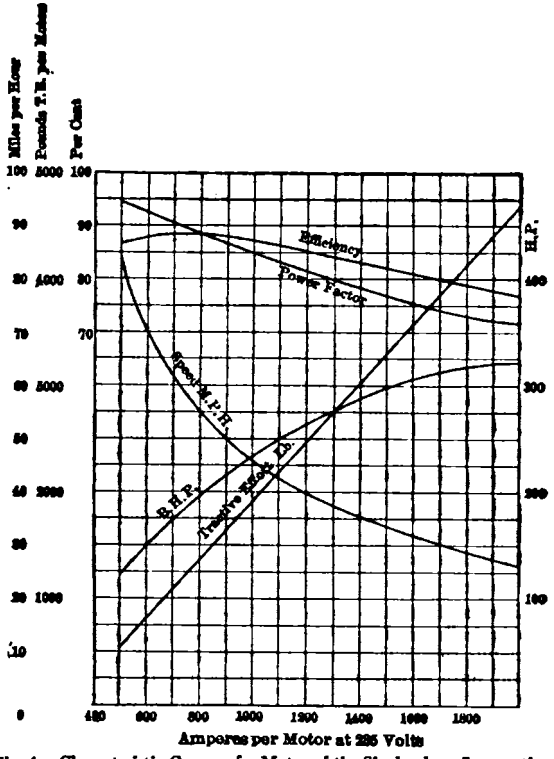


Fig. 1. Characteristic Curves of 1 Motor of the Single-phase Locomotives of the N. Y., N. H. & H. R. R. (St. Ry. Jour., Apr. 1906.)

is proportional to the product of the effective value of the flux and the effective value of the armature current. The direction of the torque may be changed

by changing the direction of the current in the field with respect to the armature, or vice versa. The power factor increases with increase of the speed and therefore decreases with increase of load. The efficiency, while not as good as that of a d-c. motor of the same rating is, however, fairly high. The motors have in addition to the losses common to d-c. motors a core-loss in the field, increased core-loss in the armature, increased commutation loss and increased RI^2 loss in special windings. In Fig. 1 are given the characteristic curves of the a-c. compensated series motors used on the single-phase locomotives of the New York, New Haven & Hartford Railroad.

APPLICATIONS. — The most general application of a-c. commutator motors in large sizes is in railway and hoisting work; see *Railways, Electric,* and *Hoists, Electric.* The same principles of operation are made use of in the devices for starting single-phase induction motors (*see Motors, Single-phase Induction*), the motor being brought up to speed as an a-c. commutator motor and then by a change of connections made to operate as a single-phase induction motor.

DESIGN. — The salient features in the design of the various types of a-c. commutator motors are described briefly below.

Straight A-C. Series Motor. — Since the torque of an ordinary d-c. series motor does not change in direction when the current through both the field and the armature reverses simultaneously, any d-c. series motor will develop a uni-directional torque when connected across a-c. mains. However, when an ordinary d-c. series motor is thus used the power factor of the load taken by it is very low, there is a large eddy-current loss in the field structure, and violent sparking occurs at the commutator. To make a series motor practicable for a-c. service, the field structure must be laminated in order to avoid eddy currents and the field coils must have only a few turns to avoid too great self-inductance, and the consequent low power factor. The greater tendency to spark in the case of the a-c. series motor is due to the *alternating* field flux which interlinks the coils short-circuited by the brushes, thus inducing in these coils a relatively large e.m.f. not present when the motor is operating on a d-c. circuit. This difficulty can be avoided to a certain extent by designing the motor for a small field flux and with but a few turns in series in each armature coil. In general, therefore, single-phase commutator motors are built for low voltages, such as 200, with one turn per coil, multiple-wound armatures and with the armature ampere turns per pole about four times the field ampere turns per pole. The effect of the armature ampere turns can be neutralized by a "compensating" winding described below. The field flux is practically limited to that value which will give 4 volts per turn in the short-circuited armature coil, as this is about the limit that may be commutated with carbon brushes.

Resistance Leads. — As an additional means of preventing sparking, high-resistance leads are frequently used between the commutator segments and the armature coils. These leads are made of a high-resistance metal strip bent back and forth several times, and imbedded in the armature slots along with the armature conductors proper. On account of the dissipation of heat in these leads a lower current density must be used in the armature conductors proper than is used in the case of d-c. motors. The arrangement of the leads is such that the main or useful current passes through two high-resistance leads in multiple as it enters the armature, while the undesirable short-circuited current passes through two high-resistance leads in series. It should be noted, however, that at any instant there is current only in those leads connected to coils which are being short-circuited at this instant.

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Compensating Winding. — To obviate the high armature reaction in an a-c. series motor and at the same time to improve the power factor, a "compensating" winding is usually employed. This consists of a distributed winding imbedded in slots in the pole faces and connected usually in series (Fig. 2) with the main field winding and armature in such a manner that the current through it sets up a magnetomotive force which practically neutralizes the effect of the armature ampere turns. When the compensating winding is connected in series with the field and armature, as shown in Fig. 2, the motor is said to be "conductively compensated." An "inductively compensated" motor has this winding short-circuited upon itself and the current in it is induced from the armature by transformer action. Inductive compensation is not operative on d-c. circuits, but is as satisfactory as conductive compensation for a-c. operation.

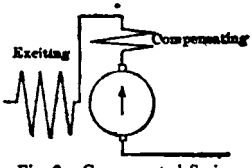


Fig. 2. Compensated Series Motor

Thomson Repulsion Motor. — This motor has a stationary structure or field with a completely distributed winding, which may be wound for any voltage. In this is placed a low-voltage armature designed with all the refinements necessary for single-phase commutator work. The brushes bearing on this commutator are short-circuited upon themselves and are so placed that the line connecting the positive and negative brushes makes an angle α with the neutral axis of the field. The field turns lying within the angle $(90 - \alpha)$ induce a current in the armature winding by transformer action and the field turns lying within the angle α constitute the "exciting" turns and set up the necessary flux to produce the driving force. The arrangement is equivalent to the circuits shown in Fig. 3, although actually there is but a single field winding. This motor then acts exactly like the combination of a transformer and a series motor in one structure. It may be reversed by changing the position of the brushes or by shifting the points of connection of the external circuit to the field or stator winding. This motor operates particularly well near synchronous speed as then it has practically a rotating magnetic field and no excessive commutation difficulties, but at starting and at low speeds the commutation is not as good as that of the compensated series type.

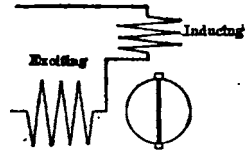


Fig. 3. Thomson Repulsion Motor

Winter-Eichberg-Latour (Fig. 4). — This motor has the special attribute that, due to the rotation of the armature conductors of the circuit B_2 in the transformer flux set up by the inducing windings, an e.m.f. is generated which is almost exactly 180° in time phase from the e.m.f. of self induction caused by the motor flux. It therefore neutralizes this inductive drop and improves the power factor of the machine. Were it not for the incidental leakage reactance the power factor would be unity at synchronous speed when the ampere turns of the inducing and exciting windings are equal. By a proper adjustment of the series transformer T this lagging voltage may be made to exceed the inductive drop at speeds near and above synchronism and cause the power factor to be anti-inductive.

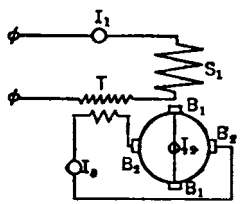


Fig. 4. Winter-Eichberg-Latour Compensated Repulsion Motor.

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The principle of this action is shown in Figs. 5 and 6, where ϕ_1 shows the transformer flux set up by the inducing winding and ϕ_2 is the motor flux produced by the series exciting current I_2 in the armature circuit B_2, in phase with I_2 and I_1. I_1 is the line or primary curent in the inducing winding S_1. I_2 is the transformer secondary current in the armature circuit B_1. The resultant of these two mf.m.'s produces the transformer flux ϕ_1. E_1 is the voltage consumed by rotation of the armature circuit B_1, due to cutting ϕ_2 and is in phase with ϕ_2, transferred to primary S_1, by transformer action. E_2 is the e.m.f. consumed by self-induction in

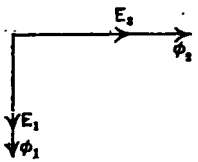


Fig. 5. Position in Space, Compensated Repulsion Motor.

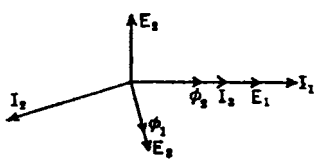


Fig. 6. Time-phase Diagram, Compensated Repulsion Motor.

B_2 by the alternation of ϕ_2. E_3 is the e.m.f. consumed by rotation in B_2 due to cutting the transformer flux ϕ_1.

Neglecting drops due to resistance and leakage reactance it can be seen that E_2 and E_3 are inductive drops in the armature, opposite in effects, and may completely neutralize each other, leaving the resultant primary voltage E_1 in phase with the primary current and giving unity power factor. By means of the series transformer T the current I_2 and thus the flux ϕ_2 may be decreased in comparison with I_1 and ϕ_1, which would make E_3 greater than E_2 and the primary current would lead the resultant line voltage

This principle has been employed in the construction of a number of types of small (1 to 20 h.p.) single-phase motors for industrial use, and these show a great superiority over the straight single-phase induction motor in the matter of starting torque and power-factor.

Wagner Repulsion-Starting, Induction Running Motor (Fig. 7).—The stator has two windings, the main or primary S_1 is connected in series with the exciting brushes B_2 on the armature as in the series motor. This gives the starting characteristics of the series a-c. motor. The armature has two sets of brushes. The main pair B_1 in line with the primary flux is short circuited, thus giving compensation as in the compensated series motor. The other pair of brushes B_2 is connected in series with the primary and across a "power factor compensating coil" S_2, wound on the stator in the same axis as the primary. A switch in this circuit is left open when starting, but is closed by a centrifugal governor just before synchronous speed is reached. Closing this switch short-circuits this pair of brushes through the compensating coil and makes the armature a two-phase rotor, and thus eliminates series-motor action and makes the action that of a true single-phase induction motor. The compensating coil being in circuit causes the anti-inductive effect in this coil to react on the primary as in the compensated repulsion motor, and give a good power-factor or

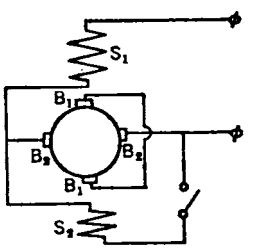


Fig. 7. Repulsion-starting, Induction-running.

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leading current. By adjusting the number of turns or current in this coil S_2 the power factor may be regulated.

To prevent the motor from running away in case the centrifugal switch should fail to act, and to relieve the brushes under load, a regular squirrel-cage winding is placed in the bottom of the armature slots underneath the commutated winding and separated from it by magnetic separators to magnify the magnetic leakage and render the squirrel-cage winding ineffective at starting. This motor is very satisfactory in practice, has a starting torque 1.5 times full load torque for a starting current of three times full load current. The power-factor is anti-inductive at light loads, unity at full load and inductive at overloads. The efficiency at full load is about 80 per cent in the 5 and 10 h.p. sizes. Reversal of rotation is effected by changing the connections to the exciting brushes. Small motors may be thrown directly on the line for starting. Large motors have a series resistance or reactance to limit the starting current to a reasonable amount.

Repulsion-Induction (R. I.) Motor of the General Electric Co. — This motor is shown diagrammatically in Fig. 8. It has two windings on the stator, the main or primary S_1 being connected directly and solely across the line as in any induction motor. The armature has two equally spaced sets of brushes displaced a small angle (20°) from the axis of the primary flux, thus obtaining the repulsion motor starting effect. The main brushes B_1 are short circuited and the auxiliary brushes B_2 connected permanently in series with the "power factor compensating coil" S_2 on the stator. The method of operation is best understood by considering the motor as being a repulsion motor and a single phase induction motor on the same shaft. At starting the repulsion-motor torque is great and the induction-motor torque is zero. Just below synchronism the induction-motor torque is great and repulsion-motor torque small. Above synchronism the repulsion-motor torque still exists but the induction-motor torque has become negative (generator). Thus at no load the repulsion motor pulls the induction motor above synchronism until the positive torque equals the negative torque and friction. At full load the speed is nearly synchronous. The compensating coil introduces an anti-inductive effect described above, and by varying the number of turns included, the power-factor may be made unity at any load. The efficiency is about 80 per cent in a 5 h.p. motor. Reversal of rotation is effected by moving the brushes or, if to be done often, by introducing a special coil in the primary whose connection is changed for reversal. An ordinary starting box is used to limit the current to about three times full load current for 1.5 times full load torque.

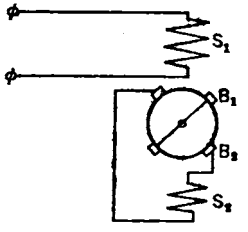


Fig. 8. Repulsion-Induction (R.I.) Motor.

Series Repulsion Motor. — Since the repulsion motor has better operating characteristics at a speed near synchronism than the series motor it is better to run with repulsion motor connections. On the other hand, the series motor has better operating characteristics during starting conditions. These facts have lead to the development of the "series repulsion" motor by one of the manufacturing companies. In the control of this motor a compensator with numerous taps is used and the connections so arranged that during starting the armature receives a very large current while the field is excited below the normal value. This gives a considerable torque with little trouble from commutation As the motor speeds up, the connections are gradually changed until at full speed

the motor operates practically as a repulsion motor with the good commutating characteristics of that motor.

Polyphase A-C. Commutator Motors. — The series a-c. motor may be constructed three-phase by providing three exciting and three compensating windings on the stator for each pair of poles and providing three equally spaced sets of brushes per pair of poles on the armature and connecting these in series to the three phase supply as in any "Y" connected machine. This machine has the typical variable speed characteristics of the series motor. The speed may also be varied by changing the position of the brushes.

In order to secure good commutation the armature must be wound for a low voltage and it therefore becomes convenient to connect the stator and rotor by means of a transformer instead of direct conduction. With this arrangement it is possible to use any desired voltage on the line. There has been a considerable development in the application of these motors in the last few years.

The armature and stator may also be connected in parallel with each other (preferable by means of a transformer) thus giving a polyphase shunt motor with constant speed characteristics. This type, however, has not found much commercial application so far.

DIMENSIONS, WEIGHT AND COSTS. — Due to the low flux densities used and the special windings required an a-c.commutator motor weighs from 50 per cent to 100 per cent more, occupies from 25 per cent to 50 per cent more space, and costs from 50 per cent to 100 per cent more than a 600-volt d-c. motor of the same rating; see *Motors, Direct-current.*

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MOTORS, DIRECT-CURRENT. — (*See also Alternating Currents; Electricity and Magnetism, Principles of; Generators, Direct-current; Motors, Industrial Applications of; Standardisation Rules.*) A motor is a dynamo-electric machine for converting electrical power into mechanical power; that is, it performs the converse function of a generator. Direct-current generators and motors are always interchangeable in function, although a machine which is designed specifically for a motor would probably not make a first-class generator and vice versa. Motors of less than 5 horse-power are usually bipolar; larger machines are multipolar.

The following is a brief outline of the contents of this article:

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Principles 1029
Shunt Motor 1030
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CLASSIFICATION. — There are four types of direct-current motors, differentiated by their characteristics and the connection of the exciting windings or circuits.

Shunt Motor (Fig. 1). — This motor has only one exciting winding, which is connected across the armature terminals and is thus in parallel or in shunt with the armature. The field winding consists of a large number of turns of fine wire on each pole, and usually the windings on all the poles are connected in series in one circuit. The current in the field depends upon the line voltage and upon the resistance of the field winding. The resistance of the field winding is purposely made high so that the field current will be between 1 per cent and 5 per cent of the full-load current of the motor. The characteristic of the shunt motor is a fairly constant speed for all reasonable values of load.

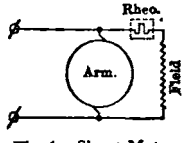


Fig. 1. Shunt Motor

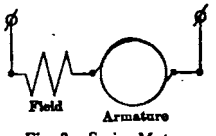


Fig. 2. Series Motor

Series Motor (Fig. 2). — This motor has only one exciting winding, which is connected in series with the armature so that all the current flows through the field as well as the armature. The field winding consists of a few turns of thick wire on each pole and the windings on all poles are connected in series. The current in the field depends upon the load and is thus large with heavy load and small with light load. The resistance of the field winding is purposely made low so that the loss of voltage and power in that circuit will be small. The characteristics of a series motor are a speed varying with every change in load,

high speed at light load and low speed at heavy load. The efficiency is high throughout a wide range of speed. The speed will be dangerously high at no load; thus a series motor must always be connected rigidly to its load. Since the torque is high at low speeds this motor is particularly adapted to work requiring frequent starting.

Compound (or Cumulative) Motor. — This motor has both a series winding and a shunt winding on each pole, wound and connected so that the two windings assist each other in the production of magnetism. It is a combination of a shunt and a series motor designed to give the good starting qualities of the series motor and to avoid the danger of excessive speed at light loads. See also *Motors, Industrial Applications of.*

Differential Motor. — This motor has a shunt and a series winding connected so that they oppose each other in the production of magnetism. The motor therefore has poor starting qualities, increases in speed with increase in load but has no tendency to run at a dangerously high speed. The applications of this motor are very limited.

Inclosed vs. Open Type. — These terms refer to the mechanical housing of the motor. The open type has all its parts freely exposed to the air and is therefore well ventilated. It is intended to be used indoors and in protected places. The inclosed type is intended to be used in exposed locations where there is a liability of dampness or dirt. Special means must be provided to circulate the air inside the machine, but even then an inclosed motor is larger and more expensive than an open motor of the same capacity.

The relative capacities in output of open, semi-inclosed, and totally inclosed motors are shown by the accompanying data on one of a line of typical commercial motors. In general an inclosed motor weighs about 15 per cent more than an open motor of the same capacity in spite of the fact that it is allowed to operate at 15° C. higher temperature by commercial convention.

Type	Output, h.p.	Temp. rise, °C.	Weight in lb. for 700 r.p.m. and given temp. rise
Open	10	40	970
Semi-inclosed	8	40	....
Totally inclosed	5.75	55	1100

METHODS OF RATING. — See *Standardization Rules of the A.I.E.E.* for limiting rise in temperature and for classification of types, Constant Speed, Multi-Speed, Adjustable Speed and Variable Speed.

The Electric Power Club, which includes representatives of most of the manufacturers of electric machinery in the U. S. A., has standardized, for commercial practice, certain temperature ratings which are based on the A.I.E.E. Rules. These regulations, which are for limiting temperatures as measured by thermometer with continuous duty, and the corresponding A.I.E.E. rules are:

	Max. rise on commutator	Max. rise on other parts
Open type	45° C.	40° C.
Protected type	55	50
Enclosed type	60	55
A.I.E.E. Rules	55	50

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VOLTAGE AND CURRENT. — Usual values of voltage for direct-current motors are:

110–125 for small motors on lighting circuits.
220–250 for motors in factories, shops, etc.; on power mains or on the outside mains of a three-wire system.
500–600 for general railway work.
1200 for special railway installations.

The current required for any motor is found by the relation

$$\text{Current} = \frac{\text{Output in h.p.} \times 746}{\text{Efficiency} \times \text{Voltage}}.$$

Usual values for the efficiencies of motors of various sizes are given below.

APPLICATIONS OF MOTORS. — This subject is treated in detail in a separate article on *Motors, Industrial Applications of* (q.v.). The chief applications of continuous-current motors are the following:

Shunt Motor. — Driving shafting, machine tools, blowers, reciprocating pumps; motor generators.

Series Motors. — Railway and all other transportation work; hoists; cranes.

Compound Motor. — Elevators, hoists and machinery that must be started often.

Differential Motor. — Very special applications of small units for peculiar speed conditions.

PRINCIPLES. — The principles upon which a direct-current motor operates are the same as those upon which a direct-current generator operates (*see Generators, Direct-current*). These principles are briefly as follows:

Force Acting on Conductor. — A conductor of length l carrying a current I and placed in a magnetic field having a flux density B is acted upon by a force which is proportional to BlI, which force is in a direction at right angles to the direction of the magnetic flux and at right angles to the length of the conductor. This in practical form gives the relation

$$T = \frac{p\phi ZI}{852\, m \times 10^8}.$$

T = torque of an armature in pounds at one-foot radius.
p = number of poles.
m = number of armature paths between brushes.
ϕ = flux per pole in armature (lines).
Z = number of active conductors or inductors on armature.
I = current taken by the armature from line.

This torque is exerted whenever a current flows and is independent of the speed. The core-loss and friction absorb some of the torque so that the torque at the pulley is slightly less than the value given by the formula.

Counter E.M.F. in Conductor. — A conductor of length l moving with a velocity V in a magnetic field of density B has induced in it an electromotive force E proportional to BlV. In practice as soon as the armature starts to move a counter e.m.f. is induced in its conductors which has the value

$$E = \frac{p\phi Zn}{m \times 10^8},$$

where n = revolutions per second.

Thus as soon as the armature moves, this counter e.m.f. tends to stop the flow of current and the impressed e.m.f. must be increased to maintain the flow of current.

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The relation between current and counter e.m.f. is given by the equation

$$E_i = E + IR,$$

where E_i = impressed e.m.f.,
E = counter or generated e.m.f.,
R = resistance of armature circuit.

In practice R is made as small as possible so that E and E_i are as nearly equal as possible.

Reversing Rotation.— From a consideration of the equation for the torque it is evident that torque is proportional to the product ϕI, i.e., to the product of the flux in the armature by the current. If the direction of the current through the armature is reversed, that is, if I becomes negative, the product becomes negative and the torque is in the opposite direction. If the direction of the flux is changed (the armature current being unchanged) the direction of torque is reversed. But if both ϕ and I are reversed the torque is not reversed. From this follows the rule for reversing the direction of rotation of any direct-current motor; viz., change the direction of flow of current in either the field or armature winding but not in both.

Speed Control. — From the equation for counter e.m.f. it follows that the speed is proportional to E/ϕ. That is, the speed varies directly as the counter e.m.f. and inversely as the flux. Thus to reduce the speed, decrease the counter e.m.f. by decreasing the e.m.f. impressed on the armature or increase the flux by increasing the field current. To increase the speed perform the converse. To decrease the e.m.f. impressed on the armature a resistance may be inserted between the source of potential and the armature terminals. This is the customary manner of controlling the speed during the starting of motors. (*See also section below on Starting of D-C. Motors.*)

SHUNT MOTOR. — Since the flux in the armature of a shunt motor is practically independent of load, the characteristics of the motor are: approximately constant speed for all reasonable variations of load, torque directly proportional to the armature current irrespective of speed, efficiency high throughout a wide range of load but for only a small range of speed see Fig. 3.

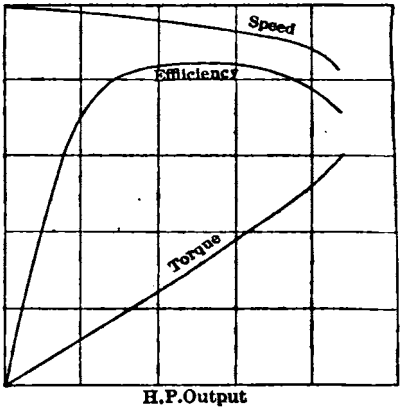


Fig. 3. Speed, Torque and Efficiency Characteristics of a Shunt Motor

Design of Shunt Motor. — The method of design and calculation of shunt motors is the same as for direct-current generators (*see Generators, Direct-current*) except for the minor details noted below.

The armature reaction of a motor is in the opposite direction to that of a generator running in the same direction, and thus the field is distorted in the opposite direction. Hence, if the brushes are to be moved to assist commutation they must be moved in a direction opposite to the direction of rotation of the armature.

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The effect of armature reaction is to weaken the field. This causes a tendency to increase the speed and also causes bad commutation.

The stability factor of a motor must be greater than that of a generator because when the motor drops in speed as the load comes on, the field must be weakened to increase the speed. Hence the field is liable to be operated at an excitation less than normal.

Testing of Shunt Motors. — (*See also Standardization Rules of the A.I.E.E.*) The tests on shunt motors may be divided into two classes: (*a*) Commercial, to determine the qualities and serviceability of particular motors; and (*b*) Special, to determine the general characteristics and actions of a type of motor. Commercial tests are the following:

Resistance measurements.
Stray power test, including core-loss and friction.
Input-output test for heating, efficiency and commutation.
Insulation test.

Resistance Measurements are made with the machine cold and later after the heat run. The resistances of the armature winding and field winding are measured, and the brush-contact resistance may be measured but is usually calculated (*see Generators, Direct-current*). For any value of current the resistance losses (RI^2) are calculated from the measured hot resistances.

"Stray Power" Test. — The term "stray power" is applied to the lumped sum of the core-loss and the loss due to friction, bearings and windage. The stray power of a d-c. machine can be determined approximately by impressing normal voltage on the field and letting the machine run as a motor without load, varying the voltage impressed on the armature from about 10 per cent above normal to about 10 per cent below normal. The speed, armature voltage and armature current for each adjustment are observed. Then the stray power for any induced voltage is equal to the armature input less the corresponding RI^2, where R is the armature resistance and I the armature current. The value of stray power for any given load on the motor is then equal to the measured value corresponding to the same counter e.m.f. E, where E is calculated from the impressed voltage E_i by the relation $E = E_i - RI$, I being the armature current for this load and R the armature resistance as before.

If it is desired to determine the stray power more accurately by taking into account the effect of armature reaction, the field current may be adjusted so that the speed on the above run is the same as the load speed. This gives a flux of the same average value as when the machine is under load.

Calculation of Efficiency from Losses. — Let P = total output in kilowatts; R_a = resistance of armature, including brushes; I_a = armature current; I_f = field current; E_i = impressed voltage; S = stray power. Then the per cent efficiency is

$$e = \frac{100\,P}{E_i(I_a + I_f)} = \frac{100\,P}{P + E_i I_f + I_a^2 R_a + S}.$$

Input-output Test with Prony Brake. — The input-output test may be made either by means of a prony or band brake on a pulley, or by using a d-c. generator as a load. If the brake test is made the output is

$$\text{Watts} = \frac{PLN}{7.04},$$

where P = net pull in pounds, L = lever arm or radius in feet, N = revolutions per minute.

Input-output Test with Generator as Load. — With large motors it is desirable to use a generator as a load in making an input-output test. In

this case it is necessary to know the resistance of the generator armature circuit. It is also desirable to have the generator separately excited and to maintain a constant excitation throughout the entire test.

The input of the motor and the output of the generator, together with the speeds of both machines, are observed. A "counter-torque" test must also be made to determine the belt friction loss and the core-loss and friction of the generator. This is performed by making two tests as follows:

(*a*) The motor input is observed when driving the unloaded generator at normal speed first through the regular leather belt and second through a light cotton belt. The difference in input to the motor in the first and second cases gives the belt-friction loss. As this loss is comparatively small, it may frequently be neglected.

(*b*) A regular stray power test (*see above*) is made on the generator when entirely disconnected from the motor. This gives the core-loss and friction of the load machine (generator).

Then for any load during the load run the output of the motor under test is

$$P_1 = P_2 + R_2I^2 + S + F,$$

where P_1 = output in watts of motor, machine 1.
P_2 = output in watts of generator, machine 2.
R_2I^2 = loss in armature winding of generator.
S = stray power of generator for speed and induced voltage at observed load.
F = belt-friction loss.

The ratio of this motor output to the electrical input as observed gives the efficiency of the motor.

Heat Run. — From the input-output test it is also possible to determine the speed regulation, commutation features and heating. The heat run may also be made by "bucking" two machines as described in the article on *Generators, Direct-current.* Small motors will reach a constant temperature in a short time and the heat run need only last 5 or 6 hours for a 100-h.p. motor. A thermometer is usually placed on the machine in a safe and accessible place and read every half hour until it indicates no further rise in temperature.

Insulation Test. — The margin of safety on a 110- or 220-volt motor is usually so great that it is not necessary to make an insulation test. If the motor has been exposed to dampness it may be desirable to make the test after the motor has been thoroughly dried out. The method is indicated in the *Standardization Rules of the A.I.E.E.* (q.v.)

Special Tests. — As a special test there may be obtained a saturation curve of the machine and possibly the distribution of potential around the commutator. These are of particular interest in an adjustable speed motor. In some of these motors with commutating poles there may exist some very high voltages between bars which are not evident except in the bar-to-bar potential test.

SERIES MOTOR. — Since the flux in the series motor is produced by the load current, the flux increases with the current. The torque is proportional to the product ϕI and therefore increases more rapidly than the current. Thus four times full-load torque can be obtained with from two to three times full-load current.

The characteristics of the series motor are: increase of torque faster than increase of current, variation in speed inversely as the load, and high efficiency throughout a wide range of speed as well as load, see Fig. 4.

Design of Series Motors. — In general the method of calculation is the same as for a direct-current generator (*see Generators, Direct-current*). The special considerations are:

A series motor is usually designed to have a large output and low speed at the one-hour rating. At any lesser output the speed will be higher, so the peripheral velocity must be quite moderate at the rated load and speed.

Since the speed is very nearly inversely proportional to the flux the speed curve depends on the shape of the saturation curve, to which very careful attention is paid in designing. By exactly fixing the flux for two extreme values of current the speed for these two values of current is fixed.

The relations between the speed and current of a series motor are shown by the formulas:

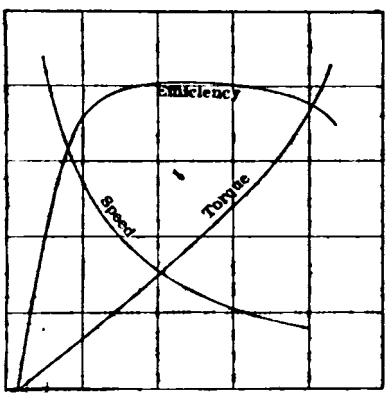


Fig. 4. Speed, Torque and Efficiency Characteristics of a Series Motor

$$E_i = E + IR,$$

$$E = \frac{p\phi Zn}{m\,10^8},$$

$$n = \frac{m(E_i - IR) \times 10^8}{p\phi Z},$$

where

E_i = impressed voltage,
E = counter e.m.f. induced in armature,
R = total resistance of armature and field,
I = current taken by motor,
p = number of poles,
m = number of parallel paths between positive and negative brush sets,
Z = total number of conductors on armature,
n = speed of armature in revolutions per second,
ϕ = total flux per pole in maxwells.

Since the current in the field of a series motor is the same as that in the armature, the ratio of the turns in each is the same as the ratio of ampere-turns or m.m.f's. Thus if the magnetomotive force per pole of the field is to be 1.5 times that of the armature the number of turns will be 1.5 times the number of turns in series in the armature.

Since a series motor is usually an inclosed motor with a one-hour rating its rise in temperature and rating are a direct function of the watts lost and the ability of the mass of the motor to store up this heat energy. In a one-hour run the amount of energy radiated is only about 10 per cent of the amount stored in the mass. For a rise in temperature of 75° C. in one hour there should be about 0.4 pound of material for each watt of loss. This assumes reasonable provision in the construction of the motor for the transfer of the heat from the armature to the field and frame.

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Much attention has been directed recently to the ventilation of these motors by drawing air from outside the motor by means of fan blades on the armature and by circulation of the air inside the motor through definite paths. This has considerably increased the weight efficiency of these motors.

In railway motors, which are the most general application of the series motor, commutating poles are very generally used, as this construction makes it possible to obtain a much greater momentary output from a motor of a given size (*see below*).

Testing of Series Motors. — (*See also Standardization Rules of the A.I.E.E.*) To determine properly the speed and torque characteristics of a series motor an "input-output" test must be made, which involves subjecting the motor to actual load and overload conditions. This may be accomplished by running the motor with a prony brake as a load or with a direct-connected generator as a load (*see section above on Testing of Shunt Motors*).

Railway Motor Test. — When two similar motors are available the method used by the manufacturers of railway motors is most desirable. The two motors are direct connected, or geared to each other, and the electrical connections made as in Fig. 5. The test is run through by keeping constant rated voltage on the motor and regulating the load on the motor by changing the load on the generator.

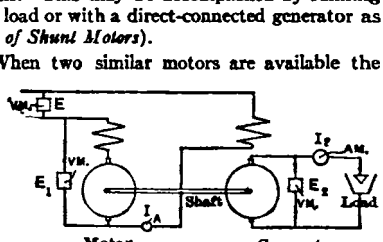


Fig. 5. Railway Motor Load Test

As the two machines are operating under almost exactly the same conditions, their efficiencies are very nearly the same. Thus

$$\text{Efficiency of set} = \frac{E_2 I_2}{EI},$$

$$\text{Efficiency of each motor} = \sqrt{\frac{E_2 I_2}{EI}}.$$

The speed and torque curves should be made for both directions of rotation of the armature as an incorrect brush setting will give results differing with the direction of rotation. The direction of rotation is changed by reversing the connections of either the field or the armature of the motor.

Commutation is observed during the speed and torque test.

The heat run is made with the same arrangement as the speed-torque test. In making the heat run the motor must start cold or at room temperature. The covers of the inspection openings of railway motors are customarily left open during the heat run.

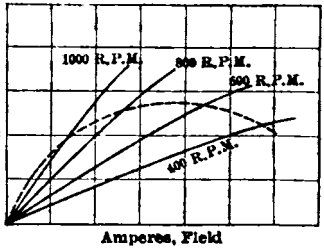


Fig. 6. Core-loss Curves of Series Motor

Losses and Efficiency of Series Motors. — For a more accurate determination of the efficiency and losses the following special tests are made:

1. Resistance of armature, brushes and field. These tests are similar to those for a shunt motor, see above.

2. Core-loss test. On account of the variable speed and variable field of a series motor this test consists in repeating the usual core-loss test as described

above for a generator at several different speeds. The field strength is varied step by step throughout the maximum range for each speed. Fig. 6 shows the curves for these different runs and the dotted line connects the points on the different curves that apply to the normal speed curve of the motor.

Insulation Tests. — See *Generators, Direct-current,* and *Standardization Rules of the A.I.E.E.*

STARTING OF DIRECT-CURRENT MOTORS. — A starting box, Fig. 8, or rheostat is always employed in starting direct-current motors in order to reduce the voltage impressed on the motor when it is not running at a high enough speed to generate the proper counter e.m.f.

Let E_i = line voltage,
E = counter e.m.f. (approximately proportional to speed),
I = current,
r = resistance of armature circuit,
R = resistance of starting box or rheostat.

Then

$$I = \frac{E_i - E}{r + R}.$$

At the first instant the motor armature is stationary and $E = 0$; thus $I = \frac{E_i}{r + R}$ and the value of R is determined by the desired value of I. As the motor accelerates, E increases. If R remained constant I would decrease to such a small value that there would not be sufficient torque to accelerate the load. The current, and therefore the torque, can be brought back to their original values by changing R to such a value R_1, that

$$I = \frac{E_i - E}{r + R_1}.$$

Fig. 7 shows the sudden rise in current when the resistance is changed and the gradual decrease in current as the speed increases. The number of steps necessary depends upon the ratio of the maximum allowable instantaneous value of the current to the final constant value, upon the value of the armature resistance and upon the inertia of the load.

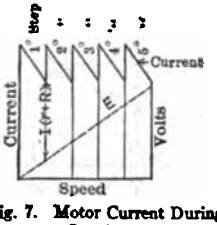


Fig. 7. Motor Current During Starting

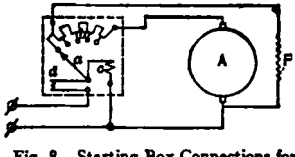


Fig. 8. Starting Box Connections for Shunt Motor

Starting Box.—(*See also article on Rheostats*). A starting box usually contains the following features, as indicated in Fig. 8: (a) a means of opening and closing the circuit supplying all the current to the motor including the field current; (b) a set of resistance steps in series with the motor armature and a means of short-circuiting this resistance step by step; (c) a magnet coil connected across the motor terminals to open the circuit if the impressed voltage fails or falls below a specified value (low-voltage release); (d) a magnet coil carrying the main current to actuate a spring and open the circuit if the current exceeds a

specified value (overload release). The usual connections of a starting box to the line and motor are shown in Fig. 8.

SPEED CONTROL. — There are three methods of varying and controlling the speed of d-c. motors, namely, potential, rheostatic and field systems.

Potential Control or Multi-voltage System. — By means of several generators and several wires various definite voltages are made available, such as 240, 180, 120, etc. By connecting the motor to the 240-volt circuit full speed is obtained; by connecting to the 180-volt circuit ¾ speed is obtained, etc. The shunt field circuit is left connected at all times to a circuit of the proper voltage. A shunt motor with normal field excitation will be stable, that is, it will operate constantly, at the fractional speed. The efficiency will be good at the fractional speeds. A series motor controlled in this manner will be unstable, but for a given torque the speed will be roughly proportional to the voltage.

Rheostatic Control. — A rheostat in series with the armature will reduce the voltage impressed on the armature by an amount proportional to the current, and thereby reduce the speed. The speed is unstable with this arrangement, changing with every change of load, and the efficiency is poor.

Field Control. — By increasing the resistance in series with the field of a shunt motor the speed is increased due to the weakening of the field. If the motor has commutating poles to assure good commutation the speed may be varied in a ratio of 1 to 2, and even 1 to 3 in small sizes. The shunt motor is stable with this method of control and the efficiency is good. In a series motor the field may be shunted by a resistance to increase the speed but the motor is not stable and this practice is not to be recommended.

USE OF COMMUTATING POLES (INTERPOLES) IN VARIABLE-SPEED MOTORS. — In motors intended to be operated over a large variation in speed, obtained by changing the field strength, and in motors which are to be subjected to heavy overloads, it is necessary to use commutating poles in order to obtain good commutation. In a motor without commutating poles the field strength must always be a certain percentage greater than the armature strength to prevent a shifting of the field flux and of the neutral point. Thus,

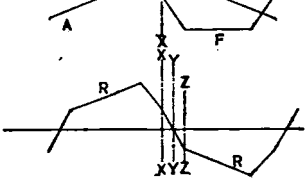


Fig. 9. Flux Distribution without Commutating Poles

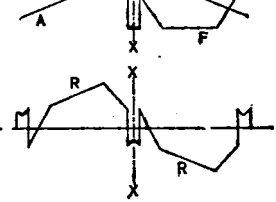


Fig. 10. Flux Distribution with Commutating Poles

If, in Fig. 9, F represents the distribution of field flux when existing alone and A represents a strong armature flux existing alone, then R shows the distribution of the resultant flux when both field and armature are excited.

It will be noticed that the neutral point has been shifted from XX at no load in a direction against rotation to YY at the load considered. The brushes would have to be shifted from XX at no load to a point ZZ beyond YY at load

in order that they shall commutate a coil in a flux which is producing a voltage helpful to commutation.

Resultant Flux with Commutating Poles. — If, however, commutating poles are placed between the main poles and excited with the armature current they will maintain at the geometrical neutral a flux of the direction and value necessary to give good commutation. In Fig. 10, *F* and *A* represent the field and armature flux separately as before and *C* the commutating pole flux that would exist at full load. When at full load these fluxes are combined there exists the resultant flux shown at *R*.

It will be noticed that there remains at the neutral point a small flux of the proper polarity and magnitude to provide an e.m.f. to reverse the current and give good commutation and it is not necessary to move the brushes.

The commutating pole must be of the same polarity as the pole towards which the brush would have to be moved if there were no commutating poles. In fact the principle of commutating poles is nothing more than bringing to the brush a part of the pole instead of moving the brush to the pole. Thus the polarity of the commutating pole is different during motor action from that during generator action. If the windings on the commutating poles are connected in series with the armature the conditions will be correct for either motor or generator action.

INSTALLATION AND ERECTION. — In the installation and erection of a direct-current motor there are certain features which must receive careful attention in order that the machine shall operate properly and not deteriorate with undue rapidity. Although this procedure varies with different motors according to their mechanical construction the following brief memorandum of points to be looked after will be found useful:

1. Base bolted down.
2. Bearings clean and filled with oil.
3. Bearings lined up.
4. Magnet frame bolted to base.
5. Field coils secured in place.
6. Field coils tested for open circuit, wrong connection and polarity.
7. Armature in place.
8. Air gap adjusted by shimming.
9. Measure resistance of armature and field.
10. Measure insulation resistance.
11. Brushes properly fitted and spaced and pressure adjusted to about 1.5 to 2 pounds per brush.
12. Commutator smooth and true.
13. Substantial connections of field circuit.
14. Field adjusted for correct direction of rotation.

The motor must be protected from moisture during shipment and if by accident it becomes damp it must be dried out before it is subjected to a voltage.

OPERATION. — In the operation of a direct-current motor several factors should be considered.

Care. — All motors should be frequently inspected and the following points noted:

1. Bearings filled with proper amount of oil.
2. Brushes securely held in proper position.
3. Brushes fit properly.
4. Commutator smooth: Danger of "high mica" or the insulation between commutator bars projecting above the bars.
5. Air gap true.
6. Commutator not worn in grooves.

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Troubles. — In the following paragraphs is given a concise list of the troubles that may be experienced in operating continuous-current motors and their causes as given by Crocker and Wheeler in *Management of Electrical Machinery*.

1. *Sparking at the Commutator.* — Causes: Armature carrying overload. Brushes improperly spaced. Brushes not at proper position. Rough commutator. Poor brush contact. Internal short or open circuit. Field too weak. Unequal strength of poles. Vibration.

2. *Heating of Commutator and Brushes.* — Sparking. Bearing trouble. Bad connections. Brush friction too great.

3. *Heating of Armature.* — Overload. Internal short circuit, moisture or ground. Reversed coil. Excessive eddy currents.

4. *Heating of Field.* — Internal short circuit.

5. *Heating of Bearings.* — Bearings dry or dirty. Shaft out of true. Bearings out of line. Thrust due to belt. Unbalanced magnetic pull.

6. *Noise.* — Armature not balanced. Brushes dry or not set at proper angle. Armature strikes.

7. *Speed Too Low.* — Wrong voltage. Overload. Armature strikes. Bearing too tight.

8. *Speed Too High.* — Wrong voltage. Field too weak.

9. *Motor Stops or Fails to Start.* — Overload, open circuit, wrong connection.

SPECIFICATIONS FOR D-C. MOTORS FOR INDUSTRIAL USE. — (*See next section for Specifications for Railway Motors.*) The following memoranda are intended to assist in writing specifications. See also article on *Specifications*.

Principal Characteristics and Conditions of Service. — Use to which motor is to be put, kind of load and method of drive. Voltage. Rating, horse-power. Speed.

Style and Description; Details of Construction. — Whether to be open, semi-inclosed or inclosed. Whether to be series, shunt or compound wound; if shunt wound, whether shunt field rheostat is to be supplied; if compound wound, state whether cumulative or differential. Requirements regarding pulley or length of shaft. Whether rails are required. Whether starting rheostat is to be supplied, and if so, its general characteristics.

Performance and Tests. — (*See Standardisation Rules of the A.I.E.E.*). Temperature rises upon which ratings are to be based. Details of overload. Efficiency at 25, 50, 75, 100, and 125 per cent load; whether rheostat losses are to be included in calculating efficiencies. Starting torque with full-load current, pound-feet. High-potential tests of insulation. Requirements regarding effect of moisture upon insulation. Regulation; the supply voltage being constant, and the field rheostat fixed, a variation of load from zero to . . . per cent of full-rated load shall cause a variation of speed not greater than . . . per cent. The shunt field rheostat to give speed variation of . . . per cent in steps not greater than . . . per cent and not less than . . . steps, and to carry the current for any speed continuously without undue heating.

SPECIFICATIONS FOR SERIES RAILWAY MOTORS. — The following memoranda are intended to assist in writing specifications. See also article on *Specifications*.

Principal Characteristics and Conditions of Service. — General statement of the service, giving type of cars, whether current is direct or alternating,

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or both, etc. The motor shall be designed for normal operation at . . . volts and shall operate safety at . . . volts.

Style and Description; Details of Construction. — The frame shall be designed so as to allow the easy removal of armature and field coils. It shall be provided with openings at both ends, and both above and below the shaft, which will enable the inside of the motor to be readily inspected and cleaned. Bearings shall be designed so that lubricant cannot enter the frame, and shall be so located that they may be easily emptied and cleaned. The diameter of the driving axle on which the motor is to be mounted shall be . . . inches. Whether motor is to be of interpole type. Whether natural or forced ventilation.

Brushes and Brush Holder. — The brush holders shall be readily removable through the hand holes. The springs holding the brushes against commutator shall not be relied on to carry current. The brushes shall be staggered or provided with adjustment parallel to the armature shaft so as to prevent the formation of ridges on the commutator.

Clearances.—The minimum distance between motor frame and back of wheel flanges shall be . . . inches, the minimum distance between bottom of motor and top of rail when tires are new shall be . . . inches.

Gears and Gear Case (if any).— Single or double reduction; what gear wheels shall be mounted on; material of wheel and pinion; description of teeth, whether cut or cast, and width of face of wheel or pinion; gear case, material, how suspended, oil-tightness.

Suspension of Motors.—General description and requirements, location of lugs on motor frames.

Data to be Furnished by Bidder. — The armature will be bound with . . . bands. Material and dimensions of the bands. Dimensions of openings in the frame. The brush holders will be adjustable so as to allow . . . inch wear with uniform pressure on the brushes, after the diameter of the commutator has been reduced by . . . inches. The current density in the carbon brushes will not exceed . . . amperes per square inch at normal rated load. The gear ratio will be . . .

Performance and Tests. — (*See also Specifications in article on Locomotives, Electric.*) Either the nominal rating and the continuous ratings at ½, ¾ and full voltage should be specified, or the following data supplied.

Line voltage.....
Number of motors per car.....
Weight of loaded car, exclusive of motors and control equipment.
Diameter of driving wheels.....
Schedule speed.....
Distance between stops.....
Duration of stops.....
Acceleration miles per hr. per sec.....
Retardation, miles per hr. per sec.....

The engineer should also give a diagram of grades and curves.

Motor Characteristics. — The bidder shall submit diagrams showing speed, tractive effort, efficiency, RI^2 losses, core losses, and any other information bearing on the performance of the motor. Requirements regarding the effect of moisture upon insulation.

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Tests. — The motor shall be tested at the Manufacturer's works in the presence of the Engineer's inspector. (In the case of new motor developments it is good practice to make the tests under service conditions; but for standard motors a stand test at the factory is sufficient.) A complete series of tests shall be made upon the first motor manufactured under this specification. These tests shall confirm all the statements made by the bidder in relation to operating characteristics. Should the motor fail to comply with any of these statements, the defects shall be corrected and any changes in construction or design which may be necessary to accomplish this shall be made at the contractor's expense. The first motor shall be submitted to a flashing test to determine the susceptibility of the motor to flash-over on opening the maximum specified line voltage across the motor when running at maximum speed. After the acceptance of the first equipment, any other motors to be supplied under this specification shall be submitted to an approved stand test. The insulation of the armature windings, commutator and field windings, shall be subjected to stated alternating voltages (*see Standardization Rules of the A.I.E.E.*) for a period of one minute.

PERFORMANCE, WEIGHT AND COSTS (Pre-war prices) *. — Usual values of the efficiency and losses, and also values of the weight, speed and cost of shunt and series motors are given in the following tables:

PERFORMANCE OF SHUNT MOTORS

H.P.	Full load efficiency, per cent	Field I^2R, per cent	Friction, per cent	Core-loss, per cent	Armature I^2R, per cent
0.5	70	5	10	5	10
1	79	4	8	4	5
2	82	3.5	7	3.5	4
5	85	3	5	3	4
10	87	2.5	4.5	2	4
20	88	2	4	2	4
25	89	2	3	2	4

WEIGHT, SPEED AND COST OF SHUNT MOTORS

H.P.	Speed, r.p.m.	Weight, pounds	Cost *	Speed, r.p.m.	Weight, pounds	Cost *
0.5	2200	60	$30	....	....	....
1	2000	100	50	1675	125	$60
2	1650	210	75	1175	250	90
5	1100	550	150	920	600	165
10	850	950	240	700	1100	280
20	680	1650	410	550	1900	470
25	650	1950	500	500	2300	600

* For 1922 prices add 50 per cent.

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PERFORMANCE OF SERIES MOTORS

Commutating Pole Railway Type

H.P.*	Full-load efficiency, per cent	Field I^2R, per cent	Friction, per cent†	Core-loss, per cent	Armature I^2R, per cent
40	79	6.5	5.3	2.2	7.0
50	82	5.0	5.0	2.1	5.9
75	84	4.5	5.0	2.0	4.5
100	85	4.3	5.0	2.0	3.7
150	86.5	3.5	5.0	2.0	3.0

* H.P. for 75° C. rise in one hour.
† Friction includes loss in gearing.

WEIGHT, SPEED AND COST OF SERIES MOTORS

Commutating Pole Railway Type

H.P.*	Speed, r.p.m.	Lb., weight per h.p. †	Cost, dollars per hp.‡
40	750	57	11
50	700	53	10.5
75	650	44	8.5
100	625	37	7
150	600	33	6.4

* H.P. for 75° C. rise in one hour.
† Weight includes cast-steel frame and gear pinion and gear case.
‡ For 1922 prices add 50 per cent.

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MOTORS, INDUSTRIAL APPLICATIONS OF.—(*See also Bearings; Belts and Belting; Blowers and Compressors; Chains and Chain Drive; Conveyors; Couplings, Direct; Cranes; Dredges, Electrically-Operated; Elevators, Electric; Fans; Flywheels for Load Equalization; Gears and Gearing; Hoists, Electric; Machine Tools, Electrical Operation of; Motors, A-C. Commutator, Direct-Current, Polyphase Induction, Single-Phase Induction, Synchronous; Pumps and Pumping Engines; Printing Presses; Ropes and Rope Drive; Shafting; Shovels, Electrical Operation of; Steel Mills, Electric Drive of; Telpherage; Unloaders, Coal and Ore; Valves.*) The application of the electric motor for driving industrial machinery, either individually or in groups, was at first thought to be of value merely in the saving of power through the elimination of the losses due to friction in line shaftings or other forms of mechanical transmissions. A still higher economy has, however, been found to lie in the remarkable effect that it has in increasing the output of the production.

ADVANTAGES OF ELECTRIC DRIVE. — The more important advantages of electric drive are the following:

Location of Machines. — The various machines can be placed in almost any desired position and the use of portable tools is readily made possible, as, for example, when a portable drill and slotter are brought to a heavy casting, the slotter being applied to the outside of the piece at the same time the inside is being drilled.

Head Room. — A clear head room is obtained by the elimination of belting. This gives better illumination and ventilation and permits overhead cranes to be used freely, which is of greatest importance in any factory as it greatly facilitates the handling of the material, resulting in a considerable saving in time and labor, and thus increasing the output.

The constant source of dripping oil from overhead bearings and shafting is eliminated, and the danger which always accompanies the use of belts is overcome.

Centralized Power. — Power can most readily be distributed from a central supply station to the different buildings, and changes or additions to the system can always be made without difficulty.

Reliability. — The electric system offers greater reliability than belt drive. A breakdown is usually confined to a single machine, but with belting and a shafting a breakdown will generally cause a shutdown of a considerable portion of the equipment.

Study of Machine Performance. — Meters of either the recording or indicating type can be installed easily where desired and the performance of every individual machine ascertained. This is a very important point in all industrial undertakings, as it is then possible to maintain all the machinery in the best operating condition. Any excess power taken is at once readily detected and the defect can be promptly corrected. An accurate record can also be kept of the cost of power for the different operations.

GROUP VERSUS INDIVIDUAL DRIVE. — There are two general systems of drive, namely, group and individual, and there is still a diversity of opinion as to the relative advantages of the two. The group drive is to a certain extent an outgrowth of the older system of line shafting. When such a system is to be changed to an electric drive, the most obvious and simple way of making the change is to split the shafting up into such sections as would be most convenient, and drive each of these by means of a comparatively large motor. On the other hand, it may frequently happen that it is necessary to operate only one machine of the entire group for a considerable time, as in overtime work,

and to do this it would then be necessary to keep the motor and the line shafting of the whole group running. Since the efficiency of the motor at this light load would be small, and the friction losses of the entire drive would have to be supplied, it is evident that such a method of operation would result in a waste of power and be most inefficient. Modern installations, therefore, indicate a tendency toward the use of both the group and individual drive.

Influence of Character of Load. — It is generally agreed that all large tools or other machinery should be equipped with individual motors, especially if their service is of an intermittent nature. With the group drive there are two distinct loads, the variable of the machines and the friction of the line shafting and belting. The lower the machine load factor, the greater becomes the percentage of friction load and the more inefficient the group transmission.

Influence of Speed. — Wide ranges of control and the possible variations of speed are reasons which in many cases are sufficient in themselves for the selection of an individual drive. With group drive the methods of speed control for the individual machines are obviously more limited. It is then generally accomplished by shifting of belts on cone pulleys or by change of gears. Both of these methods, however, take a considerably longer time than the simple manipulation of the controller with the individual electric drive.

With individual motor drive it is possible to obtain very fine speed graduations, this benefit, of course, only being derived with a variable speed motor. Another advantage is the fact that it is possible to speed up a machine with a proportional increase in power. This may be necessary whenever a change is made from carbon to high-speed steel.

Influence of Relative Cost. — The increased cost of installation is one of the principal factors that prevent the general installation of individual drives. With this drive the total horse-power rating of the motors installed in the plant will be considerably greater than with group drive, but the maximum power demand of the plant is approximately the same in either case. If power is purchased the price should be based on the actual maximum power demand and not, as sometimes is required, on the total connected horse-power capacity of the motors. This latter method would obviously give a lower basic rate for the group drive, although the higher efficiency of the individual drive would considerably reduce the actual power consumed.

The question of whether or not group or individual drive is to be installed is thus a financial one and each case must be properly analysed. Individual drive necessarily means a larger investment, but in nearly all cases a much greater percentage income will be realized than if line-shaft drive were employed.

GENERAL CONSIDERATIONS IN THE SELECTION OF MOTORS. — The conditions of capacity and efficiency are both of importance in any motor installation and should therefore be given careful consideration. The installation of a motor having too large a capacity should in general be avoided, unless an increase in the load is to be expected in the near future, because the efficiency of a motor is usually a maximum at its normal rated output, decreasing above and below this point. With alternating-current motors the effect of the power factor must furthermore be considered. This decreases rapidly below normal load, and on account of its bad effect on the regulation of the system it should be kept as high as possible, which can only be done by operating the motors as nearly fully loaded as possible. Ordinarily, however, it is possible to so group the machinery that the motors may be operated near their rated output at all times. Too small a motor is naturally also very undesirable, as it would then in all probability be subject to overloads, which may result in overheating and a burn-out of the motor, causing a shutdown, not only of the motor itself, but also of the machinery which it drives. The op-

erating conditions of the plant may furthermore be such, as for example in steel mills, that the failure of a single motor may necessitate the shutting down of the entire mill.

The selection of suitable motors requires not only complete information on the power required to drive each group of machines or each machine individually but also a thorough knowledge of the motor design and its inherent characteristics to meet the requirements of the load. Some machines will require motors with very heavy starting torque, although running under light load when up to speed, while for others the requirements may be just the opposite. With a varying speed motor the torque-speed characteristics should agree as nearly as possible with the load which the motor is to drive, and the characteristics of adjustable-speed motors as influenced by different systems of control should also be carefully investigated. See also section below on *Data Required to Determine Type and Size of Motor*.

Influence of Motor Efficiency. — A motor of high efficiency is obviously desirable, and it is generally an easy matter to estimate the saving incurred by the installation of a motor of high efficiency as compared to a less efficient one. When a motor is operated for a considerable part of the time on light load, this fact must be given due consideration in the comparison on account of the variation in the motor efficiency for different loads.

Influence of Torque and Speed. — In order to obtain the most satisfactory results from motor drive it is essential that the type as well as the size of the motor be properly adapted to the work contemplated. This is especially important in the case of individual drive, where a wrong selection of the proper motor would be more serious than in group drive. The size of the motor may be ample to operate the machine under normal load but it may not be able to develop a sufficient starting torque, or it may draw a too excessive starting current from the line. For example, to start and accelerate the bridge of a crane requires a motor capable of developing a high starting torque, but after the bridge is accelerated comparatively little power is required to keep it in motion.

The condition of maximum torque must also be given due consideration. A motor driving a heavy punch may, in spite of the flywheel, develop insufficient torque to keep up the speed. As a rule, however, where the motor is large enough for starting and normal operation, but not large enough for the maximum overload required for perhaps only a second or two, the addition of a suitable flywheel will sometimes cut down the maximum torque required. In other cases it may be necessary to install a motor larger than necessary for the average work.

The proper speed regulation is also of importance and a motor must be selected which is best meeting these requirements. The size of the motor is also influenced by the cycle of operation, i.e., whether the load is continuous or intermittent. Careful consideration should be given to this point, and, as previously mentioned, motors will undoubtedly soon be rated to conform to the particular service for which they may be required. See also section below on *Classification of Motors According to Speed*.

Alternating Versus Direct Current. — The choice of alternating or direct current depends largely on local conditions and on the service requirements. With all other conditions the same, the alternating-current system offers many advantages when the distances over which the power must be transmitted are large. A higher transmission voltage may be selected which will diminish the amount of copper needed in the line conductors. The conditions may be such that high-voltage motors can be used, but in other instances step-down transformers may have to be provided and the expense of these as well as other auxiliary apparatus connected therewith must then be considered. It is gener-

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ally conceded that the alternating-current system is more reliable than the direct current. This is mostly due to the absence of commutator trouble and to the rugged design of the induction motor.

There is no reason for installing direct-current motors except where an adjustable speed service is required, and in small plants where such a service is predominating the direct-current system would naturally be the one to install. If a varying-speed feature is only required intermittently, the phase-wound induction motor may be used to advantage, but if the motor must run at reduced speed a considerable portion of the time, the varying-speed, brush-shifting motor should be given careful consideration. As a rule, a considerable part of industrial machinery will require a constant-speed service, for which the alternating-current motor is admirably adapted, and should direct current be required it can be obtained by installing a motor-generator set.

As a rule it may be said that the alternating-current system should be selected if possible. This would furthermore permit of throwing over to a central-station service, in case it should be found that power could be more economically purchased from the central station than be generated on the premises.

CHARACTERISTICS OF MOTORS AFFECTING THEIR APPLICATIONS. — (*See also the separate articles on Motors.*) Motors are divided into two classes — direct-current and alternating-current, according to the system from which they are operated. The direct-current motors are further subdivided into three types, namely, series, shunt and compound motors.

There are also three general types of alternating-current motors, namely, induction, synchronous and commutator motors.

Series Motor. — This motor is used when a powerful starting torque and rapid acceleration are required, without an excessive instantaneous demand of energy. The torque is practically independent of the voltage and at low flux densities varies directly as the square of the current, but as the magnetization approaches saturation it becomes more nearly proportional to the first power of the current. The maximum torque exists at low speed, this being the most valuable feature of the series motor. Dangerously high speeds may be attained by the armature with very light loads, and series motors should for this reason be either geared or direct connected to the load.

Speed Control of Series Motor. — The speed of a series motor on constant potential varies automatically with the load, increasing as the load decreases. The speed may, however, be adjusted if some means of varying the impressed voltage is provided. As the work required of a series motor is very often intermittent in character, the insertion of resistance in the armature circuit to reduce the speed is permissible from an economic standpoint in such cases. In others, such as railway work, where two or four motors are used, reduced voltage is most readily and economically obtained by connecting the motors in series or in series-parallel.

Shunt Motor. — This motor has good starting characteristics and a practically constant speed, varying only slightly with load changes. The speed can, however, be adjusted, either by changing the e.m.f. impressed on the armature, or by changing the field flux.

Speed Adjustment by Armature-voltage Control, i.e., by changing the e.m.f. impressed on the armature, does not change the full-load torque which the motor is capable of exerting, since the rated torque depends only upon field flux and rated armature current. These methods are therefore constant-torque methods and are properly adapted to loads in which the torque remains constant regardless of speed. The method most generally used for varying the impressed e.m.f. with a single-voltage system is by means of inserting resistance in series with the armature. The efficiency with this method is, of course,

very low at slow speeds. The speed regulation with varying loads may also be very poor.

There are several systems of controlling the motor speeds by applying different voltages, such as by the use of three-wire generators or two-wire generators with balancer sets or by the Ward-Leonard system. This latter system, which is the most practical, consists of a constant-speed motor driving a generator which supplies current to the motor whose speed is to be adjusted. This arrangement is very satisfactory but on account of the expense of providing three full-sized machines instead of one to perform the work, the cost may be prohibitive except with very large motors, such as for hoists, etc.

Speed Adjustment by Shunt-field Control, i.e., by inserting resistance in the shunt-field circuit, is the simplest of all methods of speed variation, but with ordinary shunt motors, the range of speed variation by this means is small. Where a variation of more than from 20 to 30 per cent is desired, a motor of modified design and of a certain increased size is generally required because, the field must be more powerful with respect to the armature than in the case of standard single-speed motors. Varying or adjustable speed motors of the field-weakening type are not constant torque, but constant-output motors, i.e., the torque falls proportionally as the speed increases.

A speed variation up to 3 to 1 meets, as a rule, all requirements and such motors can readily be obtained in commercial sizes. Should a greater speed variation be desired, say 4 to 1 or 5 to 1, it is possible to accomplish this by the commutating-pole shunt motor with field control only. A combined field and armature control would, however, be a better method.

Compound Motor. — This motor is provided with both a series and a shunt field. The two fields are usually connected so that they act in the same direction, in which case the motor is called a "cumulative" compound motor. "Differential" compound motors, with the two fields opposing, are sometimes employed for special services. The cumulative, or ordinary, compound motor combines the characteristics of the shunt and series motors, having a speed not extremely variable under load changes, but developing a powerful starting torque and an increasing torque with decreasing load. Motors having a comparatively weak series field are employed extensively in shop practice where the motor may be required to start under heavy load but must maintain an approximately constant speed after starting, or when the load is removed. The heavily compounded motor is used where powerful starting torque and rapid acceleration are necessary, with a speed not varying too widely under load changes, such as for rolling mills, etc.

The speed control employed with compound motors may be any of the various methods explained in connection with the shunt motor. For certain service the control may be entirely rheostatic, the series winding being cut out after the motor has come up to speed.

Induction Motor. — The induction motor is essentially a constant-speed machine, although the speed may be varied either by varying the applied stator frequency or by introducing resistance in the rotor circuit. It is built in two distinct types, namely, the squirrel-cage and the phase-wound.

Squirrel-cage Motor. — The squirrel-cage type is used for constant-speed service with infrequent starting. It has a relatively small starting torque per ampere and draws a large starting current from the line. By increasing the resistance of the rotor, it may however also be built in the smaller sizes for a high starting torque, rapid acceleration and frequent starting, for such applications as sugar and laundry centrifugals, etc., where simplicity of control is desirable. They are also used for operating punches, shears, etc., where a flywheel is provided for storing the energy.

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Induction Motor with Wound Rotor. — For service requiring high starting torque combined with moderate starting current a motor with the wound type of rotor is best adapted. A motor with the resistance mounted inside the rotor should not be used to operate machinery having large inertia or excessive static friction, since full starting current may be required for a long period before the apparatus attains full speed, and, as the capacity of the internal resistance is small, excessive temperatures may result. This type of motor is, as a rule, not built above 200 horse-power due to mechanical difficulties involved in connection with the internal resistance.

A motor with external resistance should be used for moderate and large sizes. The rotor must then be provided with collector rings and brushes. The contact resistance of these as well as the leads and the controller fingers, which are in the circuit all the time, may impair the efficiency and regulation of the motor especially if the controller and the resistance are located some distance from the motor. The phase-wound induction motor with an external variable rotor resistance is best adapted for a varying-speed service, as the losses necessary to obtain reduced speeds are external to the motor itself.

Multi-speed Induction Motors. — It often happens that the service is such that two or three speeds will be satisfactory for the operation of the machinery and that these speeds must be independent of the load. Under such conditions multi-speed motors can frequently be used. In these motors the different synchronous speeds are produced by changing the number of poles in the magnetic circuit. Each of these speeds is fixed, if no resistance is used in the secondary circuit. With multi-speed motors, as with single-speed motors however, resistance may be used in the secondary circuit for varying the speed.

A change of the number of poles may be produced in any of the following ways:

1. By the use of single magnetic and electric circuits, changing the number of poles by regrouping the coils.
2. By the use of single magnetic circuits and independent electric circuits
3. By means of separate magnetic and electric circuits, the so-called Cascade connection.

Synchronous Motor. — The speed of a synchronous motor is constant, being fixed by the number of poles and the frequency of the applied voltage. The single-phase type is not self-starting and the polyphase type has in itself a very poor starting torque. They may, however, be made self-starting in the same manner as squirrel-cage induction motors, by the use of an ammortisseur or cage winding, similar in construction to that used for induction motors.

The speed-torque curve of a synchronous motor is similar to that of an induction motor except that the torque values are lower for a given resistance of rotor winding on account of the construction of the machine. The starting winding must be designed with both the load at start and the load at synchronous speed in mind, because too great a slip may cause the motor to shut down when the field is put on. It is, however, seldom that the same motor will be called upon to start a heavy load and at the same time synchronize a heavy load, as the load usually consists principally of either static friction, as in the use of motor-generator sets, line shafting, etc., or it comes up with the speed as in the case of a fan blower or centrifugal pump. The former case would be met by a high-resistance squirrel-cage winding and the latter would require a low resistance.

Single-phase Series Motor. — This type of commutator motor has a very powerful starting torque, high power factor and relatively high efficiency. It is most generally used for traction work, the speed being controlled by varying

the applied voltage, which can most readily be done by means of an auto-transformer with a number of taps.

Repulsion Induction Motor. — This type of commutator motor has a limited speed and an increase of torque with decrease in speed. The action of the compensating field insures a power factor approximately unity at full load and closely approaching unity over a wide range in load. In addition it serves to restrict the maximum no-load speed and also permits, where varying speed service is involved, an increase over the synchronous speed.

Starting of Repulsion Motors. — A repulsion motor, if started by directly closing the line switch, will develop about 2½ times full-load torque. The starting current corresponding to full-load starting torque is from 2 to 2¼ times full-load running current. As a general rule, starting boxes are not required up to and including 2 horsepower rating. From 2 to 5 horsepower the use of a rheostat is optional, dependent upon the degree and care to be exercised in maintaining voltage regulation. Starting boxes should, however, preferably be used on sizes above 5 horse-power, especially where light and power circuits are combined.

Reversible Repulsion Motors. — The repulsion motor may be designed for reversible service. This is accomplished by adding an auxiliary reversing winding spaced 90 degrees from the main field winding and connected in series with it. By reversing the relative polarity of the two windings, the direction of rotation is changed in a simpler manner than by mechanical shifting of the brush holder yoke. Instant reversal may be effected from full speed in one direction to full speed in the other, about 200 per cent of normal running torque being developed at moment of speed reversal in either direction.

Varying-speed Repulsion Motors. — In addition to the constant-speed repulsion motor, two other types are also available, one for constant-torque and varying-speed service, the other for adjustable speed independent of torque In general, varying-speed repulsion motors are not applicable to lathes, boring mills or similar machines where the service requires adjustable speed and constant horse-power at all speeds below and above normal. When a certain amount of varying speed is required at approximately constant torque, such as driving fans, blowers, printing presses, etc., the repulsion motor successfully meets a wide field of application.

POWER RATING OF MOTORS. — (*See also Standardization Rules of the A.I.E.E.*) These rules recommend that with the exception of railway motors, all motor ratings shall be expressed in kilowatts (Kw.) available at the shaft, On account of the hitherto prevailing practice of expressing mechanical output in horsepower, it is, however, also recommended that for machinery of this class the rating may, for the present, be expressed both in kilowatts and in horsepower, as follows: Kw. ——— h.p. ———. The horsepower rating of a motor may for practical purposes be taken as ¾ of the kilowatt rating.

It is also highly desirable that the motor ratings should closely conform to the actual service requirements, and for this reason the Standardization Rules also recommend the following two kinds of ratings:

1. **Continuous Rating,** when the motor shall be able to operate continuously at its rated output, without exceeding any of the guaranteed limitations.

2. **Short-Time Rating,** when the motor shall be able to operate at its rated output during a limited period, to be specified in each case, without exceeding the guaranteed limitations. Such service includes runs alternating with stoppages of sufficient duration to ensure substantial cooling.

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SPEED CLASSIFICATION OF MOTORS. — Motors may, for industrial application, be classified with reference to their speed characteristics. The wording adopted from the standardization rules of the American Inst. of Electrical Engineers is as follows:

Constant Speed Motors, whose speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

Multispeed Motor (Change Speed Motor). — A multispeed motor (change speed motor) is a motor which can be operated at any one of several distinct speeds (these speeds being practically independent of the load), but which cannot be operated at intermediate speeds.

Adjustable Speed Motors, in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load; such as shunt motors designed for a considerable range of speed variation.

Varying-Speed Motors, or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound wound motors, and series-shunt motors. As a sub-class of varying-speed motors, may be cited adjustable varying-speed motors, or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; such as compound wound motors arranged for adjustment of speed by varying the strength of the shunt field.

DATA REQUIRED TO DETERMINE TYPE AND SIZE OF MOTOR. — In selecting a motor for a certain application complete information must be had with regard to the machines to be driven. This is the first step and in some respects one of the most important parts of the problem, as without complete information on the subject it becomes very difficult, and in certain instances utterly impossible, to intelligently select or design a motor and control equipment which will satisfactorily fulfill the conditions to be met in actual operation. In order to facilitate the work of obtaining such information, an outline of the points to be investigated is given below.

1. **Description of Machine to be Driven.** —
   - *a.* Individual or group drive.
   - *b.* Photographs, drawings and sketches of machines and connections as complete as advisable, especially such drawings as indicate the size of heavy flywheels or rotating masses whose speed must be varied, and also drawings indicating gearings, transmission devices, etc.
   - *c.* Limiting features of product. What are the points in quality and characteristics of product which fix the condition of operation? e.g. limiting speed of tool or mechanism, etc. *Example:* A 26-inch lathe used for finishing requires approximately 3 horse-power to drive. The same lathe for roughing shafting, when equipped with high-speed tool steel and two tools, needs approximately 30 horse-power.
   - *d.* Can electric drive approach nearer the conditions wanted?
   - *e.* If group drive can be considered for several machines, some of which are only to be operated intermittently, give notes with regard to the latter machines.
   - *f.* What arrangements can be made so that intermittently-operated machines need not operate simultaneously, thus giving a smoother load curve and allowing the use of one small motor to drive several intermittent machines?

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2. Cycle of Operation. —

a. Starting condition. Torque at start of day, and start of each cycle. Is frequent starting and stopping necessary? *Example:* The adjustment of large boring mills affects the controller, etc. Starting torque may be measured approximately if necessary by adjusting a rough beam to shafting. Find distance from axis at which the weight just starts machine. Knowing the weight in pounds the torque may be calculated.

b. Curves of loads, speeds, torque, maximum and average conditions through one complete cycle. Where necessary note power required with machines both loaded and unloaded. From this may be determined losses in shafting and transmission.

c. Time in operation, days per year, per month, per week, hours per day.

d. Reversing conditions, their frequency, their time, full or partial. Some apparatus, e.g., lathes, printing presses (flat-bed type), etc., only require slight backward movement to release tool or to adjust cylinders.

e. Starting. Flywheel or line shafting, friction clutches, etc.

f. Are speeds, torques, accelerations, etc., fixed by conditions of work or of driving machine?

g. Can any parts of cycle be varied with benefit? This should be investigated carefully.

3. Present Method of Drive. —

a. Prime mover or source of power.

b. Method of speed variation and speed change or control. Must machine be shut down to change speed?

c. Adaptability to gearing, etc.

d. Speed of machine, size of pulley, size of belt, size of gear or chain.

4. Mechanical Transmission. —

a. Rope, belt, chain, gear, direct connection. Direction of pull on belt or gear. Is belt or chain pull on the top or bottom? Is belt tightner advisable?

b. Clutches. Crab clutch, friction or couplings. Rigid, flexible or insulated.

c. Method of speed variation.

d. Brakes, electric. Solenoid or magnetic. Regenerative control, dead load or pumping back.

e. Brakes, mechanical. Band-post brake, disc brake, automatic safety brake, steam, hydraulic, air- or hand-operated.

5. Conditions of Location. —

a. Near external source of heat, furnace, etc.

b. Character of dust, conductive, magnetic or wearing, marble or stone, etc.

c. Possibility of fire or explosion to be caused by sparks from motor. Combustible flyings, e.g., cotton mills.

d. Explosive gases. Coal gas, benzine fumes, etc.

e. Presence of injurious gases. Acid fumes or salt air, e.g., SO_2, Cl, etc.

f. Dampness and moisture.

g. Insurance regulations. Obtain and forward copy of State Insurance Rules, or other state or local regulations, e.g., mining laws, municipal laws. Consider also personal danger or liability due to use of high-voltage apparatus.

h. Accessibility for inspection and repairs, oiling, etc.

i. Ventilation.

j. Allowable space for installation, also space for transportation. Down mine shaft, through doorways, etc.

k. Foundations and how attached to same.

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l. Sudden temperature variations. This may cause condensation of moisture on windings and insulation.

m. If controlled from distance where will controller or switch be placed? Give approximate length of leads necessary. Must they pass through or under water, in building, on poles, underground?

6. Control. —

a. Intelligence (probable) of operators.

b. Is entire range of operation visible to operator or are special automatic features desirable?

c. Regenerative Control — See item No. 4-*d*; also *Cycle of Operation*, item No. 2.

7. Overload and Safety Devices. —

a. Can electric automatic devices be made to supersede mechanical overload safety devices, such as slipping clutches, braking shafts or crabs?

b. Should these devices be time limit or instantaneous? If former, how long?

c. Are safety devices necessary, other than those to protect overload — e.g., overrun of hoist, stoppage or cessation of load. Must emergency stop be employed, and where placed?

d. Are undervoltage releases required or advisable?

8. Probable Cost of Present Method of Operation. —

a. Steam Operation.

1. Coal. Tons per day or month; quality, cost, distance shipped.
2. Feed and other water. City mains or pumped; source, quality.
3. Is steam required for other purposes beside power? e.g., digesters, heating, etc.
4. Can steam be generated from waste gases or other waste products?
5. Distance of transmission, outdoors and indoors.

b. Air. Distance of transmission, air pressure, how obtained?

c. Water Power. Has electric installation to compete with water power? If so, report separately on this aspect.

9. Strength of Present Equipment. —

a. Strength of line shafting, foundation, transmission or gearing, machine parts.

b. Give estimate of limiting horse-power of items in (*a*), using sketch and dimensions where necessary. The above items should be considered with regard to any change in speed or torque made necessary or desirable, due to the electric drive.

10. Generating Station or Source of Electric Power. — Capacity of station or feeder, frequency, voltage, location, voltage or frequency variations.

BIBLIOGRAPHY. — It is impossible in the limited space available to give references to all the numerous papers in the technical journals dealing with the industrial applications of motors. The reader should consult the files of the *Transactions of the American Institute of Electrical Engineers, American Society of Mechanical Engineers, National Electric Light Association; also the Electrical World, General Electric Review, Electric Journal, Electrical Review, Power, Power and Engineer, Electrical Engineer, Engineering Magazine, Cassiers' Magazine.*

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MOTORS, POLYPHASE INDUCTION. — (*See also Electricity and Magnetism, Principles of; Generators; Motors, A-C. Commutator, Direct-current, Single-phase Induction and Synchronous; Motors, Industrial Applications of; Standardization Rules; Transformers.*) An induction motor may be either single, two, or three phase. Single-phase induction motors are treated in another article (*q.v.*). The induction motor is essentially a polyphase transformer with the secondary free to move; the electric energy transferred to the secondary is transformed by this motion directly into mechanical energy.

The following is a brief table of the contents of this article:

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DEFINITIONS AND PRINCIPLE OF OPERATION. — Certain terms used in connection with the induction motor can best be defined by a brief statement of the principles underlying its operation.

Primary and Secondary. — By the primary of an induction motor is meant that part which receives energy by direct connection to the source of electric energy; the other member is called the secondary.

Stator and Rotor. — That member of an induction motor which remains stationary, whether it be the primary or secondary, is called the "stator," and the revolving member is called the "rotor." In most machines the primary is the stator. A "squirrel cage" rotor is one in which the conductors are straight bars of copper all connected together at each end of the rotor by copper rings.

Poles of an Induction Motor. — In Fig. 1 is given a diagram of the primary winding of a two-phase induction motor. The small numbered circles represent the conductors forming the winding of one phase, the small black circles the conductors forming the winding of the second phase. The numbers opposite the circles give the order in which the current in phase 1 passes through the conductors, a cross indicating that the current goes down into the page and the open circles that the current is coming up.

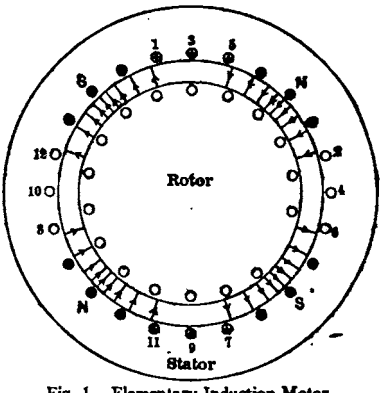


Fig. 1. Elementary Induction Motor

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The diagram is drawn to represent that instant at which the current in the second phase is zero. At this instant the distribution of flux in the air gap will be roughly as indicated by the lines with arrows on them; that is, the flux will leave the stator iron in the two regions marked *N* and enter it in the two regions marked *S*. Consequently, the current in the winding of phase 1, which consists of 4 bands or groups of conductors, will produce 4 polar regions, or 4 poles, on the stator. As will be shown below, the combined effect of the two phase currents in the two windings is merely to cause a rotation of these polar regions. The "number of poles" is always equal to the number of bands of conductors into which the total winding of each phase is divided. The bands of conductors forming one phase usually overlap the bands of conductors forming the other phase, there being then two or more conductors per slot.

Rotation of Magnetic Flux. — In Fig. 1 is shown the distribution of flux in the gap when the current in phase 2 is zero; the curve marked *A* in Fig. 2 represents this same state of affairs, the cylindrical surface of the stator here being bent out into a plane, and the ordinates of the curve giving the value of

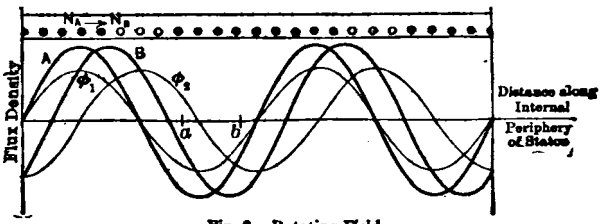


Fig. 2. Rotating Field

the flux density in the gap at each point of this surface. The flux distribution is not a smooth curve as shown, but approximates such a curve.

Next consider the case when the current in phase 1 has decreased to, say, 0.7 of its maximum value and the current in phase 2 has increased to 0.7 of its maximum value (this corresponds to ⅛ of a cycle). Then the flux distribution due to phase 1 remains in the same position as before but is reduced at each point of the gap to 0.7 of its maximum value, i.e., reduces to the curve marked ϕ_1. Similarly, the flux due to the current in phase 2 is similar in shape to the flux due to the current in phase 1, but its position is to the right of the latter by an amount equal to the width of one of the bands of conductors. The distribution of the flux due to the current in phase 2 is then as shown by the curve ϕ_2, the ordinates of which at the instant under consideration are 0.7 of their maximum values.

The resultant flux in the air gap at this instant is then the sum of the curves ϕ_1 and ϕ_2, namely the curve *B*. That is, the effect of the two fluxes due to the two phases is a resultant flux shifted forward, or moved around the gap, a distance equal to ⅛ the distance between successive north poles, but this resultant flux curve has the same shape and maximum value as before. This is strictly true only if the windings are distributed with absolute uniformity over the internal periphery of the stator. An extension of this analysis will show that the resultant flux remains constant in value at all times but travels around the air gap with a speed of

$$N = \frac{120f}{p} \text{ rev. per min.},$$

where f is the frequency of the supply and p the number of poles.

This same result holds for a three-phase machine.

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Synchronous Speed. — The speed of rotation of the air-gap flux, namely the speed N given by the above formula, is called "synchronous" speed. At light loads the speed of the rotor is very nearly equal to this speed.

Slip. — The slip of an induction motor is the ratio of the difference between the actual speed (N_1) of the rotor and synchronous speed (N) to the synchronous speed (N), i.e.,

$$s = \frac{N - N_1}{N}.$$

The slip may be expressed as a fraction or as a per cent. The slip at standstill is unity; at no load it is very nearly zero. An induction motor driven at a speed higher than its synchronous speed has a negative slip; such is the case in an induction generator.

Electromotive Forces in Secondary. — The electromotive forces in the secondary of a polyphase induction motor are induced by the rotation of the flux produced by the currents in the primary windings, just as the electromotive forces induced in the armature conductors of a generator are induced by the rotation of these conductors in the magnetic field set up by the field winding. In the generator only the conductors move, the field being stationary, but in the induction motor both the field and conductors move. In either case it is the *relative* motion of the field and conductors which determines the e.m.f. induced.

Let v be the linear speed at which the field moves, and let v_1 be the linear speed of the rotor conductors, and B the flux density at any particular conductor C at any instant. Then the e.m.f. induced in this conductor at this instant is $B(v - v_1)l = Blsv$, where s is the slip and l is the length of the conductor (*see also Electricity and Magnetism, Principles of*). The rotor electromotive force is therefore proportional to the slip. As the rotor turns, the conductor C moves slower than the rotating flux, and the state of affairs is just the same as if the flux remained at rest and the conductor moved through the field in the gap at a speed of $v - v_1 = sv$. Hence the electromotive force induced in each rotor conductor is alternating, since the flux which it cuts varies from a positive maximum to a negative maximum, and a consideration of the relative speed of the conductor and the flux will show that the frequency of this induced electromotive force is the frequency in the primary multiplied by the slip.

That is, the secondary electromotive force is proportional to the slip and has a frequency equal to the product of the slip by the frequency in the primary.

Secondary Current and Torque. — The current set up in each rotor conductor by this electromotive force will be practically in phase with this electromotive force, since the rotor conductors have but a small reactance, particularly when the rotor is revolving at a speed near synchronism. Hence the current in any chosen rotor conductor at any instant is proportional to the electromotive force in this conductor at that instant, which in turn is proportional to the flux density at this conductor at this instant. Since the force produced by a magnetic field on a conductor is equal to the product of the flux density by the current by the length of the conductor (*see Electricity and Magnetism, Principles of*), the force acting at any instant on any rotor conductor will then be equal to

$$f = Bli = Bl\left(\frac{Blsv}{r}\right) = \frac{B^2l^2sv}{r},$$

where r is the resistance of the conductor. Since the current and the flux density both change signs at the same time (being in phase) the direction of this force will always be in the same direction and will consequently drive the rotor against whatever opposing force may exist.

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Not only is the force on each conductor always in the same direction, but the *total* force acting on *all* the conductors is practically constant for a given value of the slip. Consider any two rotor conductors which are a distance apart equal to ¼th the distance measured along the periphery of the rotor between successive north poles, for example, at a and b in Fig. 2. Then, assuming a sine-wave distribution of flux in the air gap, and calling B_m the maximum flux density, the flux density at a is $B_a = B_m \sin x$ and the flux density at b is $B_b = B_m \cos x$, where x is a function of the distance measured from some fixed point in the air gap. Then the total force on the two conductors at a and b is

$$\frac{P_{sv}B_m^2}{r}(\sin^2 x + \cos^2 x) = \frac{P_{sv}B_m^2}{r}$$

and is therefore constant, since B_m is a constant. Similarly for any other two conductors this same distance apart. Hence the total force on all the conductors is constant. On any practical machine the flux distribution is not an exact sine wave, and there is a slight pulsation in the total force, and therefore in the torque, but this pulsation is extremely small.

Magnetizing Current. — The currents set up in the secondary of an induction motor produce a rotating flux, which travels with the same speed with respect to the primary and in the same direction as the flux set up by the current in the primary, but the direction of this secondary flux at any point in the air gap is opposite to the direction of the primary flux. Hence the resultant flux when there is current in the secondary is equal to the difference of these two fluxes, and this difference remains practically constant irrespective of the secondary currents, just as the resultant flux in a transformer is practically independent of the secondary current. The primary current which would be necessary to produce this *resultant* flux is called the "magnetizing" current, and is very nearly equal to the current in the primary when the motor is running without load, in which case the current in the secondary is extremely small.

METHODS OF RATING. — The Standardization Rules of the A.I.E.E. up to 1914 recommended that the rating of an induction motor should be the load in horse-power which it will deliver continuously at the shaft with a maximum rise in temperature of any part not exceeding 50° C. by thermometer. In commercial practice three variations of this have been developed to suit different conditions, as noted below. See, however, the new ratings recommended in the proposed rules of 1914, given in the article on *Standardization Rules of the A.I.E.E.*

A-Rating. — For cases where there are no excessive overloads and where the load is fairly steady, it is customary to guarantee that the motor will operate continuously at its rated load with a maximum rise in temperature of 40° C., and that subsequently it will deliver a load 25 per cent greater than the rated for two hours with a maximum rise in temperature not exceeding 55° C.

B-Rating. — For cases where there are frequent overloads and for intermittent service, that is, a low load factor, it is customary to guarantee that a motor will deliver its rated load continuously with a rise in temperature not to exceed 35° C., and that it will deliver an overload of 50 per cent for two hours with a maximum rise in temperature not exceeding 55° C.

One-hour Rating. — Certain motors for special intermittent work, as for hoists, elevators, etc., are rated in accordance with the output they will give for one hour.

Starting and Break-down Torque. — In addition to the ability to carry its rated load without excessive heating and with reasonable constants, such as

efficiency, power factor and slip, it is advisable to make sure that the motor is able to start such loads as must be brought up to speed with the motor, as good starting ability in an induction motor involves certain complications and expenses. This subject is treated at length in the section below on *Methods of Starting*. Another important point is that the motor should be able to carry momentary overloads without "breaking down" as it is called, which means gradually decreasing in speed to a standstill when the load is excessive. To be sure of this qualification we must know the maximum output of the motor, which should be at least 50 per cent greater than the rated output.

VOLTAGE. — Motors may be wound for any voltage up to 13,000 but the great majority and all the small motors are wound for voltages of 110, 220 or 440 volts between lines.

FREQUENCY AND SPEED. — Induction motors may be built for any frequency. The higher frequencies are satisfactory in those cases where the load never exceeds normal conditions. Lower frequencies, such as 25, are more favorable where frequent overloads are met with or large starting torques are required.

The speed of the rotor of an induction motor at normal loads approaches within 5 to 10 per cent of the synchronous speed. The synchronous speed is fixed by the frequency of the system and the number of poles of the winding (*see above*) so that for a given frequency of the supply circuit there are only certain speeds available. Thus for 25 cycles we have

1500 for 2 poles;	500 for 6 poles;
750 for 4 poles;	375 for 8 poles, etc.

PHASE CONNECTIONS. — Two-phase or quarter-phase motors are usually wound with independent phase windings. Three-phase motors are connected in Y or Δ, depending upon the convenience of the designing engineer.

In a single-phase and two-phase motor the voltage and current per phase are the same as the voltage between lines and current in line; in a Y-connected three-phase motor the current per phase is equal to the line current, and the voltage per phase is equal to the line voltage divided by $\sqrt{3}$; in a Δ-connected three-phase motor the current per phase is equal to the line current divided by $\sqrt{3}$, and the voltage per phase is equal to the line voltage.

CURRENTS TAKEN BY MOTORS. — Let

P_0 = horse-power output;
I = current in each line;
ϵ = efficiency as a decimal fraction;
$\cos\phi$ = power factor as a decimal fraction;
E = voltage between lines (between one outside wire and the middle wire for three-wire two-phase line).

Then for

$$\text{Two phase: } I = \frac{373\,P_0}{\epsilon E \cos\phi};$$

$$\text{Three phase: } I = \frac{431\,P_0}{\epsilon E \cos\phi}.$$

Usual efficiencies and power factors at full rated load for polyphase motors are as follows:

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POWER FACTORS AND EFFICIENCIES

Horse-power	25 cycles		60 cycles	
	Efficiency	Power factor	Efficiency	Power factor
1	0.79	0.78	0.78	0.78
5	0.85	0.88	0.82	0.83
20	0.88	0.91	0.84	0.91
50	0.90	0.92	0.87	0.92
100	0.905	0.925	0.89	0.92
200	0.91	0.925	0.905	0.92

DESIGN. — The methods of calculating two-phase and three-phase motors are practically the same. Most induction motors on single-phase circuits are made with polyphase windings, as the extra winding is necessary in starting.

The factors which must be considered in the design of an induction motor are the same as those considered for a synchronous generator with the addition of the power factor. It is desirable to have a high power factor but a high power factor requires a generous use of material, a small air gap, and a careful arrangement of windings. A high power factor at light load requires a small magnetizing current, and a high power factor at overloads requires a low value of leakage flux.

A small value of magnetizing current is obtained by using a small air gap and a large value of diameter per pole.

A low value of leakage flux is obtained by using a large value of diameter per pole and by subdividing the windings in a large number of slots.

Preliminary Choice of Main Dimensions. — In the discussion below the following symbols are employed:

E = volts per phase;
I = full-load current per phase;
D = diameter of armature, in inches;
L = length of armature, in inches;
p = number of poles;
f = frequency in cycles per second;
g = length of gap, in inches;
B = average flux density in gap, in lines per square inch;
ϕ = flux per pole, in maxwells;
S = turns in series per phase;
N = revolutions per minute;
α = quotient of no-load current divided by full-load current (ranges from 0.45 for a 1-horse-power motor to 0.25 for a 200-horse-power motor);
σ = ampere-conductors per inch of periphery. The values given in the article on *Generators, Alternating-Current*, also apply to the induction motor.
T = ratio of width of tooth at face to slot pitch (T varies from 0.6 to 0.7 for open slots and from 0.9 to 1.0 for overhung slots);
q = ampere-conductors per slot.

Diameter and Length of Rotor. — The first problem in the design of an induction motor is the estimation of the proper diameter of armature. There are three methods of determining the proper value of this very important dimension:

(a.) Reference to machines already built, which shows that t
ries directly with the number of poles and inversely as the fr
for customary values of diameter in inches divided by the numb

for 25 cycles, $D/p = 5$ to 6 inches;
60 cycles, $D/p = 2.5$ to 3 inches.

(b.) The peripheral speed, being a direct function of the diam
determines the diameter. As the value of the peripheral speed
3000 to 10,000 feet per minute, depending on the mechanical co
function is not very definite. For lack of more definite figures
minute may be considered a good average figure for peripheral s

(c.) On account of the effect of the magnetizing current on t
it is desirable to limit the value of this current to a certain per
load current (*for values see p. 988*). To accomplish this there is
mum limit to D and L which is expressed approximately in the

$$D^2L = \frac{28.7 \times 10^{12} fgk}{\alpha \sigma^2 N^2} \times (\text{Kv-a. rating}).$$

k = ratio of the actual excitation current to the excitation cu
gap; $k = 1.2$ for 60 cycles and $k = 1.4$ for 40 cycles.

This gives a relation between D and L. Assuming that for b
is equal to the pole pitch $\left(L = \frac{\pi D}{p}\right)$ a value for D is obtained.
also indicates the effect on the general design which would resu
changes in any of the quantities.

The formula given for the preliminary calculation of dim
alternating-current generator (*see article on Generators, Alter*
may also be used if proper values for T and L be selected.

Air Gap (g) varies in length according to the diameter, usu
given in the accompanying table.

Diameter, inches	Air gap, inch
0 to 12	0.02 to 0.03
12 to 26	0.03 to 0.04
26 to 50	0.04 to 0.06
50 to 100	0.06 to 0.10
100 up	Diameter/1000

Average Flux Density in Gap (B). — The usual value of t
density in the air gap for 25 cycle machines is 30,000 lines per
60 cycle machines is 25,000 lines per sq. in.

Conductors per Slot (c). — The "effective" number of con
is the number of conductors *in series* per slot, i.e., if each phas
two windings in parallel, the two conductors of the two parall
counted as one conductor. Hence the effective conductors per

$$c = \frac{2S \times (\text{Number of phases})}{(\text{Total number of slots})}.$$

The permissible number of ampere conductors per slot (q) depen
missible current density per square inch of copper, usual valu

Size of motor	Voltage	Amperes per sq. in.
Small	Low	3000
Small	High	2000
Large	Low	2000
Large	High	1600
Large	Above 6000	1000

Usual values of q are

Size of motor h.p.	Value of q
Up to 5	Up to 250
5 to 50	250 to 350
50 to 100	350 to 450
100 to 200	450 to 600
Greater	Up to 800

Number and Dimensions of Slots. — The number of slots is

$$\frac{\pi D\sigma}{q}.$$

The conductors should be arranged to give slots having a depth about four times the width, and the width of slot should be about ⅓ to ⅜ of the pitch of slots at the gap. Machines of small diameter will have slots smaller with respect to the pitch and machines of large diameter will have slots occupying more than ⅜ of the pitch.

The slots of one member at least (usually the rotor) should be overhung, i.e., partly closed at the opening. It is better if both members have partly closed slots, as this reduces the magnetizing current and improves the power factor, but it entails a more expensive method of winding.

The dimensions of the slots are determined by the size of conductors and amount of insulation. The allowance to be made is about as follows:

Type of slot	Voltage	Coil sides per slot	Allowance for insulation	
			Vertical	Horizontal
			in.	in.
Straight	500	2	0.30	0.04
Straight	2200	2	0.45	0.15
Straight	6000	2	0.65	0.25
Overhung	500	4	0.40	0.15
Overhung	2200	4	0.50	0.20

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The depth of the slot is found by adding to the total depth of cotton-insulated copper the vertical dimension given in the table.

Turns in Series per Phase (S) may be calculated from the formula

$$S = \frac{\pi D \sigma}{2 I \times (\text{number of phases})}$$

or from the formula

$$S = \frac{10^8 E}{4.44 \phi f k},$$

where ϕ is the flux per pole and is given by the formula

$$\phi = \frac{0.7 \pi B D L}{(\text{number of poles})}$$

and k is a constant depending on the wave form and winding distribution (*see next paragraph*). The value of S as obtained from these two formulas must check in the final design.

Flux per pole (ϕ). — The flux per pole is given by the formula

$$\phi = \frac{10^8 E}{4.44 f S k},$$

where k, called the distribution constant, has the values given in the following table, provided the flux distribution in the air gap is sinusoidal.

DISTRIBUTION CONSTANT k

Two phase					Three phase				
Slots per pole	Per cent winding pitch				Slots per pole	Per cent winding pitch			
	100	75	67	50		100	75	67	50
	k	k	k	k		k	k	k	k
2	1.00	....	....	0.71	3	1.00	....	0.87	....
4	0.93	0.85	....	0.66	6	0.97	....	0.84	0.69
6	0.91	....	0.79	0.64	9	0.96	....	0.83	0.68
8	0.905	0.84	....	0.64	12	0.96	0.89	0.83	0 68
12	0.90	0.836	0.78	0.63	18	0 958	0.885	0.83	0.68
Many	0.90	0.833	0.78	0.63	Many	0 958	0.885	0.83	0 68

Choice of Phase Connection. — The decision whether a motor shall be Δ or Y connected depends on such minor details of design as the convenience of arranging the conductors in the slots. For instance, if for 110 volts and Δ connection a desirable flux value and number of conductors would require 7 conductors per slot, a Y connection having 64 volts per phase and 4 conductors per slot could be substituted and would give a practical winding. 64 volts per phase, Y connected, gives 110 volts between lines.

Magnetic Circuit. — A tentative layout of the magnetic circuit is next made in the same manner as described in the article on *Generators, Alternating-*

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Current. The values there given for usual values of the flux density also apply to the *maximum* instantaneous flux density in the magnetic circuit of an induction motor. The magnetic circuit must have such dimensions that the exciting current will not be too large, and the slots must be of sufficient size to accommodate conductors of necessary size (*see above*).

Maximum Efficiency and Power Factor. — Since induction motors frequently operate on an intermittent or variable load, it is desirable that the efficiency and power factor be high at fractional loads. It is therefore quite usual to design the motors so that the maximum efficiency comes at ¾ load and maximum power factor at less than full load. This is accomplished with regard to efficiency by making the core-loss and friction small (the core-loss is made small by using low flux densities) and with regard to power factor by making the magnetizing current small by using a small air gap.

PREDETERMINATION OF PERFORMANCE OF AN INDUCTION MOTOR FROM ITS DIMENSIONS. — From the above calculations a preliminary drawing of the motor to scale may be laid out. The next step is to calculate its performance, i.e., predetermine what will be the efficiency, the power factor, and the temperature rise in the various parts. Examples of specific design and tested performance are given below.

Calculation of Exciting Current. — The first step is the calculation of the exciting current. This current is practically constant at all loads, and is equal to the no load current, i.e., the current taken by the motor when it is running light. The exciting current has two components, the magnetizing current, which leads the induced voltage by 90° and a component in phase with the induced voltage, which supplies the core-loss and friction. The magnetizing current is much the larger component, and for preliminary calculations may be taken equal to the exciting current.

Magnetizing Current. — The magnetizing current is calculated by determining the flux density in each part of the magnetic circuit and the ampere turns required for each part. This is most easily done by means of the following tabulation:

MAGNETIC DENSITIES AND M.M.F.'S

(For dimensions refer to Fig. 3.)

Part	Flux per pole	Area	B_{max}	A.T. per inch	Length path	Total A.T.
Stator core.....	$\phi/2$	$h_1 \times l$	$1 \times B_{avg}$	....	$\frac{\pi D_1}{2 \times \text{poles}}$	....
Stator teeth....	ϕ	$r_1 \times l \times \frac{\text{slots}}{\text{poles}}$	$1.57 \times B_{avg}$	....	w_1	....
Air gap.....	ϕ	See below	$1.57 \times B_{avg}$	....	g	....
Rotor teeth....	ϕ	$r_2 \times l \times \frac{\text{slots}}{\text{poles}}$	$1.57 \times B_{avg}$	....	w_2	....
Rotor core.....	$\phi/2$	$h_2 \times l$	$1 \times B_{avg}$	....	$\frac{\pi D_2}{2 \times \text{poles}}$	....
					Total.....	.....

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Stator Core or Yoke. — The flux divides in the core, one-half going each way. The maximum and average* densities are practically the same and equal to ($\phi/2$ divided by the radial depth h_2 times the effective length l). The material is laminated steel of high permeability. The ampere turns per inch length of path are obtained from a magnetization curve of the steel, see *Magnetic Properties of Iron*. The length of path is indeterminate but closely approximates one-half of the pole pitch measured on the circle of diameter D_1. By multiplying the ampere turns per inch obtained from the magnetization curve by the length of path, the ampere turns required to send the flux through this path are obtained.

Stator teeth. — The average density in the teeth is first obtained. The effective area of one tooth is the area one-third the distance from the face to the root of the tooth as shown at r_1. This gives the average magnetizing force rather than the average density. The total cross section of the path in the teeth is therefore $r_1 \times l \times$ (the number of teeth per pole). Due to the peaked or sinusoidal space distribution of the flux the maximum density in the teeth is 1.37 times the average density. The ampere turns required depend upon the maximum density. From the proper curve determine the ampere turns per inch necessary to establish this density, and by multiplying this quantity by the distance n_1 in inches, the ampere turns for the stator teeth are found.

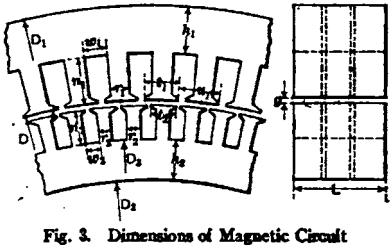


Fig. 3. Dimensions of Magnetic Circuit

Air Gap. — The flux is not uniformly distributed in the air gap, especially if the openings of the slots are fairly large. The flux passes through each tooth and spreads out from the iron when it leaves the teeth to cross the gap. The peripheries of the stator and rotor present unequal and dissimilar surfaces passing each other. The lesser of the two is the one that must be considered. The effective area of the air gap is

$$\frac{(t+g)\,l \times (\text{total number of slots})}{0.9\,p}$$

and the maximum density $= \dfrac{1.57 \times \phi}{\text{gap area}}$

(the $t+g$ allows for the spreading of the flux in one direction and $l/0.9$ allows for the spreading in the other direction).

The ampere turns per inch are 0.313 B_{max}. The length of gap being known, the total ampere turns for the gap are found.

Rotor Teeth. — The calculation of the ampere turns for the rotor teeth follows the same method as the calculation for the stator teeth.

Rotor Core. — The same as for the stator core.

The effective value of the magnetizing current is then

$$I_m = \frac{(\text{Total ampere turns}) \times p}{2\sqrt{2}\,S} \quad \text{for three phases}$$

$$\text{and } I_m = \frac{(\text{Total ampere turns}) \times p}{\sqrt{2}\,S} \quad \text{for two phases}$$

* By average is here meant the average over the cross section of the maximum instantaneous value of the flux density, which, of course, alternates between fixed positive and negative values.

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Resistance per Phase of Primary Winding. — The resistance to direct current, or ohmic resistance, is given by the formula

$$r_1 = \frac{0.0093\, S \times (\text{mean length of turn})}{12{,}000\, a n},$$

where

S = turns in series per phase,

a = cross section of one conductor in sq. in.,

n = no. of conductors or circuits in parallel,

and 0.0093 is the resistance at 60° C. of a conductor 1000 feet long and 1 square inch cross section. The mean length of turn is approximately (see Fig. 3)

$$2L + 10\frac{D}{p} \times (\text{pitch as a fraction}).$$

Due to the eddy currents set up in the primary conductors by the total flux and to eddy currents set up in the core by the leakage flux, the "effective" resistance of the primary winding is about 15 per cent greater than the value calculated by the above formula.

Resistance per Phase of Secondary Winding. — In a wound rotor the resistance per phase is found in the same manner as the resistance per phase of the stator winding. The secondary resistance reduced to primary is then equal to $\left(\frac{\text{number prim. turns per phase}}{\text{number sec. turns per phase}}\right)^2 \times$ (actual effective sec. resistance), when the secondary has the same number of phases as the primary.

The squirrel-cage rotor, in which each slot contains one bar and all bars are short-circuited at each end by a ring presents a more complicated problem. It may be solved as follows:

$$\text{Amp.-cond. per sec. slot} = \frac{\pi D \sigma}{(\text{number of sec. slots})}.$$

σ = amp.-cond. per inch for full-load current.

$$\text{Current density in sec. bars} = \frac{(\text{amp.-cond. per slot})}{(\text{area of one bar})}.$$

Watts lost in bars = 0.775×10^{-6} (vol. of bars) (amp. per sq. in.)^2.

Area of bars per pole = (area of one bar) (number of bars per pole).

$$\text{Current density in rings} = \frac{(\text{current density in bars})\,(\text{area of bars per pole})}{4\,(\text{area of ring})}.$$

Watts lost in rings = 0.775×10^{-6} (vol. of both rings) (density in rings)^2.

$$\left.\begin{array}{l}\text{Resistance of sec. in terms of primary for a}\\ \text{three-phase motor}\end{array}\right\} = \frac{\text{total loss}}{3\,(\text{full load prim. current})^2}.$$

Leakage Reactance. — When the motor is loaded the currents in the secondary set up a counter m.m.f. which causes part of the flux to pass along the air gap instead of into the secondary core. This flux does not interlink both members and is therefore a leakage or useless flux. It is proportional to the load currents and to the permeance of this path. As the greater portion of the path is in the air and is of high reluctance, therefore that part of the path in the iron may be neglected. The flux in both the primary and secondary must be calculated.

Referring to the diagram Fig. 4, the permeance of these two paths are

$$P_1 = \left[\frac{\sigma_1}{3\,w_1} + \frac{2\,r_1}{w_1 + q_1} + \frac{p_1}{q_1} + \frac{h - q_2}{6\,g} + 0.37\,\frac{l_{s1}}{L}\log_{10}\frac{1.5\,l_{s1}}{V_{s1}}\right] L,$$

$$P_2 = \left[\frac{\sigma_2}{3\,w_2} + \frac{2\,r_2}{w_2 + q_2} + \frac{p_2}{q_2} + \frac{h - q_1}{6\,g} + 0.37\,\frac{l_{s2}}{L}\log_{10}\frac{1.5\,l_{s2}}{V_{s2}}\right] L$$

where

g = length of gap in inches,
l_e = length of end connection at one end in inches,
V_e = perimeter of a *band* of end connection per pole per phase, in inches,
L = total length of iron in inches.

In these formulas the subscript 1 refers to the primary and subscript 2 to the secondary. The first three terms give the slot reactance, the fourth term gives the "zigzag" or "tooth-tip" reactance, and the last term the reactance of the end connections.

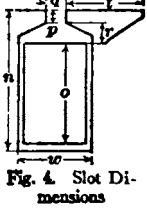


Fig. 4. Slot Dimensions

The primary reactance in ohms per phase is

$$x_1 = 3.2\, P_1 k c_1^2 s_1 \times 2\pi f 10^{-9}.$$

The secondary reactance in ohms per phase in terms of the primary turns is

$$x_2 = 3.2\, P_2 k c_2^2 s_2 \times 2\pi f 10^{-9} \left(\frac{c_1 s_1}{c_2 s_2}\right)^2,$$

where

c_1 and c_2 are the conductors in series per slot (see p. 1058),
s_1 and s_2 are the slots per phase,
f = primary frequency,
k = winding distribution constant (*see above*).

Losses in Induction Motor. — The losses in an induction motor are

Core-loss;
Friction, bearing and windage;
Primary copper loss;
Secondary copper loss.

The first two of these are approximately constant for all loads and the last two vary as the square of the current per phase.

Core-loss. — The distribution of the magnetic flux in an induction motor is quite irregular both in the core and in the teeth. The losses are therefore greater and their calculation more involved than in machines having uniform density in each part. In the primary the frequency of the passage of the secondary teeth introduces pulsations which increase the losses. In the secondary the frequency, being proportional to the slip, is so low that the core-loss is negligible.

In order to avoid too lengthy and complex calculations use is made of empirical constants, by which the easily calculated losses are multiplied to derive the practical loss. The total loss consists of hysteresis and eddy loss in the primary core and primary teeth. The loss in watts per cubic inch for one cycle per second at any magnetic density is found by the curves given in the article on *Magnetic Properties of Iron*.

The losses are then calculated as follows:

Hysteresis Loss:

In primary core $= k_h C_1 f V_c$ watts,
In primary teeth $= k_h C_2 f V_t$ watts.

Eddy Loss:

In primary core $= k_e C_3 f^2 V_c$ watts,
In primary teeth $= k_e C_4 f^2 V_t$ watts,

where V = volume in cu. in., C = respective loss per cu. in. from curves, f = frequency, k_h = empirical constant, 1 to 1.5, k_e = empirical constant, 3 to 4.

The higher values of k_h and k_e are to be used where open slots are used and where the frequency of the passage of the secondary teeth past one primary tooth is high. The core-loss is the sum of all the above losses.

Friction and Windage Loss varies greatly with the style of motor and form of structure, bearings, etc. The loss is made up of bearing friction and wind friction. The latter may be large purposely, as the motor may be designed with fan blades in order to circulate the air for the purpose of keeping the motor cool by ventilation. While each manufacturer has a formula which will calculate the friction loss correctly for machines built according to a particular plan, no general formula can be assumed. The nearest approach to an estimate is obtained from the percentage given in the table below.

Primary and Secondary Copper Losses. — The calculation of the effective resistances of the primary and secondary windings is given above. The primary or secondary copper loss is equal to the product of the number of phases, the effective primary or secondary resistance per phase, and the square of the current per phase. The total copper loss is the sum of the primary and secondary copper losses.

Power Factor. — The power factor ($\cos\phi$) of an induction motor for a given current input (I) may be calculated roughly from the formula

$$\cos\phi = \cos(\alpha + \beta),$$

where $$\alpha = \sin^{-1}\left(\frac{I_m}{I}\right) \text{ and } \beta = \sin^{-1}\left(\frac{XI}{E}\right),$$

and I_m = magnetizing current per phase,
I = total current per phase,
$X = (x_1 + x_2)$ = total reactance per phase, the secondary reactance x_2 being reduced to the primary turns,
E = voltage per phase.

For a more exact formula for power factor and for the usual values of the power factor at rated load, see *below*.

Efficiency. — The efficiency (as a fraction) for a given current input is

$$e = 1 - \frac{F + C + m(r_1 + r_2)I^2}{mEI\cos\phi},$$

where F = friction loss, in watts; C = total core-loss, in watts; m = number of phases; r_1 = effective primary resistance per phase; r_2 = effective secondary resistance per phase reduced to primary; E = voltage per phase; I = current per phase; $\cos\phi$ = power factor.

The corresponding horse-power output is then

$$P_0 = \frac{emEI\cos\phi}{746} \text{ horse-power.}$$

Usual values of the efficiency are given above in section on *Currents taken by Motors*. Usual values of the component losses for 60-cycle motors are given in the following table.

In 25-cycle motors the exciting current is usually greater than in 60-cycle motors and the IX drop less. Thus the power factor will be lower at light load and higher at overloads than in 60-cycle motors.

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Rating, h.p.	$\frac{I_m}{I}$	$\frac{XI}{E}$	$\frac{\text{Friction loss}}{\text{Input}}$	$\frac{\text{Core-loss}}{\text{Input}}$	$\frac{r_1 I}{E}$	$\frac{r_2 I}{E}$
1	0.45	0.20	0.06	0.05	0.05	0.05
5	0.35	0.14	0.035	0.04	0.04	0.04
20	0.30	0.13	0.025	0.035	0.035	0.035
50	0.27	0.11	0.015	0.03	0.025	0.03
100	0.26	0.11	0.015	0.03	0.025	0.03
200	0.25	0.11	0.015	0.03	0.025	0.03

The efficiency of 60-cycle motors naturally tends to be higher than of 25-cycle motors. This quality is usually sacrificed by economizing in material and making the 60-cycle motors lighter and cheaper, but of about the same efficiency as the 25-cycle motors.

Slip and Speed. — The slip for any given current is approximately

$$s = \frac{r_2 I}{E},$$

where the symbols are defined in the preceding paragraph.

The synchronous speed is

$$N = \frac{120 f}{p} \text{ rev. per min.},$$

where f is the frequency of the supply and p the number of poles. The actual speed of the motor is then

$$N_1 = (1 - s)\, N.$$

Values of Other Characteristics. — The energy component of the exciting current is

$$I_e = \frac{(\text{Total core-loss}) + (\text{Total friction loss})}{mE},$$

where m is the number of phases and E the volts per phase.

The total exciting current per phase is then

$$I_0 = \sqrt{I_e^2 + I_m^2},$$

where I_m is the magnetizing current per phase.

The impedance per phase at standstill ("short-circuit" impedance) is

$$Z = \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2},$$

where r_1 and r_2 are the effective values of the primary and secondary resistances per phase, the latter being reduced to primary turns and x_1 and x_2 the primary and secondary reactances per phase, the latter being reduced to primary turns.

The current per phase at standstill ("short-circuit" current) is —

$$I_s = \frac{E}{Z}.$$

The starting torque in pounds at 1-foot radius is

$$T_s = \frac{7.06\, m r_2 E^2}{N Z^2},$$

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where m, r_2, E, and Z are as defined above, and N is the synchronous speed in revolutions per minute.

The slip at maximum output is

$$s_m = \frac{r_1}{r_1 + Z}.$$

The maximum output in watts is

$$P_m = \frac{0.5\, mE^2}{1.3\,(r_1 + r_2) + Z} \text{ watts.}$$

This should be from 1.5 to 3 times the rating of the motor. A 25-cycle motor usually has a greater maximum output or overload capacity than a 60-cycle motor.

Heating. — Since in most motors the primary member is subject to both a core-loss and a copper loss and is stationary, the heating of this member is very important. As the secondary contains only a copper loss and is usually revolving, its rise in temperature is usually much less than that of the primary.

The problem therefore consists of analyzing the flow of heat and drop in thermal potential in the primary as the energy lost in the windings flows to the iron of the core through the insulation in the slots and to the air around the projecting end connections. The core itself is maintained at a temperature above the air by the core-loss. It is therefore necessary to calculate first the rise in temperature of the iron of the core caused by the core-loss and that portion of the copper loss which is conducted to the core through the slot insulation. It is then necessary to calculate the rise in temperature of the copper above the iron and above the air around the end connections.

Since at times in every motor, when the core-loss is great compared with the copper loss, the iron may be hotter than the copper, it is necessary to distinguish between that portion of the power (P_1) which passes between copper and iron (or vice versa), and that portion (P_2) which passes from copper direct to the air. The analysis must take account of the fact that sometimes the heat due to core-loss passes to the copper and is dissipated by the end connections.

The method given here is based on the more exact and elaborate treatment given by Arnold in Vol. V of his treatise *Wechselstromtechnik*, but is simplified by assuming that the copper conductors have such a high heat conductivity that they have the same temperature throughout their length. The result is a value for the average temperature of the copper such as would be found by a resistance measurement. For a method of determining the maximum temperature in any spot the reader is referred to Arnold's treatise.

Temperature Rise of Iron of Core (T_i). —The heat which is dissipated by the core surface consists normally of the core-loss and that part of the primary copper loss occurring in the portion of the winding embedded in the slots. It is

$$H = \text{core-loss} + mI^2 r_1 \left(\frac{2L}{t}\right),$$

where
m = number of phases,
I = primary current per phase,
r_1 = effective resistance of primary per phase,
L = length of armature core between heads,
t = mean length of a primary turn.

The surface consists of the outer cylindrical surface of the core, the two annular surfaces at the ends, and the surfaces in the air ducts, see Fig. 3. Since the

surface in the air ducts is not as effective as the others, only half the air-duct surface is used.

The area is $A_i = \pi D_1 L + \frac{\pi}{4}(D_1^2 - D^2)(2 + d)$,

where D_1 = outside diameter of stator in inches,
D = inside diameter of stator in inches,
d = number of air ducts.

The rise in temperature of the iron of the core will then be $T_i = \frac{kH}{A_i}$, in degrees Cent., where k ranges from 30 for narrow machines to 50 for long machines.

Temperature Rise of Copper (T_c). — A part of the heat due to the copper loss flows from the copper to the iron through the slot insulation, due to the small difference in temperature between the copper and the iron, $T_c - T_i$, where T_c is the rise in temperature of the copper above the air. The power in watts so dissipated is

$$P_1 = A(T_c - T_i),$$

where

$$A = \frac{U_s L S_1}{d_1 k_1}$$

and U_s = perimeter of slot insulation,
S_1 = total number of slots,
d_1 = thickness of slot insulation,
k_1 = a constant, 200 to 250 (say, 210).

Sometimes T_i is greater than T_c and P_1 becomes negative, which means that some of the energy of the core-loss flows to the windings and is dissipated by the end windings.

Another portion, P_2, of the copper loss flows through the insulation of the end connections to the air. Here there are paths, insulation and air, in series, across which there is a drop in temperature of T_c°C. The flow of energy to the air is affected by the movement of the air, which, in turn, is a function of the peripheral speed V of the rotor. The value of P_2 is

$$P_2 = BT_c,$$

where

$$B = \frac{U_c l_c Z_1}{d_2 k_2 + k_3}$$

and U_c = perimeter of end connections, in inches,
l_c = length of end connections, in inches,
Z_1 = total number of coils,
d_2 = thickness of insulation on same, in inches,
k_2 = a constant, 400 to 500 (say, 430),
k_3 = resistance to flow of heat from insulation to air and is given by the formula,

$$k_3 = \frac{170}{1 + 0.015\,V};$$

where V = peripheral speed of rotor in feet per second.

The total copper loss is $P = P_1 + P_2$, whence

$$T_c = \frac{P + AT_i}{A + B}.$$

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This is approximately the average difference in temperature between copper and air as it would be determined by a measurement of resistance.

TESTING OF INDUCTION MOTORS. — (*See also Standardization Rules of A.I.E.E.*) Induction motors may be given either an "input-output" test at load under working conditions, from which the efficiency and power factor may be determined, or the motor may be given a no-load excitation and no-load short-circuit test, from which all the characteristics may be calculated. The latter method requires very little power and is preferable in the case of large motors where it would be expensive to supply power and inconvenient to dissipate the energy.

Excitation Test. — In this test the machine is operated without load at constant frequency with the voltage varied through a range from 30 per cent above rated value down to as low a voltage as will cause the machine to rotate. The current in each phase is noted and by means of two wattmeters the power required is noted. This test is sometimes also made with the machine operating single phase for the purpose of checking the core-loss. The curves are plotted with voltage as abscissas and amperes and watts as ordinates. At very low voltages the core-loss is negligible and therefore the watts input may be taken as friction loss. Around normal voltage the real core-loss may be determined by subtracting from the input the small copper and the friction loss.

Short-circuit Impedance Test. — In this test the starting resistance, if there is any, is short-circuited and the armature is blocked to prevent rotation. A low voltage is applied to the primary until the ammeter in the primary circuit shows a current of from 1 to 1.5 times the full-load value. Two wattmeters are used to read the power input. As the leakage flux, and hence the reactance, varies with the relative position of the rotor and stator teeth, it is customary to take readings with the rotor in several positions. Sometimes the rotor is allowed to revolve very slowly at, say, two to three revolutions per minute. From this test the impedance (Z) of the machine is obtained by dividing the volts per phase by the current per phase; the combined effective resistance (R) of primary and secondary is found by dividing the watts input per phase by the square of the current per phase. This latter is the effective value of the resistance, since the watts input includes all losses due to eddy currents. From these values the total reactance (primary and secondary) of the motor is $X = \sqrt{Z^2 - R^2}$. With the results of the two preceding tests and the measured resistances of the two members, the characteristics of the motor may be calculated either by the Steinmetz Method or the Circle Diagram. (*See below under Performance, Calculation of.*)

Stationary Torque Test (Fig. 5). — This test may be made at the same time the impedance test is made and consists in the measurement of the torque of the motor by means of a brake arm and spring balance. When the current of the machine has been adjusted to a suitable value the brake arm (to which a known weight has been attached to overcome bearing friction) and the spring balance are allowed to move downward through a small arc, during which the spring balance will register a pull (P_1) equal to torque (T) plus the weight (W) minus the friction (F), that is, $P_1 = T + W - F$. The spring balance and brake arm are then raised against the torque through the same small arc and the spring balance will then register a pull (P_2) equal to the torque plus the weight plus the friction, that is, $P_2 = T + W + F$. From these two readings the friction can be eliminated

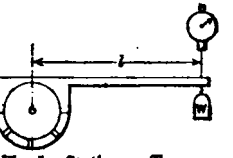


Fig. 5. Stationary Torque Test

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and the actual torque of the armature on the shaft is determined. This shou be done at two or three equally spaced positions of the rotor, as the torque vari considerably with the position. The corrected torque of the machine is found l solving the two equations for T and multiplying T by the lever arm of the bra in feet; this gives the torque in pounds at 1-foot radius.

Load Test. — To make this test on a small machine a prony brake is require while for a large machine a direct-current generator may be conveniently em ployed as a load. The induction motor and generator are direct-connected possible, otherwise belted together. All the constants of the generator a determined, so that its losses under any condition may be calculated. Th motor is then allowed to drive the generator, the rated voltage being impresse upon the motor, and the generator is loaded by means of a rheostat or a wate box so that any load may be obtained. The voltage across each phase of th motor, the current in each phase, the total watts input (by two meters), spee and, if possible, slip (by a slipmeter, *see below*) are all read. Care must b taken that correct voltage and frequency are supplied to the motor. The loa on the motor is increased step by step to the maximum output point, which easily known, since when it is reached a decrease in speed is not accompanied b any increase in output of the motor. The motor is still stable at the maximu output condition, since maximum torque occurs at a lower speed than max mum output.

After the load run the direct-current generator is run as a motor with th same field strength as before, to determine the mechanical losses, first drivin the induction motor at the proper speed, and then running alone at the sam speed or speeds at which it ran in the load test. Knowing the no-load frictio of the induction motor as previously determined in the *Excitation Test*, th increase in friction due to the belt and load is determined and half of it charge against the motor. Let

EI = the output of the direct-current generator in watts,
I^2R = the hot resistance loss in the direct-current armature,
CT = the counter torque or stray power losses in the direct-current generato plus one-half belt loss,
P_0 = watts input to induction motor.

Then efficiency of the motor = $\dfrac{EI + I^2R + CT}{P_0}$.

From these tests, curves may be plotted for the speed, efficiency, power factor current and torque of the induction motor for any horse-power output.

Use of Stroboscope to Measure Slip. — One type of slipmeter consists of a disk which is attached to the motor shaft and on which alternate sectors of black and white are shown, preferably as many black sectors as there are poles on the motor. If this rotating disk is illuminated by means of an arc light supplied with the frequency impressed on the primary of the motor, the disk will appear to rotate at a speed proportional to the difference between synchronous speed and actual running speed. The number of these revolutions for one minute, will be the slip in turns per minute, which may be translated into a fraction or percentage of synchronous speed.

Slipmeter. — Another type of slipmeter has two disks of insulating material mounted on the same frame, one carrying a wiping finger which makes contact with a button on the other disk. One of the disks is connected to a small synchronous motor which is driven from the same power source as the induction motor under test; the other disk is arranged to be readily attached to the shaft of the induction motor. The circuit of a miniature tungsten lamp is closed when the wiping finger and button are in contact. The number of flashes

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of the lamp per minute gives the slip in revolutions of the induction motor behind the synchronous speed.

Heat Runs. — On machines of moderate size heat runs are advisable, but on large size machines heat runs are expensive. It is not always necessary to make a heat run in order to know whether the motor is properly designed, as the losses can be accurately calculated from the excitation and short-circuit tests, and the machine may be run without load but with losses equivalent in value to the losses at full load. The usual heat run consists in operating the machine at a certain output for a period from three to six hours, depending on the size, measuring the resistance before and after the run and taking temperatures by thermometer on the following parts after the run: primary winding, the iron surfaces in the air gap, secondary winding, bearings, frame.

A heat run which will indicate whether there is anything radically wrong with a motor consists in operating it for an hour or two with a voltage 15 per cent above normal, but without load.

Insulation Tests. — High-potential tests are made on the primary in the manner described under *Testing* in the article on *Generators, Alternating-Current*. The value of the high potential for the primary is chosen in accordance with its rated voltage from the *Standardization Rules of the A.I.E.E.* (q.v.). The potential applied to the secondary, however, has no relation to the rated voltage of the machine; as the working potential in the secondary is low, 1000 to 1500 volts is the usual range of testing potential for the secondary.

PERFORMANCE, CALCULATION OF. — The performance of an induction motor at any load may be determined directly from the load tests described above, or the performance at any load may be calculated from the excitation and short-circuit tests by either of the two methods given below. These methods are also applicable to the calculation of performance from the values of the constants calculated from the dimensions of the machine. The first method is given in detail by Steinmetz in his *Elements of Electrical Engineering*, and the Heyland Circle Diagram is given by McAllister in his *Alternating Current Motors*. The former is recommended where accuracy is desired and the latter (graphical) for the student desiring a general understanding of the relations.

Steinmetz Method. — This method is based upon the equivalent circuit of a transformer, as given in the article on *Transformers*. Let

E = impressed voltage per phase,

m = number of phases,

r_1, r_2, x_1, x_2 = resistance and reactance of primary and secondary respectively, per phase and reduced to terms of primary,

s = slip as a decimal fraction (assumed),

g = primary no-load conductance $= \dfrac{\text{core-loss}}{mE^2}$,

b = primary no-load susceptance $= \dfrac{I_m}{E}$.

Assume a slip s and calculate

$$a_1 = \frac{sr_2}{s^2x_2^2 + r_2^2},$$

$$a_2 = \frac{s^2x_2}{s^2x_2^2 + r_2^2},$$

$$g_1 = g + a_1,$$

$$b_1 = b + a_2,$$

$$c_1 = 1 + r_1g_1 + x_1b_1,$$

$$c_2 = g_1x_1 - b_1r_1.$$

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Then

Counter e.m.f. per phase	$e = \frac{E}{\sqrt{c_1^2 + c_2^2}}$,
Current per phase	$I = e\sqrt{g_1^2 + b_1^2}$,
Total volt-ampere input to motor	$P' = mEI$,
Watts input to motor	$P = me^2(g_1c_1 - b_1c_2)$,
Watts output of armature	$P_0' = me^2a_1(1 - s)$,
Watts output of pulley	$P_0 = P_0' -$ (friction in watts),
Efficiency	$\epsilon = \frac{P_0}{P}$,
Power factor	$\cos\phi = \frac{P}{P'}$.

Circle Diagram or Graphical Method (Figs. 6 and 7). — The method of the circle diagram is based on the fact that the electrical reactions in an induction motor (or transformer) may be represented without any great error by the reactions in two parallel inductive circuits as in Fig. 6. I_e and I_m represent the two components of the exciting current, which is assumed constant. R_m and X_m represent the total resistance and reactance (both assumed constant) of the motor and are in series with a variable resistance R_L representing the load.

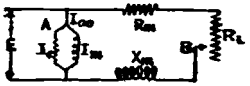


Fig. 6. Equivalent Circuits

The vector relations of the currents are as shown in Fig. 7, where

OE = the impressed voltage per phase,
OM = the current I_{oa} in A,
MP = the variable current in B (not drawn).

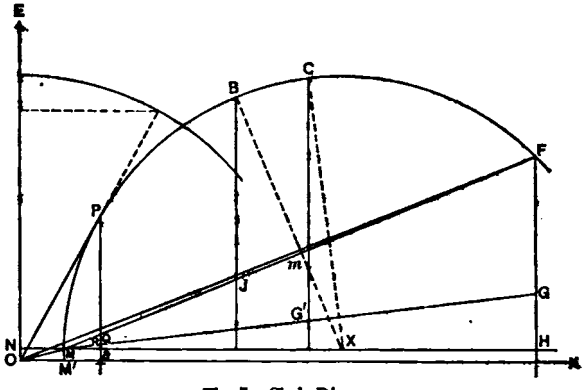


Fig. 7. Circle Diagram

Since the current represented by MP is equal to $\frac{E}{\sqrt{(R_m + R_L)^2 + X_m^2}}$, as R_L varies the point P will describe a circle through M, P and F, where $MF = \frac{E}{\sqrt{R_m^2 + X_m^2}}$. The total or resultant current will then be OP.

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eyland Circle Diagram (Fig. 7). — The circle diagram upon which ving discussion is based is a modification of Heyland's transformer, or motor diagram.

impressed voltage per phase.
at 90° to OE.
exciting current per phase, drawn in phase and magnitude.
short circuit current per phase, drawn in proper phase and magnitude.
energy component of OF.
and F; then MF is the secondary short-circuit current in terms of primary circuit.
F at m.
perpendicular to MF at middle point, intersecting NH at X.
as center and either XM or XF as radius, draw the semicircle MCF. This is the locus of the primary current.
$\times IF$ = watts input at standstill, draw HG such that $OE \times HG$ = primary I^2R at standstill.
$\times GF$ = secondary I^2R at standstill.
I. The vertical distance between GM and NH at any point gives a current which if multiplied by OE gives the power loss in primary.
ny point P on circle; then OP = current per phase.
$\sphericalangle POE = \cos\phi$ = power factor.
drawn) = secondary current reduced to primary turns.
OE = power input to primary, in watts.
OE = no-load loss, in watts.
OE = total motor loss.
OE = total primary loss in watts.
OE = primary copper loss, in watts.
OE = secondary input, in watts.
OE = secondary copper loss, in watts.
OE = motor output, in watts.
OP = per cent magnetizing current.
OP = per cent leakage reactance voltage.

These are all per phase

perpendicular to MG and CG' perpendicular to NH.
$' \times OE$ = maximum torque in synchronous watts.
B perpendicular to MF and BJ perpendicular to NH.
$\times OE$ = maximum output in watts.
RP = per cent slip (in case of induction motor).
OE = volt amperes input.

n pounds at 1-foot radius T_s = synchronous watts $\times m \times \frac{7.06}{N}$, where
ber of phases and N = synchronous speed in rev. per min.

cteristic Curves. — The observed or calculated values (by either of e methods) of the slip, power factor, efficiency, apparent efficiency, per phase and torque may be plotted as ordinates with horse-power t the shaft as abscissas. An example of the characteristic curves tted is shown in Fig. 8. Usual values of the various quantities rent sizes of motors at rated load are given above. The "power shows the relation between the true power input of the machine and rent power, called the "volt-amperes." A poor power factor does not ny greater registration of the watt-hour meter or cost of energy to he motor, but it does involve poor regulation of voltage in the system le and larger capacity of wiring, transformers, etc. The "apparent " is equal to the product of the power factor and efficiency, or is equal

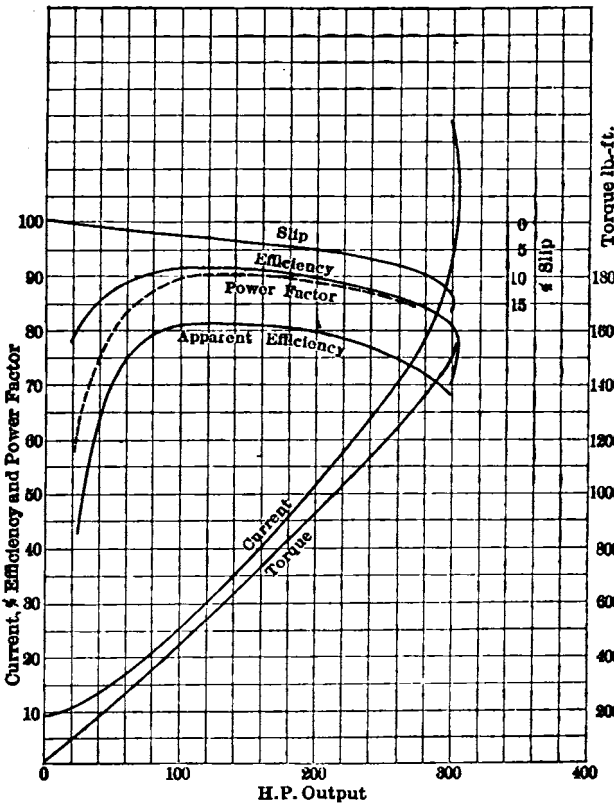


Fig. 8. Characteristic Curves of an Induction Motor

to the ratio of output in watts divided by input in volt-amperes. Its value determines the actual capacity of the lines and transformers supplying the motor.

EXAMPLES OF DESIGN AND PERFORMANCE. — In the accompanying tables are given the essential data for both mechanical and electrical features of six three-phase induction motors. The list of items will be found useful as a guide in collecting data on various machines. Performance data are deduced from tests.

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INDUCTION MOTORS

Mechanical Data. (Dimensions in Inches)

e	1	2	3	4	5	6
	3-ph.	3-ph.	3-ph.	3-ph.	3-ph.	3-ph.
oles.....	4	4	4	6	6	8
p.....	5	15	30	5	10	20
in.....	750	750	750	1200	1200	900
et. lines..	440	220	220	220	440	220
tions.....	Y	Y	Δ	Δ	Δ	Δ
.....	25	25	25	60	60	60
r						
punchings	17	21	28	17	18.25	26
punchings	12.06	15.07	19.07	12.094	11	19.07
of iron...	6	7.5	8	5	3.75	6
.....	0	0	0	0	0	0
h duct...	.....	.....	.....	.....	.....	.....
ts.....	60	72	72	54	72	96
t.....	1.25	1.25	1.44	1.56	1.5	1.25
t.....	0.32	0.34	0.39	0.50	0.3	0.33
at face...	0.32	0.34	0.39	0.25	0.3	0.33
t.....	36	16	16	64	30	16
.....	No. 14 B. & S.	No. 10 B. & S.	No. 8 B. & S.	No. 14 B. & S.	No. 15 B. & S.	No. 13 B. W. G
ltiple.....	1	2	2	2	1	2
es per ph..	360	96	96	288	360	128
pitch....	100	72	67	100	100	75
r						
punchings	12	15	19	12	10.95	19
punchings	8	11	12	8.5	6	14
ts.....	37	47	67	72	127	71
ts.....	0.56	0.47	0.47	0.94	0.5	0.47
ts.....	0.56	0.56	0.56	0.34	0.12	0.56
ts at face.	0.063	0.063	0.063	0.19	0.02	0.063
t.....	1	1	1	4	1	1
or bar....	0.5×0.45	0.35×0.5	0.35×0.5	0.34×0.11	0.35×0.09	0.35×0.5
iple.....	1	1	1	4	1	1
n each n.	1.3	0.94	2	.....	0.198	1.2
el. to cop-						
.....	2	2	2	.....	1	2
ne side...	0.03	0.035	0.035	0.047	0.025	0.035

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INDUCTION MOTORS

Electrical Data. (All quantities per phase)

Type	1	2	3	4	5
Volts per phase, E	254	127	220	220	440
Current per ph. at rating	6.6	38	42	8.1	7.3
Flux per pole, megalines	0.636	1.2	2.07	0.29	0.48
Magnetizing current I_m	2.1	9	13	2.64	2.4
Friction, watts	80	175	530	150	295
Core-loss, watts	150	390	1240	180	210
Primary res. at 60° C., ohms	2.86	0.193	0.13	1.15	2.78
Second. res. at 60° C., ohms	1.76	0.18	0.17	1.11	3.5
Short-circuit current	36	212	362	29.4	26
Y = (Sh. cir. cur.) $\div I_m$	17	23.6	28	11.2	10.8
Reactance per ph.	5.52	0.55	0.54	8	5.05
Eff. at rating	0.83	0.853	0.883	0.83	0.86
Power factor at rating	0.905	0.91	0.917	0.845	0.90
$I_m \div I$	0.32	0.24	0.31	0.33	0.33
Fr. $\div P_0$	0.018	0.013	0.02	0.033	0.034
Core-loss $\div P_0$	0.033	0.029	0.049	0.04	0.024
$IR_1 \div E$	0.074	0.058	0.025	0.042	0.046
$IR_2 \div E$	0.046	0.054	0.032	0.041	0.058
$IX \div E$	0.143	0.165	0.103	0.29	0.084
Slip, per cent	0.017	0.042	0.032	0.03	0.038

METHODS OF STARTING. — In order to start an induction m any size without injurious heating either a resistance must be connecte secondary circuit or the voltage impressed on the primary must be The two general methods of starting induction motors are known as "P Control" and "Rheostatic Control." The same methods are used f control (*see below*).

Starting by "Potential Control" Method (Fig. 9). — This method consists of reducing and regulating the voltage impressed on the primary, usually by means of a starting compensator or auto-transformer which provides one or two fractional voltages. In order to make use of this method the secondary must be of higher resistance than with other methods of starting. For this reason and for the reason that there is no need of making any change in the windings, a squirrel-cage rotor winding is customarily used with this method of starting. This winding is made up of one bar per slot, and all bars are connected at both ends to rings. To start the motor the primary is connected to taps on the compensator wh a voltage of from ½ to ⅔ the rated voltage if it is a small motor, a ½ if it is a large motor. A small motor may be brought up to full s this voltage but a large motor may require an intermediate step. The tions are shown in Fig. 9. It is customary to adjust the motor resista starting voltages to give the relations in the accompanying table.

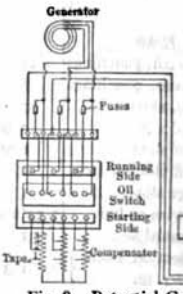


Fig. 9. Potential Co

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Voltage on Motor, per cent	Current in line, per cent	Starting torque, per cent
33	75	22
50	175	50
66	300	88
100	700	200

Boucherot Winding. — This type of winding for the rotors of induction motors is a device designed to give good torque at starting by means of high secondary resistance and inherently to reduce this resistance as the motor accelerates, so that at full speed the secondary resistance will be low, the slip small and the efficiency high.

The device consists of two independent windings on the secondary (usually squirrel cage), one, a high resistance winding of brass or German silver bars is placed near the periphery of the rotor in the usual form of slots. The other winding is of low resistance (large copper bars) and is placed in slots like tunnels below the bottom of the surface slots. A narrow slit or shaft extends from the bottom of the outer slot to the top of the inner slot.

The outer winding acts like any high resistance winding, giving good starting conditions. The inner winding is so highly inductive that at stand-still, when the secondary has full frequency, it has a very high reactance, carries very little current and contributes but little to the action of the motor. At speeds near synchronism the secondary frequency is very low (of the order of one cycle per second), the reactance is low, and the inner low-resistance winding carries most of the current; consequently under running conditions the motor has practically the same characteristics as one having a single low-resistance secondary.

Starting by "Rheostatic Control" Method (Fig. 10). — Better apparent torque efficiency, that is to say, more torque for a given current, is obtained by inserting in the secondary circuit a much greater resistance than can be left permanently in circuit. This is accomplished by having a special starting resistance connected in series with the armature winding and a switch for short-circuiting the resistance either step by step or as a whole, as the motor speeds up. There are two practical methods of doing this:

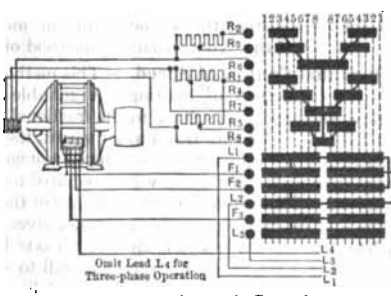


Fig. 10. Rheostatic Control

The first is intended to be used only when the torque required at starting is not very great, in which case the starting resistance may be small and located inside the armature spider. The switch lever is so arranged that the resistance can be short-circuited in steps while the armature is revolving. This obviates the need of collector rings and external connections.

The second method consists in bringing the three terminals of the secondary winding to collector rings. From brushes bearing on these rings conductors lead to external resistances with steps or taps so that the resistance may be

short-circuited gradually. This scheme is used where a large starting torque (greater than full load torque) is required. It may be used also for speed control as shown in Fig. 12

The proper value of resistance per phase in the secondary is determined by the relation

Torque in pounds at 1 foot =

$$\frac{E^2 r_2}{Z^2} \times \frac{7.06\, m}{\text{r.p.m.}} = \frac{7.06\, m r_2 E^2}{NZ^2},$$

where

E = primary voltage per phase,

r_2 = total secondary resistance per phase in terms of primary,

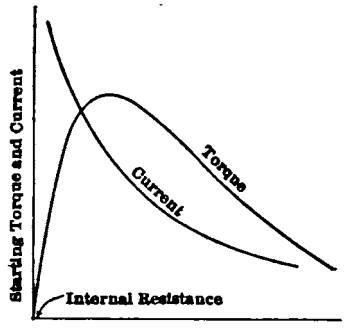


Fig. 11. Starting Resistance, Torque and Current

$Z = \sqrt{(r_1 + r_2)^2 + X^2}$, where r_1 is the resistance per phase of primary and X the total reactance per phase of both primary and secondary,

m = number of phases;

N = synchronous speed in revolutions per minute.

The relation between starting torque and total resistance of the secondary is shown by the curve in Fig. 11.

SPEED CONTROL OF INDUCTION MOTORS. — (*See also Hoists, Electric.*) The speed of an induction motor may be controlled in five ways:

(a) By varying the potential applied to the primary of motor having a suitable permanent resistance in the secondary.

(b) By varying the resistance in the secondary circuit.

(c) By changing the connections of the primary winding in a manner to change the number of poles.

(d) By varying the frequency of the applied voltage.

(e) By connecting the secondary of one motor to the primary of another, called the "concatenation" method of control.

Potential Control of Speed. — This method is an elaboration of the potential-control method of starting. A suitable resistance or auto-transformer reduces the impressed voltage to the fractional value desired (two-thirds is the usual ratio). The auto-transformer wastes less power than a resistance but is more expensive. Because of the reduced voltage the flux and torque-per-ampere are reduced and more current will be required for a given torque. The induction motor should have a very large resistance in the secondary, which is preferably of the squirrel-cage type. This resistance gives the motor a speed characteristic such that its full-load speed is some 10 per cent less than that of a normal motor. As the load is increased the speed may fall to about 30 per cent of the no-load value without the motor breaking down or falling out of step, which in the normal motor usually takes place at about 80 per cent of the full-load speed. This motor is not stable in speed as each slight change in the load will cause a change in the speed more or less inversely proportional to the load. The advantages of this method of control are the simplicity of the connections and devices. The disadvantages are the greatly increased heating in the motor itself with the decreased speed. Thus the motor must be larger than if other speed-control methods are used. The table given below shows the efficiencies obtained.

Rheostatic Control of Speed. — With this method (an elaboration of the method of the same name for starting) the secondary or rotor must have a definite winding (which costs more than the squirrel-cage winding used in the preceding method) with slip rings and brushes to lead out the current. The friction and resistance losses due to these brushes decrease the efficiency of the motor a slight amount. The action of this method is based on the principle that in an induction motor the drop in speed for any given torque is proportional to the resistance of the secondary circuit.

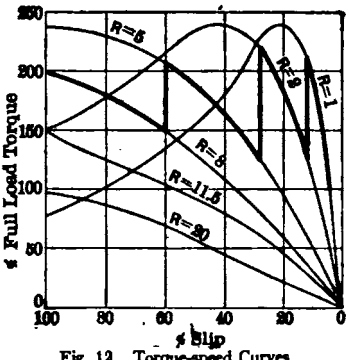


Fig. 12. Torque-speed Curves

Assuming a motor which has at full speed a net resistance of the secondary proper of 1 ohm, the speed-torque curve would be as shown for $R = 1$ in Fig. 12. This motor would have a slip of 5 per cent for full-load torque and of 25 per cent for maximum torque, a torque at starting of 80 per cent of full-load torque and a very large starting current. If by some means this resistance is doubled the speed-torque curve would be as shown for $R = 2$, which shows a slip of 10 per cent for full-load torque and of 50 per cent for maximum torque. For $R = 5$, $R = 8$, etc., there would be other speed curves. By starting with a resistance of 8 ohms a torque of about 200 per cent of full-load torque would be obtained at starting with about twice full-load current. By allowing the motor to follow this curve until the torque has dropped to the full-load value, the motor would reach 60 per cent of synchronous speed, or 40 per cent slip. Then by reducing the resistance in steps the torque and speed would follow the heavy zigzag line until the motor reached full speed.

With this method of control the torque per ampere remains practically constant as in a shunt motor regulated by resistance in the armature circuit. The efficiency varies directly with the speed as shown in the table below.

The advantages of this method are the higher efficiency and particularly the smaller losses in the motor itself. The losses are in the rheostat. The disadvantages are the necessity of collector rings, brushes, controllers, etc. The motor is not stable at any fractional speed but the speed will change with every change of load.

Change of Poles to Control Speed. — By a proper design of the windings an induction motor may be made to operate with either 4 or 8 poles, 6 or 12 poles, or even 4 or 6 poles or 6 or 8 poles. This is accomplished by a throw-over switch to which taps from the windings are brought. In this arrangement the pitch of the primary winding must be made a compromise between the proper value for the different numbers of poles, and therefore the constants of the motor are not as good as those of a standard motor. It is also necessary to use a squirrel-cage armature, since this is suitable for any number of poles without change of connections. This type of motor operates advantageously only at the two speeds corresponding to the two arrangements of poles and is stable at each of these speeds. If a wider range is desired the potential-control scheme may be combined with it. The speeds and efficiencies with this scheme of control are given in the following table. At half-speed the efficiency is almost double that obtained with the other methods, but the losses in the motor are greater than with the rheostatic control.

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COMPARISON OF METHODS OF SPEED CONTROL

(For constant torque equal to torque at full load)

Nominal speed	Potential			Rheostatic			Change of poles		
	Speed	Volts	Eff.	Speed	Volts	Eff.	Speed	Volts	Eff.
No load	1.00	100	..	1.00	100	..	1.00	100	..
Full speed	0.89	100	81	0.96	100	86	0.96	100	86
Three-quarter speed	0.67	66	59	0.72	100	65	....	...	..
Half speed	0.45	57	37	0.48	100	43	0.48	100	74
Quarter speed	0.22	56	17	0.24	100	22	....	...	..

Change of Frequency Method of Control. — The speed of an induction motor at any load varies directly with the frequency of the supply circuit. If two circuits from two alternators of different frequencies are provided the motors may be connected to one circuit for one speed and to the other circuit for another speed. This method of speed control requires as many separate generators and circuits as the number of speeds desired. It is, therefore, costly and not widely used.

Concatenation Control or Cascade Control. — If two motors have definite windings in both the primary and secondary and are rigidly connected to a common shaft, they may be operated at a fractional speed corresponding to a number of poles equal to the sum of the number of poles on the two motors. With the concatenation control the primary (stator) of motor No. 1 is connected to the supply circuit, the secondary (rotor) of No. 1 is connected to the primary (rotor) of No. 2, and the secondary (stator) of No. 2 is connected to a resistance which is eventually short-circuited. When the two motors have the same number of poles, which is the usual commercial condition, motor No. 1 transforms half the power into mechanical power at the shaft at *half speed* and the remainder into electrical power at half frequency. Motor No. 2 receives this electrical power and transforms it into mechanical power at this same speed. If the number of poles is different, the speed in r.p.m. of the combination is

$$N = \frac{120f}{p_1 + p_2}.$$

These simple relations are exact only on the assumption of no losses and the secondary of No. 2 short-circuited.

The objections to this method of control are that the first motor has to carry the magnetizing current of both motors, thus having a low power factor. The first motor must receive the power for both motors; therefore, it must be the larger of the two and specially designed or there is an inefficient use of material in the second motor. If the two motors are alike (the usual commercial condition) the torque of the two motors in concatenation is not as great as that of the two motors in parallel.

The efficiency at fractional speed is, however, better than with the rheostatic method of control. Only two "free-running" speeds are available with two motors having the same number of poles. This scheme has been adopted frequently for the speed regulation of induction motors used on electric locomotives in foreign countries. In such applications it is frequently the custom to allow one motor to be idle at the higher speed.

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INSTALLATION AND ERECTION. — Induction motors are usually built, even in large sizes, as a unit including the bearings, which are usually a part of the end frame of the motor proper. They may be either direct-connected or belted to their load, but the latter method is more general, since each induction motor can only be built for a certain definite speed corresponding to a certain number of poles. The smaller motors need no foundation, and in fact are frequently attached to the wall or to the ceiling, the bearings and end shield being made in such a manner that they may be turned through 90 degrees or 180 degrees so that the oil rings will operate properly under these conditions. In most motors reasonable ventilation, free from dust and dirt, must be available. For certain applications such as cement mills or mines, the motors are built totally inclosed and may then be even submerged in water. In this case, of course, a motor of a given rating is larger and more expensive than one of the open type.

OPERATION. — Small motors are designed to start merely by closing the main switch. With larger motors if the starting switch is at the proper position, potential may be applied to the motor and the starting resistance gradually cut out by moving the switch.

Induction motors are very sensitive to variation in the impressed voltage. A decrease in impressed voltage from 100 to 80 would cause the maximum output and maximum starting torque to decrease from 100 to 64 and roughly would cause a proportional increase in the heating for a given load.

Unequal voltages in the different phases also cause a decrease in the maximum output and an increase in the heating for any given output. An unbalancing of 25 per cent in voltage would double the heating effect at full load, i.e., would give the same heating as an overload of 50 per cent.

Care in Starting. — Before starting the motor for the first time it is desirable to make sure that the starting device is in operating condition and in the proper position, in order that the motor should not become injuriously heated. Attention should be paid to having the wiring so proportioned as to carry the starting current without an excessive drop in voltage (*see above*).

Faults. — Some of the more common faults occurring in induction motors, together with their signs and remedies, are the following.

Secondary Open-circuited. — The motor will not start and will not take a current greater than the exciting current. The cause is probably due to the starting resistance not being connected in.

One Phase of Secondary Open-circuited. — The motor has a tendency to remain at half synchronous speed although the current is apparently normal. If the armature is blocked it will be found that the current in the three phases will be unbalanced.

One Phase of Primary Open. — The motor will not start and the current will be unbalanced.

One Phase of Primary Reversed. — The currents in the primary will be very much unbalanced when the motor is running and the starting torque will be very slight.

Short-circuited Coil in Primary. — There will be humming when potential is applied to the motor and excessive local heating around the short-circuited coil.

Vibration. — Vibration due to mechanical unbalancing is chiefly noticeable at high speeds and particularly in high-speed machines. If the vibration is due to magnetic unbalancing it is probably caused by inequality in the air gap at different portions of the circumference and with different positions of the armature. This may be detected by measuring the air gap with taper wedges

at various points around the circumference, first with the armature in one position and then in several other positions.

SPECIFICATIONS FOR INDUCTION MOTORS. — The following memoranda are intended to assist in writing specifications. See also article on *Specifications*.

Principal Characteristics and Conditions of Service. — Use to which motor is to be put; kind of load and method of drive. Voltage and number of phases. Rating, horse-power. Frequency and speed.

Style and Description; Details of Construction. — Whether to be open, semi-inclosed or inclosed. Requirements regarding pulley or length of shaft. Whether rails are required. Method of starting; compensator, external resistance or internal resistance; whether motor is to be run at speeds other than full speed. Whether the starting devices are to be supplied.

Performance and Tests. — (*See Standardization Rules of the A.I.E.E.*). Temperature rises upon which ratings are to be based. Details of overload capacity. Efficiency at 25, 50, 75, 100, and 125 per cent load. Starting torque with full-load current, pound-feet. High-potential tests of insulation. Requirements regarding effect of moisture upon insulation.

WEIGHT AND COST (Pre-war prices)*. — The weight and cost of an induction motor vary with the type of its armature winding and the character of its mechanical frame and housing, as well as with the speed, frequency and voltage.

The curves in Figs. 13 and 14 give an idea of the weights and costs of a line of 25-cycle and 60-cycle motors respectively, having squirrel-cage rotors (the

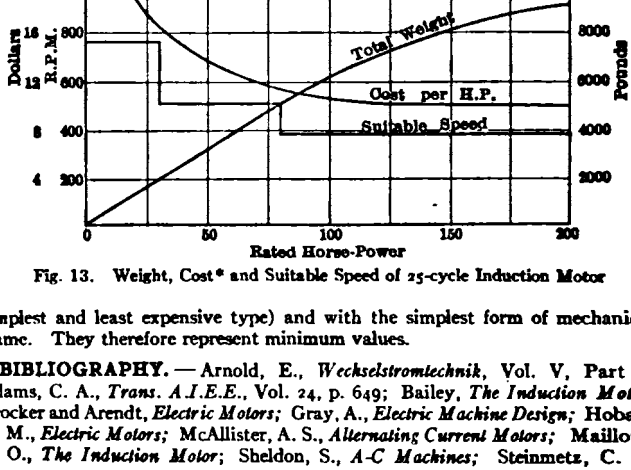


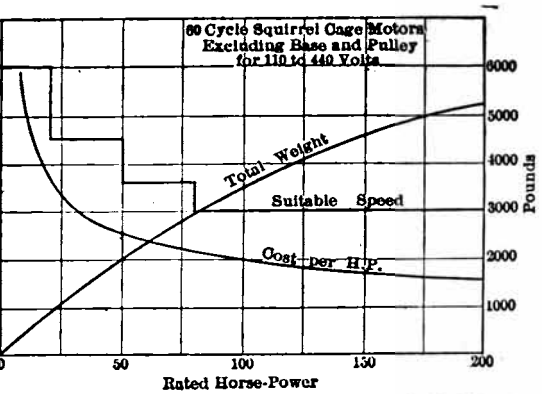
Fig. 13. Weight, Cost* and Suitable Speed of 25-cycle Induction Motor

simplest and least expensive type) and with the simplest form of mechanical frame. They therefore represent minimum values.

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* For 1922 prices add 50 per cent.

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4. Weight, Cost * and Suitable Speed of 60-cycle Induction Motor.

nena; Thompson, S. P., *Dynamo-Electric Machinery*, Vol. II; Smith, *t of Voltage and Frequency Variations*, Elec. J., Mar., 1917; Smith, *rical Design of Induction Motors*, Electrician, Aug. 6, 1915; Crosby, *Control of Induction Motors*, G. E. Rev., June, 1914.

* For 1922 prices add 50 per cent.

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MOTORS, SINGLE-PHASE INDUCTION. — (*See also Motors, Polyphase Induction; Motors, A-C. Commutator*). A two- or three-phase induction motor may be operated as a single-phase machine after it is brought up to speed. Under these conditions it operates at a lower efficiency, lower power factor and with a lower maximum output than it would have as a polyphase motor. The slip for a given output is less in a single-phase motor than in a polyphase motor.

Load and Voltage Rating. — On account of the poorer operating characteristics and particularly on account of the lower maximum output or maximum torque, it is necessary to rate the motor at a lower capacity. When a three-phase motor is operated single-phase with the same voltage between lines, its maximum output will be approximately 40 per cent of the three-phase maximum output.

For best conditions, such as best distribution of losses and ratio of rated to maximum output, it is customary to use a three-phase motor, to reduce the rated output of the motor and to increase the rated terminal voltage in a definite ratio. Thus, if P be the rated output, in watts, of a given motor when operating on a three-phase circuit having a voltage between lines equal to E, then it would be advisable to operate the motor single-phase with a voltage between lines equal to 1.3 E, and to assign the motor a rating of from 0.67 P to 0.75 P.

This will result in a distribution of losses in the motor quite similar to that which obtains during three-phase operation. The maximum output as a single-phase motor (at the higher voltage) will be about 67 per cent of the maximum output of the three-phase motor. The efficiency and power factor will be reasonable.

In case the voltage of the single-phase supply circuit must be the same, the winding of the motor is changed to give about 75 per cent as many turns in series per phase as for normal three-phase operation.

Exciting Current and Power Factor. — At a given voltage between terminals the volt-amperes input at no load for excitation are practically the same for single-phase and polyphase operation. Thus the no-load current of a single-phase motor is considerably greater than when operating polyphase. The increase in the applied voltage or the decrease in the number of turns makes a still greater increase in the magnetizing current. Thus the power factor of a single-phase motor is very poor at light loads and not very good at rated load.

CALCULATION OF PERFORMANCES. — To predetermine the characteristics of a single-phase motor it is calculated as a three-phase motor for the same voltage between lines as the single-phase circuit. The magnetizing current, core-loss, resistance per phase, and reactance per phase are all calculated as usual. The motor primary may be connected either delta or Y, but for purposes of calculation it is desirable to pro-rate the constants of a Y-connected motor on the assumption that it is delta connected.

To pro-rate the resistance and reactance per phase of primary and secondary, multiply the values for a Y-connection by 3 to obtain the values for the equivalent delta constants. The voltage per phase is presumed to increase in the ratio 1 to 1.73, while the voltage between lines remains the same.

The magnetizing current and the core-loss current are found by dividing the 3-phase values by 1.73.

The single-phase magnetizing current is found by dividing the volt-amperes excitation for three-phase conditions by the single-phase voltage. The core-loss in watts remains practically the same single-phase and the energy component of the single-phase exciting current is equal to core-loss watts divided by rated voltage.

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The resistance and reactance of the primary of a single-phase motor are taken the same as the equivalent delta values per phase.

The resistance and reactance of the secondary of a single-phase motor are taken as ⅓ of the three-phase equivalent delta values.

These values are then substituted in the formulæ of the Steinmetz method (*see Motors, Polyphase Induction*) and the characteristics calculated for several assumed values of slip. The only difference in calculation is that the torque in synchronous watts is

$$T = e^2 g_1 (1 - s)$$

and the output of the armature is

$$P = e^2 g_1 (1 - s)^2.$$

It is of course understood that in a single-phase motor the output calculated for one phase is also the total output of the motor.

METHODS OF STARTING. — A single-phase motor has no torque at standstill. It must be started by some device such as a phase-splitting device. It may be started in either direction and as soon as it starts to rotate a slight torque develops which increases with the speed. When this torque has reached a great enough value to overcome the friction and inertia the special starting apparatus may be disconnected and the motor will continue to accelerate to its proper speed.

Starting of Small Motors. — Small motors may be started without auxiliary electric circuits by giving the armature a spin by hand, after which (if there is no load) they will accelerate. Certain small motors are designed with a loose pulley which is clutched at a predetermined speed of the armature by means of a centrifugal governor. These motors are provided with "shading coils" or a small external phase-splitting device, to give them just enough starting torque to overcome their own friction.

Starting of Large Motors. — A phase-splitting device is generally used; either a reactor and resistor or a condenser and resistor may be employed. Commutator devices are also used.

Use of Reactance Coil and Resistor. — The connections employed are shown in Fig. 1. This device consists of a resistance and a reactance connected so as to advance the phase of the e.m.f. impressed on one circuit of the motor and retard the phase of the e.m.f. on another circuit, while the line voltage is impressed on the third winding. This may be accomplished either by connecting the resistance and reactance across the line terminals and in multiple with the motor windings as shown in Fig. 1 A, or by connecting the resistance and reactance in series with the respective windings as shown in Fig. 1 B.

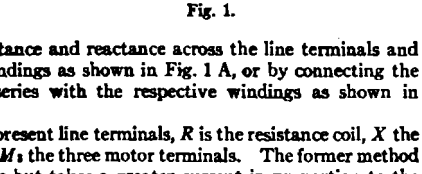


Fig. 1.

In these figures L_1 and L_2 represent line terminals, R is the resistance coil, X the reactance coil and M_1, M_2 and M_3 the three motor terminals. The former method gives a greater starting torque but takes a greater current in proportion to the torque. The latter method is more efficient. The motor must have sufficient resistance in its secondary circuit to give good starting characteristics as a three-phase motor.

The principle of this device is that the voltages between the outside terminals and the middle point are out of phase with each other and form a somewhat

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flattened vector triangle similar to that of an unbalanced three-phase system. The ratio of the starting torque obtained with such a device to the normal starting torque with balanced three-phase voltages is the same as the ratio of the altitude of the triangle of vector voltages to the altitude of the equilateral triangle. Thus in Fig. 2 the ratio of altitudes is $30/95 = 0.316$; thus the single-phase starting torque would be 31.6 per cent of the three-phase starting torque.

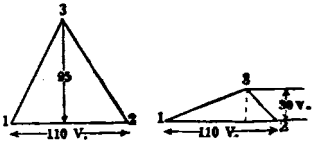


Fig. 2.

Use of Condenser and Resistor. — If a condenser of the proper capacity is substituted for the resistance the starting torque will be increased and the efficiency improved, but this is much more expensive and frequently involves the addition of a transformer across the condenser.

Use of Commutator. — Another method of starting single-phase motors involves the use of a commutator which permits the motor to start as a repulsion motor (which has good starting qualities; see *Motors, A-C. Commutator*), and after the motor has reached a considerable speed the brushes are removed from the commutator and a short-circuited squirrel-cage winding comes into play.

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MOTORS, SYNCHRONOUS.—(*See also Alternating Currents; Generators, Alternating Current; Motors, Industrial Applications of; Motors, Polyphase Induction.*) Any alternator will operate as a motor. If two synchronous alternators are connected in parallel to bus-bars supplying a load, and the driving power be removed from one prime mover, the alternator connected to this prime mover will continue to run at the same speed as before, taking power from the other alternator and driving its own prime mover or other apparatus coupled to it; i.e., this alternator acts as motor. The speed of such a motor depends solely upon the speed of the generator or generators supplying electric energy to it; it is therefore said to run in "synchronism" with the source of supply and is called a synchronous motor. The synchronous speed of a synchronous motor having p poles, when supplied with a current of a frequency of f cycles per second, is

$$N = \frac{120f}{p} \qquad \text{rev. per min.}$$

If the load on such a motor increases the speed will not decrease, unless the load reaches such an excessive value that the maximum output or "pull-out torque" is reached, when the motor will drop out of step and come to rest, while the current taken will increase to short-circuit value and the torque decrease to a negligible value.

Differences between an Alternator and Synchronous Motor. — The difference in construction between an alternator and a synchronous motor is that the latter has placed in the face of the field poles, a squirrel-cage winding, which is intended to give good starting torque and to prevent hunting while running. A synchronous motor usually operates better with a higher value of armature reaction than that of a well-designed generator of the same kilowatt rating. This increase in armature reaction is usually obtained in practice by operating the machine as a motor at lower voltage than that for which it would be operated as a generator. Thus a standard 2300-volt generator will operate very satisfactorily as a motor at 2080 volts, and as these are the natural values of the generated and delivered voltages, this characteristic of the synchronous motor fits in very well with customary distribution practice. Thus a standard generator may have a squirrel-cage winding added to its poles and become a good synchronous motor.

Field Excitation. — Synchronous motors always require direct current for field excitation and if a suitable d-c. source is not available an exciter must be provided.

Number of Phases. — Synchronous motors may be single, two or three phase. The single-phase motor is not self-starting and has a considerably lower efficiency than the polyphase motor. It is also more liable to hunt (*see below*) and be unstable, and is therefore far less desirable than a polyphase motor. The two-phase and three-phase motors are very similar in all their characteristics. There is a slight economy in the three-phase over the two-phase motor as there is in the three-phase over the two-phase generator (q.v.).

Terminal Voltage. — Since synchronous motors are usually built with a revolving field and a stationary armature, it is possible to insulate the armature winding for voltages as high as 13,000 and thus obviate the need of transformers in many cases.

Advantages and Disadvantages of Synchronous Motors. — The advantages of synchronous motors as compared to induction motors are: higher efficiency, higher power factor, power factor may be controlled, constant speed,

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high voltage, lower cost. The disadvantages are: need of an exciter, will not start under load, possibility of hunting.

Relations of Voltage and Current. — The relations between line voltage and phase voltage are the same as in a-c. generators (q.v.). The current in each line of a three-phase motor is

$$I = \frac{746\,P}{\sqrt{3}\,\epsilon E \cos\theta},$$

where

P = horse-power output,
E = voltage between lines,
ϵ = efficiency at load assumed,
$\cos\theta$ = power factor (may be unity).

Usual values for efficiency are about the same as for a-c. generators (q.v.).

APPLICATIONS. — In order to transform from alternating to direct current, or from one kind of alternating current to another differing in frequency, potential or phase relation, motor-generator sets, consisting of a synchronous motor direct connected to one or more generators, are often employed. By this means the potential of the secondary or distribution circuit is independent of the variation in potential of the primary circuit supplying power to the motor. In certain cases it is desired to take power from a 25-cycle circuit and supply power at 60 cycles for lighting purposes. Here a synchronous motor-generator set would be used. Such a set is frequently called a "frequency changer" (see *Frequency Changers*). In some applications of electric drive by induction motors one synchronous motor is installed for the purpose of making it take leading current in order to neutralize the lagging current taken by the induction motors. This effect is produced by over-exciting the fields of the synchronous motor. Such a synchronous motor is called a "rotary phase modifier" or "rotary condenser." It may incidentally be used to drive any machinery that does not require a large starting torque.

GENERAL PRINCIPLES. — In any synchronous generator or motor when a current flows in the armature there is a loss of voltage proportional to IZ_0, where I is the current and Z_0 is a hypothetical quantity called the synchronous impedance, which includes the effect of the resistance, the leakage reactance and the demagnetizing effect of the armature current. This quantity is obtained by the synchronous impedance test (*see below*) and is expressed in complex quantities as $Z_0 = r + jx_0$ and in algebra $Z_0^2 = r^2 + x_0^2$ where r is the effective resistance per phase and x_0 is the synchronous reactance per phase. IZ_0 is therefore the drop in voltage per phase in the armature, and this voltage and the current differ in phase by an angle θ, where $\tan\theta = x_0/r$ and $\cos\theta = r/Z_0$. If a synchronous motor is running and generating a counter e.m.f. e and is connected to bus-bars of voltage E, the current flowing in the armature will be proportional to the vector difference between E and e and inversely proportional to Z_0, all taken per phase.

Vector Relations for Motor Action. — In Fig. 1 let E represent the bus-bar or line voltage (per phase) impressed on the terminals of a synchronous motor. Let e represent the counter e.m.f. of the motor and in this case assume $e < E$ and directly opposed to E. Then the difference between E and e will set up a current in the armature of the motor. IZ_0 will be the voltage and the current will lag behind IZ_0 by an angle θ where $\cos\theta = \frac{r}{Z_0}$. Thus the motor takes a current I lagging behind the impressed voltage E.

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the relations when $e > E$, then IZ_0 will be reversed in phase as
ll always lag behind IZ_0 by the angle θ and will be found drawn
s behind e and IZ_0 but I leads the impressed e.m.f. E by an
. Thus when the field excitation is increased so that e tends to

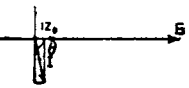


Fig. 1.

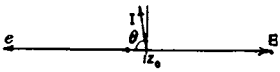


Fig. 2.

than E, the machine takes a current leading with respect to the
. As in a synchronous generator the field excitation required
ninal voltage depends upon the phase relation of the external
ad, so conversely in a synchronous motor the phase relation of
the armature at a given terminal voltage depends upon the
and the load.

the relations when e is more than 180 degrees behind E, that is,
position it had in the preceding examples by an angle α. The
of E and e will be IZ_0 as shown, leading E. The current I
IZ_0 by the same angle θ, but is now almost in phase with E
y slightly. Thus power ($EI \cos \phi$) is being sent into the ma-

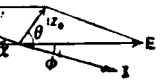


Fig. 3.



Fig. 4.

ts as a motor, transforming electrical power into mechanical
he machine is running as in Figs. 1 and 2 the power is very small.
nechanical load is applied, the armature will drop back in posi-
amount. This causes e to drop back in phase and the machine
ws power from the line.

4, power is applied to make the armature move forward and
nce in the opposite direction, the resultant IZ_0 is thrown down-
ging behind IZ_0 by θ, is thrown around almost in phase with e.
nen becomes a generator, transforming the mechanical power
trical power $eI \cos \phi$.

nous Position. — In the discussion of the action of a synchro-
s convenient to employ the term "synchronous position," by
the position which any definite point on the revolving member
same period of each cycle of time. It is only necessary for the
nge in synchronous position by a very slight angle α to cause
current to flow. If α should become 90 degrees, theoretically
l become a maximum, and any increase in α means that θ be-
han 45 degrees, the power decreasing and the machine falling
hen α becomes 180 degrees a total e.m.f. equal to the sum of
t-circuited by Z_0 and the current is enormous and the power

orque. — If the speed changes for a short instant of time suffi-
a point on the armature to drop back in synchronous position
h of one pole (90 electrical degrees), the motor torque will in-
to the maximum available in the motor. Thus, for any torque
naximum the armature (or revolving field) need only change
tly to drop back some distance less than one-half the pitch of a

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pole. If the load demands a torque greater than this maximum the s drop back more than 90 degrees and will fall out of step and come most synchronous motors the maximum torque is about 6 times no

DESIGN AND CALCULATIONS. — (See also *Generators, Alt rent.*) The design and calculation of synchronous motors is ver the design and calculation of alternating-current generators. The ence in the proportioning of certain details and there are certain are of importance in generators that are not important in motors tion) and the converse is also true.

Armature Reaction. — The armature reaction of a synchron expressed as $\frac{1.5\sqrt{2}SIk_2k_3}{p}$ for a three-phase machine and $\frac{\sqrt{2}SIk_2}{p}$ phase machine, where S = turns in series per phase, I = full-load curre k_2 and k_3 have the values given in the article on *Generators, Alterna* and p = number of poles. The armature reaction of a motor is us cent to 50 per cent greater than that of a generator of the sam frequency. The higher value gives greater synchronizing torque a better starting torque, and reduces the cross-currents between case of hunting. The armature-reaction ampere turns at full l equal to the field ampere turns at no load. Too great an armat is objectionable, because it reduces the energy transfer between t and therefore reduces the synchronizing power, that is, the tend machines to hold each other in step.

Excitation. — The excitation of a motor is calculated in the s as the excitation of a generator. The magnetic densities are usu less. The capacity of the field winding depends upon whether the motor is to be used as an ordinary motor or to regulate the powe system by over-excitation.

Leakage Reactance. — The leakage reactance may be higher in a in a generator as regulation is not of so great importance. Howev a reactance will reduce the starting torque of the motor.

Short-circuit Current and Synchronous Impedance. — The current of the motor depends upon the leakage reactance and th reaction. The short-circuit current and the synchronous impeda predetermined from the no-load saturation curve and the calcula reactance per phase.

Let F = excitation in ampere turns per pole for which it is desire short-circuited current,
I = rated current per phase,
x = leakage reactance in ohms per phase,
E = voltage per phase due to F at no load,
S = turns in series per phase,
p = number of poles.

Then the ampere-turns synchronous impedance for full-load current

$$\frac{2.12\,SI}{p} + \frac{IxF}{E},$$

and the short-circuit current with excitation F is

$$I_0 = \frac{EpF}{2.12\,SE + xpF}.$$

The synchronous impedance at this excitation is $Z_0 = E/I_0$, a

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chronous reactance is $x_0 = \sqrt{Z_0^2 - r^2}$, where r is the resistance of the armature per phase.

Efficiency and Losses. — The losses are predetermined as in a generator. They are: A = friction, B = excitation or field RI^2, C = core-loss, D = armature RI^2; then

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + A + B + C + D}.$$

Phase Characteristics or V-Curves. — The phase characteristic is a curve showing the variation in armature current for any given load with varying field excitation. Fig. 5 shows the shape of the curves, which may be determined both by calculation and test. The phase characteristic for any particular load has the general shape of the letter V, and the group of such curves for various loads are frequently called the "V-curves" of the machine. There are two methods of calculating the phase characteristics, the electromotive force method and the magneto-motive force method.

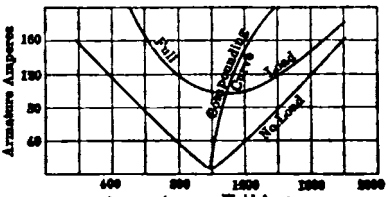


Fig. 5. Phase Characteristics of Synchronous Motor

Electromotive Force Method. —

Let E = line voltage per phase,
e = motor counter e.m.f. per phase corresponding to the excitation to be used,
i = component of current in phase with e,
ei = mechanical output of armature,
i_1 = reactive component of current, positive for **leading**, negative for lagging,
r = armature resistance per phase,
x_0 = synchronous reactance per phase,

then $E^2 = (e + ri - x_0 i_1)^2 + (x_0 i + r i_1)^2 = e_1^2 + e_2^2$.

E, r and x_0 are constant, e is set by the value of the field current assumed, then i = (watts output)/e and i_1 remains the only unknown quantity. Solving for i_1 the total current $I = \sqrt{i^2 + i_1^2}$ and the power is $e_1 i - e i_1$ (for i_1 lagging). If e is greater than E, then i_1 is leading, and the power factor is $(e_1 i + e i_1)/EI$.

Magneto-motive Force Method. —

Let E = line voltage per phase,
F = field ampere turns per pole for this voltage,
D = any value of field ampere turns per pole,
I = armature current per phase,
i = energy component of current = (power input) ÷ E,
p = number of poles,
ν = field leakage coefficient of machine,
S = turns in series per phase,
i_1 = wattless component of current for excitation D.

Then

$pF = pD - 2.12\, Si\nu$ and

$$i_1 = \frac{pD - pF}{2.12\, S\nu},$$

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and

$I = \sqrt{i^2 + i_1^2}$ is the current in armature for power input Ei and for the excitation D assumed. If i_1 is negative ($F > D$) then i_1 is lagging. If $D > F$ then i_1 is positive and leading.

Angular Lag Due to Load (α). — For any load on a synchronous generator there is an angular advance of the generated e.m.f. ahead of the terminal e.m.f., and in a synchronous motor there is an angular lag of the generated e.m.f. behind the terminal e.m.f. This phase displacement is accompanied by a shift in the synchronous position of the armature, which may be calculated and actually measured (*see Tests of Synchronous Motors below*).

To calculate this angle α expressed in electrical degrees (360 degrees per pair of poles), let

E = line or terminal voltage per phase,
e = induced or counter e.m.f. per phase; may be taken from no-load saturation curve for given excitation,
r = resistance of armature per phase,
x_0 = synchronous reactance per phase,
I = current per phase,
ϕ = phase angle between E and I.

Then

$$e^2 = (E - Ir\cos\phi - Ix_0\sin\phi)^2 + (Ir\sin\phi - Ix_0\cos\phi)^2,$$

and

$$\alpha = \sin^{-1}\left[\frac{(Ir\sin\phi - Ix_0\cos\phi)}{e}\right],$$

or roughly

$$\sin\alpha = \frac{I\cos\phi}{\text{short-circuit current}}.$$

The mechanical displacement of the armature for the load $EI\cos\phi$ per phase is $2\alpha/p$.

Synchronizing Torque. — The synchronizing power of a machine is a measure of the ability of a machine to keep in step with its supply circuit. It may be expressed in terms of torque per degree of displacement. If P is the kw. output of a motor and α is the angular displacement of the armature in electrical degrees for this load, then

$$\text{Motor torque} = \frac{7050 \times (\text{kw.})}{\text{rev. per min.}},$$

$$\sin\alpha = \frac{(Ir\sin\phi - Ix_0\cos\phi)}{e},$$

and

$$\text{Synchronizing torque} = \frac{7050 \times (\text{kw.})}{\alpha \times (\text{rev. per min.})}.$$

A high resistance between machines reduces the synchronizing torque as it reduces E. A reactance between machines is not as bad as resistance. Increasing the excitation increases e and improves the synchronizing torque.

Hunting; Natural Period. — The rotating part of every synchronous machine acts like a pendulum, tending to swing ahead and behind its normal synchronous position. The mass of the armature (and its flywheel) acts like the mass of the pendulum, and the torque of the machine being proportional to the displacement (α) corresponds to a spring or gravity acting on a pendulum. Such a combination has an "electro-mechanical period" of its own, and if the frequency of this period is in tune with any other pulsating force in the system, such as engine impulses, "hunting" or "surging" may occur.

d Kapp have shown that the natural period of any synchro-
pressed in seconds or fraction of a second is given by the formula:

$$T = 0.308\, N \sqrt{\frac{Wk^2}{fgmEI_0}},$$

. of revolving part,
weight of revolving part including any flywheel in pounds,
s of gyration of W in feet,
ency of current, cycles per second,
eration of gravity, in ft. per sec. per sec. = 32.2,
per of phases,
nal voltage per phase,
-circuit current of machine per phase and at excitation used.
of the natural period expressed in impulses per minute is

hows that the greater the flywheel effect kW^2 (*see Flywheels*)
e the periodic time of a swing. The greater the short-circuit
tion the shorter will be the periodic time. The periodic time
d by connecting reactance coils in series with the machine be-
als and the bus-bars.
eriodic time of any other pulsating force in the system, as the
n engine, the danger of hunting is greatest when

$$T/T_0 = 1/4,\ 1/3,\ 1/2,\ 1.$$

hunt is damped by solid pole pieces, bridges between poles or,
irrel-cage winding in the pole face.

utput. — As the current which would flow during maximum
hronous motor is so great that it would burn up the windings
ut should last more than a fraction of a second, the value of
tput is only of theoretical interest. In practice the maximum
ven voltage) is only reached under two conditions: (1) when,
is causes, the line voltage decreases to a fractional value, the
t decreasing as the square of the voltage; (2) when, due to
tion, the flow of energy into and out of the machine reaches
momentarily. In one of these swings the power may reach
maximum output or exceed it and the machine shut down.
wer of the machine drops off gradually after the point of maxi-
been reached, the motor is unstable in this region and is more
ut down when the condition is reached.

ue. — Synchronous motors may be started either as hysteresis *
tors. In the former case the motor requires a high voltage
l current, but as the torque is very slight this method is seldom
When starting as an induction motor a high armature reaction
a low leakage reactance. A squirrel-cage winding in the pole
vided, and as in an induction motor this squirrel-cage winding
ss-section approximating a certain value. If the cross-section
currents will be excessive and the starting torque not the best.
ion is too small, the currents will be small and the starting
est. While the cross-section of the squirrel-cage winding may
etermined by treating the machine as an induction motor, this

n in a rotating field has a torque produced on it due to the hystere-
nts set up in it. Such an arrangement may be called a "hysteresis"
ircuited field of a polyphase synchronous motor therefore forms a

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method is not accurate because the construction of the field renders the calculation of the leakage reactance inaccurate. It is thus much better determined empirically.

Rotary Phase Modifiers or Rotary Condensers. — Synchronous motors are sometimes used to improve the power factor and reduce the line current of an installation of a number of induction motors. If a factory has an installation of 100 kv-a. of induction motors having an average power factor of 71 per cent and taking I amperes, then by installing a synchronous motor of 100 kv-a. rating, designed to be overexcited, the power available will be doubled and the line current only increased by 41 per cent or to 1.41 I. Such a machine is called a "rotary condenser" and if it is rated at 100 kv-a. it may give 71 kw. of power and 71 kv-a. to balance the reactive effect of the inductive apparatus. Other relations may be obtained in accordance with the principle of vector combinations.

Let P_1 = true power taken by the induction motors, kw.,
Q_1 = reactive power taken by the induction motors, kv-a.,
$L = \sqrt{P_1^2 + Q_1^2}$ = total kv-a. of induction motors,
P_2 = true power taken by rotary condenser, kw.,
Q_2 = reactive power taken by rotary condenser, kv-a.,
$K = \sqrt{P_2^2 + Q_2^2}$ = total kv-a. of condenser,

then

$$\text{Line kv-a.} = \sqrt{(P_1 + P_2)^2 + (Q_2 - Q_1)^2}.$$

TESTS OF SYNCHRONOUS MOTORS. — Certain tests on synchronous motors are the same as those made on an a-c. generator; the methods of carrying out such tests are described in the article on *Generators, Alternating Current*. The first five of the following tests are of this character:

1. Resistance of armature and field circuits both cold and hot.
2. Saturation curve at no load and under special circumstances at full load.
3. Core-loss.
4. Short-circuit or synchronous impedance.
5. Insulation tests.

6. **Phase Characteristics or V-Curves** at no load, full load and any other specified load. The machine is operated as a motor with the specified load kept constant throughout the run. The voltage and frequency impressed upon the motor are also kept constant. The current in the field is varied from the minimum at which the motor will operate to the maximum (from ¼ normal to 1½ normal) and the variation in current input to armature noted. Readings are taken of load, volts armature, amperes armature and amperes field. A curve is plotted with amperes armature as ordinates, and amperes or ampere turns per pole in field as abscissae. This gives the characteristic V-curves of the synchronous motor (see Fig. 5). The point of minimum current input for each load is very clearly shown. At this point the power factor is unity. At lesser values of field current the armature current is lagging and the power factor poorer. At greater values of field current the armature current is leading. The point of minimum current occurs at a higher value of field current for the greater loads because the field excitation must be increased with the load to overcome the armature reaction due to the load current.

Compounding Curve. — The curve connecting the points of minimum armature current in the group of V-curves is called the compounding curve for unity power factor.

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g Tests. — A low voltage is impressed on the armature and grad- until the motor starts. The field circuit is open in two or more h potential voltmeter connected across one section to determine uced in the field spools by the rotating magnetic flux. The for several different initial positions of the revolving part and e of the time required for the machine to reach synchronism. ich synchronous speed is reached may be determined by the duced voltage in the field becomes zero. Readings are taken re, amperes armature, initial position, maximum volts field, nchronism. See also section on *Starting*, below.

re Phase Position. — The phase position of the armature usly may be measured, although the item is only of theoretical of commercial importance. A synchronous motor is supplied a special alternating-current generator, and on the end of the achine is placed a contact-making disk, as shown in Fig. 6.

s connected in series with a current, the two disks, and sing on the disks. The volt- s a maximum when the two contact with the metal strips e. The brush on the motor over a graduated scale or position may be varied and gular movement measured.

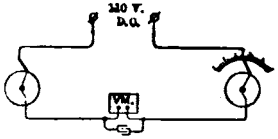


Fig. 6. Contact Method of Measuring Armature Phase Position

he generator remains stationary. As the load on the motor is be found necessary to move its brush in order to keep the volt- t its maximum value, and the angle β through which the brush for the change in load gives the phase position of the motor respect to the generator armature. It will be found that the irectly proportional to the load. The difference in phase of e forces in electrical degrees will be β multiplied by the number of the motor. If hunting exists, the maximum angle of swing ned by moving the motor brush first one way as far as the effect , and then in the other direction. (*See Morecroft, Laboratory*

TIONS. — Synchronous motors are rated in the same manner generators, and the same heating limits and specifications *nerators, Alternating Current.*) It is customary to specify the rrent taken by the motor in starting with no load other than s own bearings, or its own friction plus that of the machine to nected, in case it is part of a motor-generator set. It is also ioned in the specifications that the motor will not hunt pro- resistance drop between the generator and motor is less than alue (10 per cent or 15 per cent).

TION AND OPERATION. — The precautions to be taken in the same as for a-c. generators (q.v.). Direct current must be citation. If a synchronous motor is operated on a polyphase unbalanced voltages it will take unequal currents in the differ- nd to balance the voltages. These unequal currents, however, ting somewhat for a given load.

Provision must be made for a reduced voltage for starting the means of taps on the transformers or by means of a starting v.). Large motors require two steps in starting, ⅓ and ⅔

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of normal voltage. Small motors will start with one step at ½ voltage. The field circuit is opened by the field "break up" switch and a voltage applied to the armature. When the armature current has decreased from its large value at starting to a reasonable value the voltage is increased, step by step. When the motor has reached maximum speed the field is excited and the motor pulls into synchronism. The field current is then adjusted until the condition of minimum armature current is found or until the power-factor indicator records unity power factor. The load may then be applied.

If a synchronous motor is to be started often (several times a day) it is desirable to provide a special starting motor which brings the synchronous motor up to a speed a little above synchronism. Synchronizing must then be effected as in a-c. generators. Such a starting motor would require only about 30 per cent of the full-load current of the motor, and therefore have very little effect on the regulation of the system and not cause disturbance to the lights and other motors on the system. It usually requires less than a minute to bring a motor up to speed.

DIMENSIONS, WEIGHT AND COSTS. — These are approximately the same as for synchronous generators of the same kv-a. rating. (See *Generators, Alternating-Currents.*)

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OHMMETERS. — (*See also Bridges for Electrical Measurements; Galvanometers.*) The name ohmmeter is applied to any portable device designed for the direct measurement of electrical resistance. The simplest form of ohmmeter consists of a slide-wire bridge, battery and galvanometer all mounted in a portable case. Another form of ohmmeter utilizes a special form of galvanometer whose deflection, measured on a properly calibrated scale, gives the value of the unknown resistance directly in ohms.

BRIDGE TYPE OF OHMMETER (Fig. 1). — This ohmmeter is based on the Wheatstone-bridge principle, but differs from most Wheatstone bridges in that the rheostat resistance R is kept constant and bridge arms, formed by the wire W, are varied by moving a contact C. Ohmmeters of this type are made in many varied forms. In some a straight slide wire is stretched over a cardboard scale and contact on the wire made with a metallic stylus. In others a slide wire is wound on an insulating cylinder. The scale may be equally divided, or may be divided to read directly the ratio of the resistance measured to the resistance of the fixed rheostat resistance R.

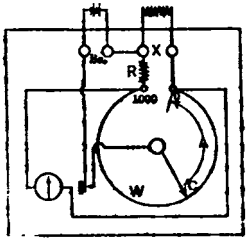


Fig. 1. Slide Wire Ohmmeter

EVERSHED MEGGER (Fig. 2). — This instrument is of the galvanometer type. It is principally useful for the measurement of insulation resistances and other high resistances where extremely high accuracy is not required. The scale is graduated to read directly in megohms, whence the name.

Referring to Fig. 2, D is a small hand-driven d-c. magneto and G a special form of moving-coil instrument. One pair of bar magnets supplied the flux for both. The galvanometer contains three coils rigidly attached at a fixed angular distance apart to the shaft which carries the pointer P. The unknown resistance is connected at X.

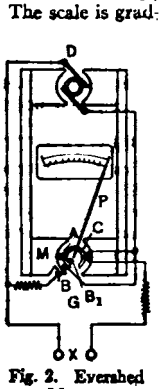


Fig. 2. Evershed Megger

The coils BB_1, called the pressure coils, are permanently connected through a resistance across the terminals of D. The current coil A is made to move through an annular gap in such a manner that the field in which it moves is uniform, whereas the pressure coils BB_1 move from a position midway between the poles, where the field is at a minimum, into a stronger and stronger field, the connections being such that the torque due to the current in the current coil is opposed by the torque due to the current in the pressure coil. With no current in the current coil, that is to say, when the resistance to be measured is infinite, current through the pressure coils will cause them to come to rest with their plane at right angles to the magnetic field. When the current through the current coil is increased by putting in lower resistances the current coil drags the moving system round in a clockwise direction; since the pressure coils come into a stronger and stronger field, the resistance to this motion becomes greater and greater. Hence a definite position is assumed by the system for the particular resistance at X. An increase in voltage would increase the current in both current and pressure coils in the same proportion; consequently the instrument is independent of the voltage of the generator.

In the cheaper instruments the generator gives a variable voltage depending upon the speed of rotation of the handle. In the higher priced instruments

the generator is designed to give a constant voltage for a consid in the speed of driving. The voltage at which an insulation test is of great importance (*see Resistance and Conductance*). Con meggers are especially useful for testing insulation resistance asso large electrostatic capacity, where a varying test voltage would c and discharging currents to flow with resulting fluctuations in the

WESTON DIRECT-READING OHMMETER. — This is a magnet moving-coil instrument having two windings on the movin adjustable magnetic shunt. Terminals are provided for the unk ance and an auxiliary battery. Before use, the instrument is check a plug in the checking position. On closing the key, a current fro divides through the two windings. The ampere-turns of one win in series with a fixed resistance, tend to deflect the pointer up sc ampere-turns of the other winding tend to return it to zero. W voltage which is within the designed limits, the magnetic shunt ma to bring the pointer to full-scale position. If the plug be now shift range position, a resistance equal to that of the low range is remo circuit whose ampere-turns tend to deflect the moving coil dow resistance equal to that of the low range be now connected ac posts, the previous condition will be restored, and the pointer wil full scale position. For any value of resistance less than this ampere turns will be greater, and will bring the coil back to a low the scale. For zero resistance across the "X" posts, the ampere two windings will balance each other, and the coil will stand at t scale, corresponding to the unstressed condition of the springs.

Double and triple ranges are available by shifting the plug to th ing positions. This form of ohmmeter is very rapid in operation in the e.m.f. of the auxiliary battery are taken care of by periodic the checking operation.

VAWTER INDICATING OHMMETER. — This instrum galvanometer type, containing two coils carried by a shaft and field of a permanent magnet. The core is specially shaped to give such scale characteristics as may be desired. Connections to the coils are made by spirals of negligible torque, so that the position of the pointer does not depend on the value of the auxiliary current nor upon the strength of the permanent magnet. The instrument can therefore be operated on a generator source of voltage. This ohmmeter is made in portable form with from one to four ranges; in switchboard form, applicable for determining the resistance of the windings of electrical machines under load, and as a rail bond tester.

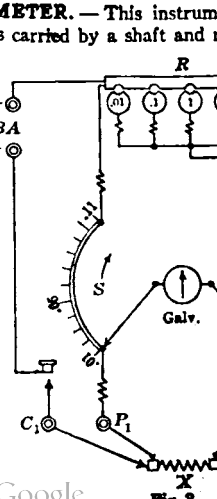


Fig. 3.

KELVIN BRIDGE OHMMETER (Fig. 3). — This is a portable type direct reading ohmmeter used for measuring low resistances.

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Current and potential leads are provided which are connected to the unknown resistance.

The two slide wires S and S_1 are mounted on the same disc and move together. The reading on a scale mounted on this disc gives the ratio of x/R. The reading multiplied by the value of R plugged in gives the value of x between potential points.

COST, RANGE AND ACCURACY. — Bridge type ohmmeters range in price from $60 for ohmmeters having a range of from 0 to 100 ohms and an accuracy of about 2 per cent to $80 for ohmmeters having a range from 0 to 10,000 ohms and an accuracy of ½ per cent. Meggers range in price from $225 for variable voltage meggers having a range of from 0 to 10 megohms and an accuracy of 5 per cent to $530 for constant pressure meggers having a range of from 10 to 2000 megohms and an accuracy of about 4 per cent. Kelvin bridge ohmmeters having a range of .0001 ohm to 11 ohms cost about $100. The above prices are approximate for the year 1921 and should be used only as a rough guide.

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OIL, TRANSFORMER. — (*See also Transformers; Circuit Breakers; Insulating Materials, Testing of.*) Oil is used in transformers, electrolytic arresters and feeder regulators as an insulating and cooling medium, and in oil-circuit breakers as an insulating and extinguishing medium. For these various uses, it must have certain general characteristics as follows:

(1) It must have high dielectric strength.

(2) It must have sufficiently high flash point to prevent its ignition during the opening of circuit breakers, and the failure of transformers, feeder regulators or electrolytic lighting arresters.

(3) Where oil is used for cooling purposes, it must have low viscosity to allow free circulation and must be free from deposit to prevent the obstruction of oil ducts.

(4) For use in oil circuit breakers it must have high viscosity to prevent undue splashing.

(5) For use in electrolytic arresters the oil should not emulsify with the electrolyte.

Mr. D. B. Rushmore gives the following as the characteristics of oil usually furnished with large, high-voltage, water-cooled transformers:

Flash point	130° C.
Burning point	145° C.
Freezing point	−15° C.
Color	white
Spec. gravity at 15.5° C.	0.830
Viscosity (Saybolt 40° C.)*	40

Dielectric Strength and Specific Inductive Capacity. — The dielectric strength of clean dry oil should not be less than twenty-two thousand (22,000) volts, when tested between one-inch disks set one-tenth (0.10) inch apart.

Oil in service, except in electrolytic lightning arresters, should be filtered when it fails to stand a pressure of sixteen thousand five hundred (16,500) volts when tested between one-inch disks set one-tenth (0.10) inch apart.

According to Tobey, the dielectric strength of transformer oil increases with increase of temperature, the increase from 30° to 90° C. being about 25 per cent.

On the other hand, the insulation resistance of oil decreases very rapidly as the temperature increases. In a typical test Tobey found the insulation resistance of a given sample to fall from 1200 megohms at 50° C. to 250 megohms at 90° C.

The specific inductive capacity of transformer oil is about 2.5 between 25 and 100° C.

Dryness and Purity. — Great care should be taken to keep the oil absolutely dry under all conditions. The presence of water in as small amount as one one-hundredth of one per cent is sufficient to impair seriously the dielectric strength of the oil.

Great care should be taken to remove from oil before it is used, foreign material, such as scale from iron drums, which may become dislodged during shipment; also to keep foreign material from entering the oil when the apparatus is in service.

The presence of mineral acid or of alkali in insulating oil is not permissible as they are corrosive or destructive in their action upon the materials of the apparatus. An oil practically neutral is preferable. It should contain no free sulphur, because sulphur in its free form attacks copper. All petroleum oils contain sulphur compounds, but in this form it is not objectionable.

* The time in seconds required for a certain definite quantity of oil to flow through a definite opening as measured with a Saybolt viscosimeter.

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Deposit or Sludge. — An oil for transformers and feeder regulators should be as free from deposit as possible. Deposit is objectionable primarily because it clings to the coil windings and fills the coil ducts, thus seriously affecting the cooling action.

The forming of deposit is a function of the temperature and length of time the oil has been used. Different grades of oil differ as to the temperature at which deposit will appear. A satisfactory oil should not show a deposit or any change other than a possible darkening of color when operated continuously under temperature conditions experienced during actual operation.

Pour Point or Freezing Point. — The pour point or freezing point is usually of no great importance, except for oil for apparatus where there is a movement of parts. The oil used in transformers, lightning arresters and regulators usually has a pour point of about 0° C. For outdoor installation of regulators and oil circuit breakers in extremely cold climates and all oil fuse cutouts and moving coil constant current transformers, the oil used should have a pour point of about −30° C.

PURIFYING AND DRYING. — All new oil as it is taken from the drums or tank cars, and all old oil that has been in use for some time, that shows the presence of sediment or dirt, should be filtered. In placing the oil in the transformer case it should be run in through about two thicknesses of finely woven cambric, which has been washed to remove all sizing and thoroughly dried.

The presence of large quantities of moisture in transformer oil is easily detected, since water is heavier than oil and will settle to the bottom, if allowed to stand. If not present in sufficient quantity to settle in this manner, the oil may still contain considerable moisture in a suspended state. If a sample of clean oil shows too low a dielectric strength, there is moisture present and the oil must be dried.

The best method of purifying oil is by means of one of the commercial filter presses produced by the various manufacturing companies. The oil is treated in a filter press by being forced through several layers of blotting paper which remove all moisture and solid matter held in suspension by the oil.

In filtering oil it is preferable to filter from one tank and discharge into another, as in this way the oil is given a more complete treatment than if drawn from the bottom and discharged into the top of the same tank. The latter method is, however, very useful in cases where apparatus cannot be removed from service long enough to empty it completely.

For satisfactory operation of the press, it is important to see that the filter papers are changed with sufficient frequency and are properly assembled. Only new clean filter paper should be used, and it should be thoroughly dried in an oven before being placed in the press. Filter paper will take up moisture from the air rapidly and must therefore be stored under dry oil in case it cannot be used directly from the oven.

If a drying outfit is not available, the oil may be dried in a fairly satisfactory, although slow and inconvenient manner, by passing it through clean, dry, unslaked lime and filtering afterward to remove all particles of foreign matter. Various other methods have been suggested or tried, but they are not to be recommended. For example, passing hot, dry air through the oil is not desirable because of the difficulty of removing all the moisture from the air, and the heating of the oil for a considerable length of time involves the liability of injuring it by such treatment.

TESTING. — The most important and frequently made test of transformer oil is the test for dielectric strength. Additional tests are: (*a*) viscosity, (*b*) flash point, (*c*) fire point, (*d*) pour point, (*e*) acidity, and (*f*) sulphur content.

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Complete directions for making all these tests are given in *A.S.T.M. Standards*, D 117-21 T.

The following brief description of the test for dielectric strength from Instruction Book 5094-B, published by the Westinghouse Manufacturing Company.

For testing oil for dielectric strength, use some standard form device such as that shown in Fig. 1. The gap terminals are flat d in diameter, with square edges. The standard gap setting is 0.10 inch.

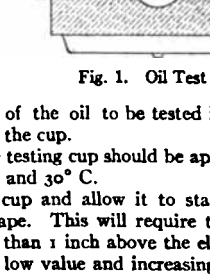


Fig. 1. Oil Test

The following precautions should be observed: Wipe out the testing cup with a clean, dry cloth, being careful to remove any particles of cotton fiber that may adhere to the surface. Adjust and fix the gap in its correct setting and then rinse the cup thoroughly with benzine or gasoline, being particularly careful to see that no particles of dirt remain. Then give a final rinsing with a portion of the oil to be tested before placing the testing sample of oil in the cup.

The temperature of both the oil and the testing cup should be ap the same and between the limits of 20° C. and 30° C.

Pour the test sample into the testing cup and allow it to sta minute air bubbles have had time to escape. This will require t minutes. The oil level should not be less than 1 inch above the el

Apply the testing voltage, starting at a low value and increasin the rate of approximately 3000 volts per second without opening until breakdown takes place. The testing transformer should hav of at least 1 k-va.

After each break, jar the testing cup but do not cause the oil to sufficiently to take up air bubbles. This will tend to loosen the carbonized oil from between the electrodes. Do not introduce any the oil for stirring, as it is likely to cause low breakdown voltages of introducing minute particles of foreign matter or moisture.

Repeat the application of voltage until five breakdowns have bee use the average value as the breakdown value of the test sample of

Sometimes a small, bright spark passes across the gap, but do an arc or cause circuit breaker or fuse to open the circuit. Such should be disregarded in recording results. They are not likely sufficient time is allowed for all air to escape before applying volta

The testing cup should preferably be used in connection with a voltage testing outfit, provided with suitable means for regulating voltage. If a testing outfit is not available, a generator and a high voltage transformer may be used, control of the testing vo obtained by variation of the generator field. If such an arrangeme high resistance (about 1 ohm for every volt of testing voltage) shou in series with the testing cup.

BIBLIOGRAPHY. — *Properties, Treatment, Inspection and Insulating Oils*, N. E. L. A. pamphlet, 1922 (from which a large article is taken); *Tentative Methods of Testing Transformer and* A. S. T. M. Tentative Standards, 1921; *Instruction Book*, 5094B, W Mfg. Co.; Tobey, H. W., *Trans. A.I.E.E.*, 1910, Vol. 29, p. 1189; *Determination of Moisture in Transformer Oils*, Electric, 82, p. 103, *lating Oils*, Inst. El. Eng. J., 54, p. 497, 1916.

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OSCILLOGRAPHS. — (*See also Braun Tube; Wave Analysis.*) The oscillograph is essentially a galvanometer of very short period. It is applied in the observation of potentials or currents, as voltmeter or ammeter, mainly when variations are too rapid to be indicated by the more usual instruments; for example in observation of potential waves of generators, potential and current waves in inductive apparatus, short-circuits or switching of transmission lines. As in many cases it is necessary to have two or more curves taken together in their relative phase relation, more than one element is necessary in a practical instrument; it is regularly built as a three-element oscillograph, giving one, two or three curves, as may be required, on the record. One element may be used as a chronograph by connecting it to record a timing wave from an a-c. source of known frequency.

Types of Oscillographs. — The most common form of oscillograph is the moving-coil type, the "coil" being two small thin strips or ribbons arranged very close together, thus forming the two sides of a coil of one turn. A moving iron vane can also be used, but this type has not received extended practical application. The electrostatic oscillograph, which is particularly well adapted for direct observation of high potentials, consists of two insulated strips maintained at a constant potential difference, these strips being caused to vibrate by the varying force of attraction and repulsion due to the charges on two fixed plates connected to the varying high-potential source. The vibrator is similar in construction to the vibrator of the ordinary oscillograph, except that the two strips are connected by a light insulating thread. The strips are connected to the terminals of a storage battery, the middle of which is kept at a potential midway between the potential of the two plates, by being connected between two equal condensers in series across the attracting plates. Still another form of oscillograph is the cathode ray, or Braun, tube (*see Bibliography for references*). This last type of oscillograph finds its most valuable application in the laboratory study of high-frequency and high-voltage phenomena which are beyond the range of the ordinary oscillograph. The practical application of this type has been found rather difficult.

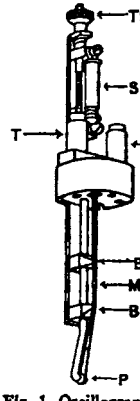


Fig. 1. Oscillograph Vibrator. B, B_1 bridges for supporting strip; P, pulley; SB, spring balance indicating tension; TS, tension screw; M, mirror

DESIGN OF MOVING-COIL OSCILLOGRAPH. — The ordinary or moving-coil oscillograph is described in detail below.

Construction of Vibrator. — The vibrator, or moving element (Fig. 1), consists of two strips of flattened wire stretched over bridges, with a very small mirror cemented directly to the strips; the arrangement constitutes a one-turn galvanometer coil of elementary form. The vibrator is placed between the wedge-shaped poles of an electromagnet or of a permanent magnet. It is immersed in a liquid which provides critical damping. The vibrator conductor passes from one terminal post T over the bridges BB_1 in narrow grooves, over a pulley P, back over the bridges in grooves very close to the former, to the other terminal post T_1. The width of the strip is usually 0.005 inch to 0.007 inch. The mirror M is cemented to the strips midway between the bridges, its usual size being 0.060 inch by 0.017 inch. Tension is applied to the strips, for the ordinary vibrator 6 oz. for the two strips, indicated by a small spring balance SB. The vibrator is readily rewired in case of break or burn-out.

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For efficient operation vibrators are made interchangeable. This is necessary to make expeditious operation possible, and to minimize delay due to accidental destruction of vibrator parts.

Construction of Field Magnets. — The galvanometer field is an electromagnet with wedge-shaped poles. The vibrator is so mounted that the strips lie in the narrow air gap between these poles. A direct current through the winding of the electromagnet produces a very strong field in this air gap. The ampere turns of the electromagnet are sufficient to saturate the pole tips and render the strength of the field practically independent of the voltage applied to the electromagnet windings, at least for ordinary voltage variations. One terminal of the vibrator may be connected electrically to the core of its field magnet, each core being insulated from its field winding for a working pressure of 2300 volts.

A permanent magnet can be substituted for the electromagnet as the oscillograph field. This construction is practicable for two elements. The permanent magnet oscillograph is somewhat inferior in sensibility, and greatly inferior in insulation between elements, compared with the electromagnetic type of oscillograph.

Optical System. — The light for the oscillograph from a projection arc lamp enters the case at the shutter aperture, and, after being reflected toward the vibrator cell by a total reflecting prism (one for each element), passes through a slit which adjusts the width of the image. It is then reflected by the small vibrator mirror, and passes through a cylindrical lens to the image on screen or film. Very careful adjustment of the optical system is essential to secure records of good photographic intensity.

The arc lamp used as a source of light for the oscillograph is usually a hand-feed lamp with small carbons at right angles, taking 5 to 8 amperes, with *solid positive* carbon in the horizontal position. The light is rendered parallel by a simple projection lens. Any convenient arc lamp, however, may be used with good results. If only an a-c. source is available for the arc, records of fluctuating intensity are obtained, which, however, are usually legible throughout their length. Sunlight source with a heliostat, when circumstances permit, gives photographic records of superior intensity.

The astigmatic optical system of the oscillograph, due to the cylindrical lens, is quite a distinctive one; the geometrical light source for the image in the vertical direction is the adjustable slit, in the horizontal direction it is the vibrator mirror.

Means for Obtaining Photographic and Visual Records. — The photographic record is taken on a moving film or plate. The most practical arrangement is a film, having a length of about 12 inches, on a drum driven at suitable speed by a small motor. A contactor opens the shutter for one revolution of the drum, giving exposure once over the film. The exposure can be adjusted to start at the beginning of the film, or if a record is taken in response to a signal, as of switching or short-circuit, the exposure can be started instantaneously at any part of the film. A long film is desirable in some cases, as in transmission line switching, where the whole disturbance lasting perhaps several seconds is to be taken. By the use of a suitable attachment for long films, records can be taken on films 3 to 5 feet in length.

The motion of the spot of light reflected from the vibrator mirror may be projected as a standing wave on a tracing table, for examination or demonstration. An oscillating mirror, actuated by a cam driven by a small synchronous motor, is given a uniform angular velocity during alternate cycles of the current or voltage observed, and draws out the wave longitudinally. Only alternate waves or cycles are utilized, the intervening waves being cut off by a revolving screen on the motor shaft during the return motion of the mirror. The recur-

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rences of the waves are so rapid as to produce an image sensibly continuous to the eye. The synchronous mirror is removed by shift of a simple mechanism to permit photographic record to be taken in the usual manner by revolving film.

Free Period of Vibrator. — The free period of the vibrator is about 1/6,000 second, but some have been constructed to have a free period as high as 1/10,000 second. The higher the free period the less the distortion of the higher harmonics in the current and voltage waves. A free period of 1/6,000 second, is ample to secure practically accurate values of all harmonics having a frequency of less than 1200 cycles per second; with a free period of 1/10,000 second harmonics having a frequency as high as 2000 cycles per second are recorded with practical accuracy.

The free period of a vibrator depends upon the moment of inertia of the vibrating system and upon the tension on the strips; the less the moment of inertia and the greater the tension, the shorter will be the free period. The free period of a given vibrator may therefore be slightly shortened by increasing the tension on the strips, but this in turn decreases the sensibility, i.e., the deflection for unit current through the strips.

To measure the free period of a vibrator it is placed in the cell between the poles of magnet, in the usual way, but with no damping liquid in the cell. It is connected to a d-c. source through an interrupter which makes or breaks the circuit one or more times during the exposure of a film running at as high a speed as possible. The free vibration in decreasing amplitudes is shown on the film, and the period is readily counted, the film speed being known.

Sensibility of Oscillograph. — An oscillograph having a free period of 1/6,000 second requires from 0.1 to 0.2 ampere through the vibrator to give a curve of good amplitude; or about 0.006 ampere is required to give a millimeter deflection from the zero line on the film or tracing table. As ordinarily constructed a deflection of 45 mm. on each side of the zero may be obtained, but a deflection of more than 30 mm. is seldom necessary. The resistance of the vibrator is from 1 to 1.5 ohms; hence to obtain a deflection of 30 mm. about 0.2 volt is required across the vibrator terminals. The sensibility of a vibrator may be much increased by using thinner strips and smaller mirrors, but such arrangements are more delicate and should be used only to meet special requirements.

CONNECTIONS AND ADJUSTMENTS. — For potential, or voltage, curves the oscillograph is connected similarly to a voltmeter; E in Fig. 2. A suitable amplitude of curve is obtained by an external adjustable resistance.

For current curves the oscillograph is connected similarly to a millivoltmeter across a non-inductive shunt; I in Fig. 2. A shunt potential drop of at least 0.1 volt is required, but for convenient adjustment it should be larger, 0.5 volt being a suitable value where practicable. If the current measured is less than 0.2 ampere, no shunt is used, the whole current being taken by the vibrator.

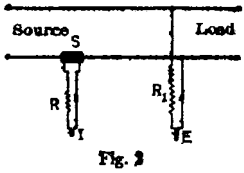


Fig. 2

For waves of flux distribution in generators or motors, the oscillograph is connected to give the voltage of an exploring coil; sometimes in d-c. machines the voltage between commutator bars can be used.

Potential and current transformers are used where the line voltages and currents are too high for practical or convenient direct observation. The oscillograph potential circuit can be connected to the potential transformer along with voltmeter or other instruments, as it is only a fraction of the rated

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potential transformer load. For current curves a shunt is connected in the current transformer secondary circuit.

Adjustment of Vibrator and Optical System. — Individual vibrators are provided with movements for vertical and horizontal adjustment of the image. The beam of light is brought vertically to the middle, or axis, of the cylindrical lens; this adjustment is left unchanged, but should be examined occasionally to insure its correctness; this may conveniently be done by viewing the position of the light spot on a thin sheet of paper held against the case where the light comes through to form the image on film or ground-glass screen; the light spot should appear central in the aperture. The horizontal adjustment brings the image to the proper position on the record, and is changed freely according to circumstances. When two curves are to be taken on the record, the images are usually placed for clearness so as not to overlap. If, however, the phase relation is important they are placed with their zero positions near together; it is better not to make them coincident, however, as good superposition is not always secured. After the principal exposure, an auxiliary exposure for zero line is taken with vibrator circuit opened, except in occasional records where the zero line is unnecessary.

Quantitative Measurements with Oscillograph. — The values of the curves may be obtained quantitatively when necessary by reference to a d-c. measurement. For potential curves an observation is taken of a d-c. source of known voltage; for current curves similarly an observation is taken of a measured d-c. current. During these d-c. measurements the resistances in the vibrator circuit should be the same as used during the observations. If a number of observations are taken at different resistances, two or three d-c. calibrations can be made with known resistances, and the calibration for the other resistances computed, assuming the deflection proportional to the total resistance of the vibrator circuit. When potential and current transformers are used, the voltages and currents as directly measured are reduced to terms of line voltages and currents by the transformer ratios. In case of short-circuit currents, where it is not practicable to obtain d-c. currents comparable in amount with those of the observation, a measured d-c. voltage, as from dry cells, can be applied to the oscillograph leads detached from the shunts, the corresponding currents being computed from the shunt resistances.

In many cases, the curve is self-calibrating, a portion of the curve being at a constant d-c. value which can be measured by d-c. instruments, as for instance on generator-field voltage and current curves of short-circuits.

COST OF OSCILLOGRAPH (Pre-war cost). — An oscillograph complete with a three-element electromagnet galvanometer, optical system, shutter and shutter-operating mechanism, motor and countershaft, photographic and tracing attachments, six film-holders, and the following repair parts: 6 extra suspension strips; 6 vibrator mirrors, 1 box special gold-leaf fuses, 1 bottle mirror cement, 1 bottle damping liquid, costs about $650.

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PAPER, IMPREGNATED. — (*See also Insulating Materials, Wires and Cables, Insulated.*) Wires and cables may be insulated by winding paper ribbon helically around the conductor in successive layers until the desired thickness of insulation is obtained. The paper-covered cable, after being thoroughly dried in a hot vacuum dryer is immersed in oil until saturated, and then passed through a lead press, which covers it with a continuous sheathing of lead. The paper serves the triple function of affording a conveyance for the oil, adding to the insulating value of the oil, and being a mechanical separator between the conductor and sheath.

THE PAPER. — The most commonly used paper for such cables is that made of Manila hemp or musa textilis, a fiber grown in the Philippine Islands for rope making. The original fibers are about 6 millimeters long and have a diameter of 0.024 millimeter but the length is materially decreased in the process of beating described below. The paper made from this fiber is not necessarily the best for cable insulation, but the fact that it has stood the test of twenty years use, makes American manufacturers slow to try others. Hemp papers are often called Manilas, and at the present time mixtures of hemp and musa have come into general use, a common proportion being one of hemp and two of musa. Jute is sometimes added, but as it is not permanent and adds nothing to the strength, it should be avoided. German manufacturers are using paper containing long fiber wood-pulp in large quantities or even made exclusively of such wood-pulp, and claim that they are better than Manila papers (C. Beaver). American manila paper used for cables is made of old Manila rope.

MANUFACTURE OF THE PAPER. — The process of manufacturing Manila paper is as follows: The fibers are cut up, placed in a boiler with lime and caustic soda and boiled under a pressure of from 30 to 50 pounds for between 5 and 10 hours. They are then emptied out, washed free of alkali and put in a beaker where the fibers are partially disintegrated and washed. Sometimes bleaching is performed at this stage, by adding a solution of chloride of lime and again washing. The material is then put into the beater, where it is reduced to the condition necessary for the paper machine. After suitably diluting the material it is passed over sand tables, where gritty matter is deposited and then through strainers, where any coarse particles are retained. It then passes in a continuous flow to the endless wire of the Fourdrinier machine, where the fibers are deposited in the form of a sheet; then to the couch rolls and to the press rolls, where the water is squeezed out. Finally it passes over a series of drying cylinders where it emerges dry and is taken upon reels.

NECESSARY PROPERTIES OF THE PAPER. — The paper should have the following qualities.

1. Porosity, in order that it may hold a large amount of oil.
2. Strength and elasticity, in order that it may not break either while being wound or while suffering shrinkage in the desiccator or while being installed. Impregnation with oil should not impair the strength.
3. Freedom from excess of mineral matter, not only to give greater porosity but to avoid electrical weakness.
4. Freedom from alkalies, in order that the impregnating oils shall not be saponified.
5. Freedom from metallic salts, such as chlorides and sulphates, in order to avoid short-circuiting the oil by an electrolyte and also to avoid injuring the conductor.

STRENGTH OF THE PAPER. — The tensile strength of Manila rope paper is usually about 6000 pounds per square inch, and the elongation at the

breaking-point is about 3 to 4 per cent. The resistance to folding and to tearing are, however, much more important than the resistance to straight pulling, but as no standard methods of test have been agreed upon, it is not practicable to give average values for these quantities. The tearing strength of paper 8 mils thick is between 6 and 18 ounces, depending upon its humidity. The maximum strength is obtained with about 12 per cent of moisture.

OIL FOR IMPREGNATING. — Two classes of oils are used for impregnating the paper, rosin oil containing rosin in solution, and a special grade of carefully dried mineral oil or petrolatum, with or without rosin and other substances in solution. The rosin oil has higher dielectric strength at low temperatures, but does not maintain it at high temperatures; furthermore it occasions greater dielectric losses, an important consideration in high voltage cables.

SPECIFIC RESISTANCE. — The specific resistance of impregnated paper, depends upon its dryness and upon the nature and quantity of the substances dissolved in the oil. The value of K in the formula $M = K \log \frac{D}{d}$ (see article on rubber) varies from 500 to 1500, the usual value being about 800.

POWER FACTOR. — The power factor depends greatly upon the temperature, the dryness and the resistivity of the impregnating compound. In the case of paper impregnated with petrolatum compound, the accompanying values are typical.

Temperature, deg. C.	Power factor, per cent	
	Minimum	Maximum
40	0.4	2.5
60	0.9	7.5
75	1.5	13.0
80	1.7	15.0
85	2.0	18.0
100	3.4	30.0

TEMPERATURE COEFFICIENT OF RESISTANCE. — The effect of temperature changes upon the resistance of oiled paper is greater than upon rubber and less than upon varnished cloth. The table below is representative of a typical paper insulation, but the properties of different makes vary considerably.

DIELECTRIC STRENGTH. — The dielectric strength of impregnated paper insulation is a very indefinite quantity. It is greatly reduced by crinkling and by the presence of moisture and it decreases rapidly with increasing temperature. The dielectric strength across the cellulose fiber is much greater than along them. It is therefore not surprising to find different experimenters reporting widely different values of this quantity. Thus, E. Jona says that the average commercial impregnated paper subjected to electric stress for an hour with progressingly increasing potential, will stand from 8 to 10 kilovolts (effective a-c.) per millimeter and that it is not uncommon to find samples with 20 or 30 per cent greater dielectric strength. E. J. Berg gives 250 to 300 kilovolts per inch, or 10 to 12 kilovolts per millimeter. P. Human says that high-grade

Temperature °F.	Per cent of resistance at 60°
60	100
65	62.5
70	42.6
75	30.0
80	23.3
85	18.5
90	15.2

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impregnated paper will stand 20 kilovolts per millimeter. The usual testing strength H, in the formula

$$H = \frac{E}{r \log_e \frac{R}{r}}$$

is about 4 kilovolts per millimeter or 100 kilovolts per inch, but the validity of this formula when applied to paper saturated with ionizable oils is very doubtful. F. Fernie (Beauia, Sept., 1921), says that the failure of single-conductor impregnated paper cables occurs when the stress *at the sheath* is about 100 kv. per cm. as calculated by the formula

$$H = \frac{E}{R \log_e \frac{R}{r}}.$$

In the case of triplex sector cables, failure occurs when the average stress between conductors exceeds about 100 kv. per cm. When impregnated paper is punctured electrically, the paper itself chars, so that even though the oil tends to flow into and repair the gap, the short-circuit is maintained (*see Wires and Cables, Insulated*).

SPECIFIC INDUCTIVE CAPACITY. — The specific inductive capacity of dry Manila paper (without oil) is from 1.7 to 1.8 while that of Manila paper impregnated with petrolatum compound is between 2.75 and 3.5 at ordinary temperatures, when measured with alternating current.

SPECIFICATIONS. — Specifications for impregnated paper insulation for wires and cables will be found in the article on *Wires and Cables, Insulated*.

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PERMUTATIONS AND COMBINATIONS. — (*See also Factorials.*) Each of the *arrangements* which can be made by taking some or all of a number of things is called a permutation.

Each of the *groups* or *selections* which can be made by taking some or all of a number of things is called a combination.

The number of permutations of n things taken r at a time is

$$n(n-1)(n-2) \ldots (n-r+1).$$

The number of combinations of n things taken r at a time is

$$\frac{n(n-1)(n-2) \ldots (n-r+1)}{r(r-1)(r-2) \ldots 3.2.1}.$$

The number of combinations of n things taken r at a time is equal to the number of combinations of n things taken $(n-r)$ at a time.

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PHASE CONVERTERS AND PHASE BALANCERS. — (*See als Generators, Alternating-current; Motors, Polyphase Induction; Motors, Syn chronous; Transformers.*) — A phase converter is a machine for convertin single-phase power into polyphase power, or vice versa. A phase balancer is machine for balancing the load on one or more polyphase generators when thes generators are supplying an unbalanced load to the circuit to which they ar connected.

PHASE CONVERTER. — The phase converter is a single unit two-phas induction motor, or a two-phase synchronous motor with an extra heav squirrel cage.

Polyphase to Single-phase Conversion. — It is well known that a two phase induction motor or synchronous motor after once started will continu to run on one phase. The disconnected phase of the motor may be used as source of single-phase power. The voltage and current of this phase are nearl 90 degrees displaced from the voltage and current of the phase connected t the supply.

In order to change from two-phase to single-phase the connections shown i Fig. 1 are used. Phase *A* of the converter is connected across one phase of th supply and phase *B* in series with the load across the other phase. The voltage of *B* adds to the voltage of the supply, making the total voltage at the load $2V$. When the current in the load is I the volt-amperes in *B* are VI, and the volt-amperes in phase *A* are approximately VI. The volt-ampere capacity of the machine must equal the volt-amperes of the load. If the current or the power-factor of the load changes, the currents and power-factors of phases *A* and *B* of the machine change an almost equal amount. The action of this machine is entirely automatic, no complicated regulators being required to control its action.

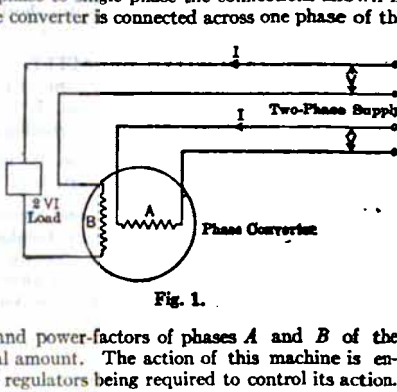


Fig. 1.

The machine is started as a quarter-phase induction motor, and after it is up to speed one of the phases is reversed and connected to the supply in series with the load. The converter is located near the single-phase load. The phase converter is well adapted to supply electric furnaces or electric welding outfits with single-phase power from polyphase systems.

Single-phase to Polyphase Conversion. — The Norfolk and Western Electric Locomotives receive single-phase power through a single trolley. Three-phase induction motors are used to drive these locomotives. The connecting link between the single-phase and polyphase system is a two-phase induction motor operated as a phase converter. The connections to change from single-phase to an approximately balanced three-phase system are shown in Fig. 2.

The machine is driven by power supplied to phase *A*. Phase *B* corresponds to the teaser coil of a transformer T-connection. This phase has an e.m.f. induced in it of the proper magnitude and phase position to make the voltages across the three phases approximately balanced.

The phase converters on the Norfolk and Western are started by single-phase commutator motors. The operating speed of the converter is high, permitting a design of minimum weight for a given output. The converter is

addition to furnishing power to polyphase motors may be used to drive auxiliary apparatus. Polyphase motors receiving their power from phase converters may be used for regenerative braking.

PHASE BALANCER (Fig. 3). —The so-called shunt phase balancer consists of a large and a small unit mounted on the same shaft. The large unit has the same capacity as the unbalanced load, and resembles a synchronous motor, with an extra heavy squirrel cage attached to the rotor. The small unit has an ordinary polyphase winding on the stator, and two separate windings displaced 90 electrical degrees on a cylindrical rotor. The rotor for the small machine is wound for the same number of poles as the large unit. The strength and position of these poles is determined by relative amounts of the excitation furnished by two exciters connected to the separate rotor windings.

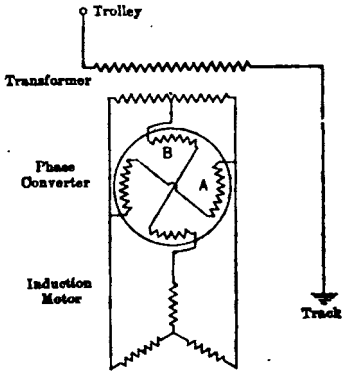


Fig. 2.

The stator windings of the two units have the same current rating and are connected in series in opposite phase rotation as shown in Fig. 3.

The phase balancer connected in this way to an unbalanced polyphase system will, if properly adjusted, take balanced current from the system and enable the main generators to deliver balanced currents. This machine will automatically and almost instantly balance any single-phase load, at any power-factor, on any phase, provided the net unbalancing is within the capacity of the machine. It is well adapted to cases where a large single-phase load is taken from polyphase generators for traction purposes. For example, the Philadelphia Electric Co. furnishes single-phase power to the Paoli Division of the Pennsylvania R.R. The outputs of the polyphase generators are balanced by two 5000 kv-a. phase balancers.

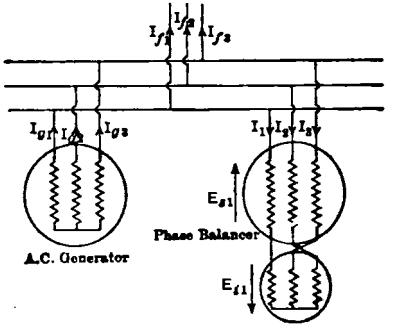


Fig. 3.

The currents taken by a phase balancer can be resolved into "synchronous" and "inverse" components. The synchronous components have the same phase rotation as the bus-bar voltages and are required to keep the machine turning. The inverse components have a phase rotation opposite that of the bus-bar voltages, and are responsible for the balancing action.

It is well known that the addition of an unbalanced polyphase load to a

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balanced polyphase load of inverse phase rotation results in a balanced polyphase load. With respect to the synchronous component of the current the large unit acts like a synchronous motor. By proper excitation the synchronous component can be made small and of negligible value compared to the inverse component. With respect to the inverse component of the current the large unit acts like a motor generator. That is motor and generator action takes place in the same machine. The large unit of the phase balancer with inverse currents flowing through it serves as a medium for transferring power from the under-loaded phases of the system to those which are overloaded. The net power input to the phase balancer due to the inverse currents is zero.

Inverse currents flowing through the armature of an ordinary synchronous motor would encounter considerable impedance. To reduce this impedance the large unit is equipped with a heavy squirrel cage on the rotor. The small unit assists in the circulation of the inverse currents through the balancer. In fact the e.m.f. generated by this unit overcomes the total impedance drop in the balancer due to these currents. This drop is small compared with the supply voltage, and accounts for the lower voltage rating and smaller capacity of the small unit.

Value and Phase Position of Currents in Balancer. — The magnitude and phase position of the inverse currents required to balance an unbalanced polyphase system depends on the magnitude of the unbalancing. If I_{f1} and I_{f2} represent the feeder currents in two of the feeders in Fig. 3, the value of inverse current required to balance the system, in vector notation, is:

$$\dot{I} = \frac{-j\rho^2 \dot{I}_{f1} + j\dot{I}_{f2}}{\sqrt{3}},$$

where

$$\rho = \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right).$$

The vector diagram showing the relation between the supply voltages, feeder currents and inverse currents is given in Fig. 4.

The value of the inverse current taken by the balancer is also equal to $\frac{E_4}{Z}$, where E_4 is the e.m.f. of the small unit and Z is the impedance of the balancer to the inverse currents.

If the load on the unbalanced system changes, the value and the phase position of the inverse currents are likely to change. It is evident that automatic regulators in the field of the small unit must not only regulate the magnitude of the induced e.m.f., but also its phase position with respect to the bus-bar voltages. The magnitude of the e.m.f. of the small unit is determined by the current in the rotor (field) windings, and the phase position of the e.m.f. is determined by relative values of the currents in these windings. The entire action of the small unit is controlled by two special voltage regulators. The regulators in the Philadelphia Elec-

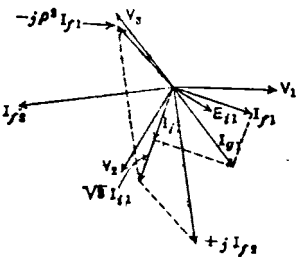


Fig. 4.

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tric installation each control a 1.6 kw. exciter and each small exciter controls a 50 kw. exciter.

The phase balancer is comparatively easy to operate. It may be brought up to speed by induction motor action. When started in this way a special switch must be provided to change the connection between the machines, so they will have the same phase rotation, and a proper starting resistance must be inserted in the rotor of the small unit.

The phase balancer may be installed in the power house or placed anywhere along the line. A phase balancer when installed should be protected from short circuits by suitable relays and circuit breakers. The impedance of a phase balancer to inverse currents is very small and a short circuit on one of its phases might ruin an unprotected machine.

Rating, Dimensions and Weight of the Phase Balancers of Philadelphia Electric Co. — Large unit 5000 kv-a. 6-pole, 13,200-volt, 3-phase, 25-cycle, 219 amperes.

Small unit 550 kv-a., 6-pole, 840-volt, 3-phase, 25-cycle, 219 amperes.

One of these balancers will balance 5000 kv-a. continuously, 6000 kv-a. for one hour, and 12,000 kv-a. for 5 minutes.

Weight of complete set 172,660 pounds.

Overall dimensions, 20 feet 9 inches by 12 feet 2 inches by 10 feet 1 inch high.

COMPARISON OF METHODS FOR OBTAINING SINGLE-PHASE POWER. — A power company furnishing single-phase power to its customers can do it in the following ways:

1. By a single-phase alternator driven by a steam turbine.
2. By a single-phase alternator driven by an induction motor.
3. By a phase converter connected to a polyphase supply.
4. By taking single-phase directly from the bus-bars of a polyphase system and balancing the generator outputs with a phase balancer.

Method 1 is reliable, but not very economical, because it is an established fact that it is cheaper to generate polyphase power than single-phase power. Method 2 has the disadvantage that the single-phase system is not independent of the polyphase system. Method 3 is good where the load is sufficient to permit the purchase of the converter. This method does not enable power-factor correction. Method 4 is most flexible, because the single-phase load can be taken from any phase. With this method power-factor correction is possible, but has the disadvantage of requiring expensive regulating apparatus.

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PHOTOMETRIC QUANTITIES. — (*See also Illumination, Laws of; Photometry; Vision, Laws of.*) The names and sense of the common photometric units are conventional, though a uniform value of the basic unit of the system, viz., the international candle, was established in 1909 by the national standards laboratories of Great Britain, France and the United States. The standard unit in Germany is the Hefner unit, but the relation that 1 Hefner unit equals 0.9 international candle was officially recognized. The terminology and definitions that follow are in agreement with those recognized by the Geneva Congress in 1896 and the proposals made by the Committee on Nomenclature and Standards of the Illuminating Engineering Society in 1912 (*Trans. Ill. Eng. Soc., Vol. 7, p. 723. See also Standardization Rules of the A.I.E.E.*)

LIGHT FLUX is a measure of the rate of flow of light from a luminous body. It is not identical with the flow of radiant energy but is an evaluation of radiation in terms of the corresponding light sensation. Light flux is proportional to two factors, power radiated and a stimulus coefficient K_λ. The stimulus coefficient varies with the wave-length of radiation as shown in Fig. 1 in the article on *Vision, Laws of.* (*See also Phil. Mag., Vol. 24, p. 853.*)

Lumen. — The lumen, or unit of light flux, denotes the light radiating within one steradian from a source having a uniform luminous intensity of one candle. The steradian, or unit solid angle, is the angular space subtended at the center of a sphere by a portion of its surface equal to its radius squared. An entire sphere includes 12.5664 steradians and a hemisphere 6.2832 steradians. The symbol for luminous flux is F, that for luminous intensity I, and that for steradians ω. The following relations hold:

Flux in any solid angle,	$F = \int I \, d\omega$;
Total flux from source,	$F_s = 12.5664\, I_{ms}$;
Flux in lower hemisphere,	$F_{lh} = 6.2832\, I_{mlh}$;
Flux in upper hemisphere,	$F_{uh} = 6.2832\, I_{muh}$;
Flux in any zone	$F_z = \omega_z\, I_{mz}$;

where the I's have the designations given in the following paragraph.

LUMINOUS INTENSITY, commonly termed candle-power, denotes the solid angular density of light flux emitted in the direction considered, or

$$I = \frac{dF}{d\omega}.$$

Although luminous intensity refers in the strict sense to a single direction, mean intensities within certain limits are widely used. The following designations are employed in this article and also the articles on *Illumination, Laws of,* and *Photometry.*

Mean horizontal intensity,	I_h.
Mean spherical intensity,	I_s.
Mean zonal intensity,	I_{mz}.
Mean upper hemispherical intensity,	I_{muh}.
Mean lower hemispherical intensity,	I_{mlh}.

International Candle. — The international candle is the official unit of luminous intensity in France, Great Britain and the United States. The Hefner unit, which is standard in Germany equals 0.9 international candle. For further discussion of photometric standards see *Photometry.*

Distribution Curves. — The luminous intensities at various angles about a light source are commonly represented by polar curves of horizontal and vertical

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distribution. Caution should be observed in interpreting such curves. The mean horizontal intensity is equal to the mean polar radius of the curve of horizontal distribution. The mean polar radius and the inclosed area of the curve of mean vertical distribution are entirely lacking in significance. For methods of computing mean intensities from vertical distribution curves, see *Illumination, Laws of.*

Spherical Reduction Factor. — This factor is the ratio of the mean spherical intensity of an illuminant to its mean horizontal intensity.

ILLUMINATION denotes the density of light flux intercepted by a surface or traversing an area in space. The unit of illumination corresponds to unit flux per unit area and is commonly one lumen per square foot, or foot-candle. The metric unit of illumination is the meter-candle, or lumen per square meter, sometimes called the "lux." Based on a suggestion by Blondel, the unit of one lumen per square centimeter is designated by the title "phot." One foot-candle is 10.764 meter-candles and one meter-candle is 0.0929 foot-candle.

For methods of measuring illumination see *Photometry;* for the calculation of illumination, see *Illumination, Laws of;* for values of illumination required for various purposes, see *Vision, Laws of.*

INTRINSIC BRILLIANCY OF COMMON ILLUMINANTS

Illuminant	Candles per sq. in.	Candles per sq. cm.
Crater, carbon arc	84,000	13,000
Magnetite arc	4,000	620
Nernst glower	3,010	470
Incandescent electric lamps:		
Tungsten, 1.25 watts per c-p	1,060	164
Graphitized carbon, 2.5 watts per c-p	750	120
Tantalum, 2 watts per c-p	580	90
Carbon, 3.1 watts per c-p	485	75
Carbon, 3.5 watts per c-p	400	63
Acetylene flame, 1-foot burner	53	8.2
Acetylene flame, 0.25-foot burner	33	5.1
Welsbach mantle	31	4.8
Welsbach mantle, mesh	56	8.7
Mercury arc	14.9	2.3
Kerosene flame	9.0	1.4
Gas flame	2.7	0.4
Frosted tungsten lamp, tip	1.67	0.26
Frosted tungsten lamp, side	6.0	0.93

BRIGHTNESS OR INTRINSIC BRILLIANCY is the luminous intensity per unit area of a surface projected on a plane normal to the line of sight. It is measured in candles per square inch or per square centimeter of projected area. Let b denote surface brightness, S the area and θ the angle between the normal to the surface and the line of sight, then

$$b = \frac{dI}{dS \cos \theta}.$$

The specific luminous radiation is closely akin to surface brightness as it denotes the flux emitted per unit area. If the emission agrees with the cosine

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law the specific luminous radiation E' and the surface brightness normal to the surface b_0 bear the relation

$$E' = \pi b_0.$$

The brightness of illuminated surfaces is conveniently expressed in lumens emitted per square foot, but this should be clearly distinguished from illumination, or lumens received per square foot.

Mean values of brightness or brilliancy of various illuminants are given in the preceding table (*Ives and Luckeish, Elec. W., Vol. 57*).

The presence in the field of view of illuminants of high brilliancy depresses to a marked degree the sensibility and acuity of vision. The upper limit of brightness consistent with best vision has been variously estimated between 4 and 7.5 candles per square inch. (*See Glare in article on Vision, Laws of.*) For method of measurement of surface brightness see Ives and Luckeish, *ref. cit.*

REFLECTION OF LIGHT. — Reflection is regular or diffuse according as the reflector is a polished surface or a matte. Regular reflection is characterized by equal angles of incidence and reflection, the formation of images and the invisibility of the reflecting surface. Diffuse reflection scatters light in all directions, produces no images and renders the reflecting surface luminous. The intensity of light reflected by a perfect matt surface varies in proportion to the cosine of the angle of departure from the normal, and the total flux reflected equals π times the normal intensity. However, some regular reflection always accompanies diffuse reflection and these laws can be applied only approximately. Fair diffusing plates can be prepared from barium sulphate, magnesium oxide or other white materials of extremely fine and even grain. Opal glass with both surfaces carefully depolished is fairly satisfactory for diffuse reflection and transmission of light. Wall coverings of paper, plaster, fabric, paint and kalsomine deviate considerably from the cosine law of diffusion and its corollary and caution must be observed invariably in applying these laws to calculations of illumination. All materials not white, gray or black are selective and vary in their reflecting power with the spectral composition of the light received.

The following approximate values of reflection factors have been collected from various sources and are useful in calculations dealing with reflected light:

Reflector	Factors	Reflectors	Factors
Polished silver	0.92	Orange yellow paper	0.34
Silvered mirror	0.80	Light green paper	0.25
White blotting paper	0.80	Light pink paper	0.25
White bond paper	0.75	Light blue paper	0.18
White kalsomine	0.75	Medium blue paper	0.12
Flat white paint	0.66	Dull green paper	0.08
Chrome-yellow paper	0.62	Light red paper	0.10
Cream paper	0.56	Medium red paper	0.08
Flat cream paint	0.53	Medium brown paper	0.08
Flat ivory paint	0.50	Deep red paper	0.06
Light buff paper	0.45		

The above values refer to light having the spectrum of commercial incandescent illuminants. In general flat paints are slightly below papers of the same tone in reflecting power, whereas glossy paints exceed papers by 0.10 to 0.15 on account of regular reflection.

For further information on brightness values and on the percents of reflected

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light from various surfaces see "Principles of Interior Illumination" by Cravath, Harrison and Pierce, and "Modern Lighting Accessories," by W. F. Little, *Illuminating Engineering Practice*, 1916 Lectures, I. E. S.—U. P.

A device for the measurement of diffuse reflection factor applying to matte surfaces which follow Lambert's law fairly closely, is described by Nutting, *Trans. Ill. Eng. Soc., Vol. 7, p. 412.* The more satisfactory method however, is that in which the integrating sphere is used.

TRANSMISSION OF LIGHT.— Transmitting medias possess qualities quite analogous to reflecting surfaces with respect to regular and diffuse transmission and selective absorption depending on color. The absorption of light in the varieties of glassware most used in the lighting art is approximately as follows (*see Trans. Ill. Eng. Soc., Vol. 6, p. 98*):

Kind of glass	Absorption in per cent	Kind of glass	Absorption in per cent
Clear	5–12	Ground	20–30
Light sand blast	10–20	Medium opalescent	25–40
Alabaster	10–20	Heavy opalescent	30–60
Canary	15–20	Flame	30–60
Light blue alabaster	15–25	Signal green	80–90
Heavy blue alabaster	15–30	Ruby	85–90
Ribbed	15–30	Cobalt blue	90–95
Opaline	15–40		

It should be remembered in interpreting the values in this Table, that the absorption percentages are, in reality, 100 per cent less the transmission, which in itself, does not represent true absorption, but loss by reflection and absorption taken together. For example, the true absorption of clear glass is probably in the neighborhood of 1 per cent or less, depending upon its thickness, but losses take place also by reflections of the incident light away from the surface, which make the apparent absorption percentages higher, as in the above table.

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PHOTOMETRY. — (*See also Illumination, Laws of; Vision, Laws of; fo definitions of quantities and symbols see Photometric Quantities.*) Photometr is the science of light measurement. Its chief aspects are the determination o (*a*) the intensity of light sources in definite directions, (*b*) mean vertical ligh distribution, (*c*) the mean intensity and light flux emitted within specifie limits of distribution, (*d*) the illumination of surfaces, (*e*) the reflecting prope ties of surfaces and (*f*) the analysis of the color of light. Its methods are es sentially visual and consist in equating the brightness of two diffusing surface As an instrument of physical measurement the eye lacks precision as an estimat ing device, but serves well in the judgment of equality. Photometric devic are of four general types, according to the method of comparison employed, viz (1) by equality of brightness of two surfaces visible simultaneously, (2) b equality of contrast between two pairs of surfaces differing slightly in brightnes (3) by the disappearance of flicker when two surfaces are viewed in rapi alternation, and (4) by acuity of vision. The latter process does not admit precision and is used only for rough comparisons.

Methods of Obtaining Photometric Balance. — The methods of obtai ing photometric balance are: (1) varying the distance of one or both ligh sources from the surfaces compared, according to the law of inverse squar (*see Illumination, Laws of*); (2) varying the angle of incidence of light accordin to the cosine law (*ibid*); (3) varying the proportion of light received by mean of a sector disk or slit and collimator; and (4) by means of the Nicol prism In cases (1) and (2), given two diffusing surfaces illuminated to equal brigh ness b by respective light sources of intensities I_1 and I_2; the reflection or tran mission coefficients of the surfaces as K_1 and K_2; the angles of incidence as α_1 and α_2; and the distances from the light sources d_1 and d_2 respectively; then $\alpha_1 = \alpha_2$ and $K_1 = K_2$ and I_2 is the known intensity of a standard lamp,

$$I_1 = \frac{I_2 d_1^2}{d_2^2}.$$

If α_1 and α_2 or K_1 and K_2 differ slightly, a sensibly correct result is obtained b interchanging the light sources for half the observations and using the mea distances in the inverse square relation.

STANDARD LAMPS. — A primary standard possesses two essential quali ties, definiteness and reproducibility from specifications. None of the existin standards of luminous intensity meet both requirements. Of the flame stan dards, the Hefner and pentane lamps are approximately reproducible and fairly definite with standard atmospheric conditions and fuel. The incandes cent electric lamp is capable of definite calibration, but is not strictly reproduc ible. The present unit of luminous intensity, the international candle, is derived from the mean intensity of a group of incandescent electric lamps maintained by the U. S. Bureau of Standards, in coöperation with similar custodians in France and Great Britain.

Hefner Standard. — The Hefner standard which is the official standard of Germany and which has been extensively used in the United States, is a wick lamp burning amyl acetate of definitely specified chemical and physical proper ties. Its standard intensity is 0.9 international candle. Expressing the actua intensity as I, corrections for various atmospheric conditions are made as fol lows:

For variations from the standard flame height of 40 mm.

$$I = 1 + 0.025\,(h - 40) \text{ or } I = 1 - 0.034\,(40 - h)$$

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r heights greater or less than 40 mm. respectively, where h is the flame eight in millimeters. For barometric variations

$$I = 1 + 0.00011\ (b - 760),$$

here b is the barometric pressure in millimeters. For atmospheric humidity

$$I = 1.049 - 0.0055\ x,$$

here x signifies the liters of water vapor per cubic meter of air at 760 mm. and ee from CO_2.

For atmospheric vitiation by CO_2

$$I = 1.012 - 0.0072\ y,$$

here y signifies the liters of CO_2 per cubic meter of dry air.

The objections to the Hefner standard are its low intensity, its reddish color, s flabby flame and its sensitiveness to variation in flame height. The element uncertainty associated with it is at best not less than 2 per cent.

Pentane Standard. — The pentane standard, as represented by the Vernon-arcourt type, is essentially an argand burner supplied with pentane-air gas nd preheated air. The fuel is formed by passing air over pentane in a satura-r box subdivided by baffles. The burner is surmounted at a height of 47 mm. y a cylindrical chimney. An annular chamber surrounding the chimney upplies the interior of the flame with preheated air. The flame is shielded om drafts by a conical, blackened hood having a slit at one side through which ne flame is exposed. The chimney is fitted with a mica window showing a auge line to which the flame height is closely adjusted. Under standard tmospheric conditions, viz., a barometric pressure of 760 mm. and a humidity f 8 liters of water vapor per cubic meter of air the flame should have a horizontal ntensity of 10 candles. Experience indicates, however, that it is usually less y 2 to 4 per cent and that it is desirable to calibrate the lamp against a more efinite standard. Variations from the above standard atmospheric conditions ay be corrected by the equation:

$$I = I_n\,[1 - 0.00567\ (e - 8) + 0.0008\ (b - 760)],$$

here I is the actual intensity, I_n the standard intensity, e the liters of water apor per cubic meter of air and b the barometric height.

The color and intensity of the flame are convenient for practical purposes, specially for the measurement of the illuminating power of gas. An added dvantage in the testing of luminous flames of all sorts resides in the fact that heir intensities are affected by atmospheric variations in a manner correspond-ng quite closely to the changes in the pentane lamp, whereby somewhat trouble-ome corrections are avoided.

Carcel Lamp. — The Carcel lamp is the recognized standard of luminous ntensity in France. It has a central-draft ring burner fitted with a wick of he light-house type burning colza oil. Its standard intensity is 9.61 international andles.

Standard candles are now discredited for all accurate work, though still sed extensively in the routine testing of gas.

Incandescent Electric-lamp Standard. — The incandescent electric lamp s superior to all other working standards where corrections for flame lu-minosity due to atmospheric variations are not required. Carefully selected arbon-filament lamps aged by burning until the hot resistance is constant main-ain their candle-power sensibly unchanged for a period of 10 hours or more. With the most precise photometric apparatus such lamps may be standardized

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with the mean error of any single determination not exceeding s
1.0 per cent.

Lamps are standardized for use in a fixed position or in rota
principal axis. No difference exists between the precision of the
Lamps are standardized in terms of a definite voltage or curren
incidentally calibrated for power consumption. It is desirable
standardized in terms of both voltage and current for the constan
can be relied upon as long as both standard conditions exist s
Carbon filament lamps were formerly widely used as standards
Mazda B lamp is even more satisfactory from the standpoint
than the carbon, and the Mazda C lamps are now used with ver
It is best to keep on hand a group of well-seasoned lamps of all co
and to select from these the most appropriate working standard
against the primary carbon standard, so that the latter is used onl

Other Standards have had a very limited use. Among these
ene flame; the Methven screen, which is essentially a sharply-
of a luminous gas flame, calibrated against a primary standard;
lamp, which is a kerosene lamp of the student type having a
of its flame exposed by a screen. The utility of these standar
the routine testing of gas.

Relations of Luminous Standards. — The relative intensiti
standards under standard conditions are given in the following t

	International candle	Hefner	10-c-p. pentane	Carcel	Bougie
International candle	1.00	1.11	0.10	0.104	1.0
Hefner	0.90	1.00	0.09	0.0936	0.9
10-c-p. pentane	10.00	11.11	1.00	1.04	10.0
Carcel	9.61	10.66	0.96	1.00	9.6
Bougie decimale	1.00	1.11	0.10	0.104	1.0
English candle	1.04	1.154	0.104	0.1	1.0
German candle	1.055	1.17	0.105	0.109	1.0

SIGHT BOXES. — A photometric sight box consists of tw
faces and accessories to facilitate the comparison of brightne
described following are of greatest utility.

Bunsen Sight Box. — The bunsen screen is a disk of white
a well-defined region of which is made translucent by impregnatio
or other material. The disk is set transversely in a sight bo
interior, as shown on the plan in Fig. 1. Light from the sources
enters the apertures A–A, and falls normally on the disk surf
mirrors M_1 and M_2 enable both sides of the disk to be viewed at t
The opaque portion of the disk reflects diffusely, while the tra
partially reflects and partially transmits the light received.
balance exists when the two sides of the disk appear alike. If
alike in color and the absorption of both regions of the disk is e
ary disappears and both sides appear uniformly bright. Wi
sorption, balance exists when equal contrast exist between t
translucent regions on both sides of the disk. The contrast pri
tinct advantage with slight color differences. The sensitivenes
depends largely on the definition of the boundary of the impregn

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Leeson Disk. — This is a useful modification of the Bunsen type built up pasting opaque paper disks with accurately matched star-shaped apertures the two sides of disk of translucent paper. By a careful selection of the terials the disk may be made to embody either the equality-of-brightness or equality-of-contrast principle. The paper used should agree closely with cosine law of diffusion. The later types of Leeson disks are not pasted, but two outer thin sheets are pressed tightly against the centre opaque sheet h glass. This makes a very sensitive and satisfactory type of disk.

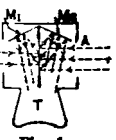


Fig. 1.

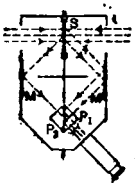


Fig. 2.

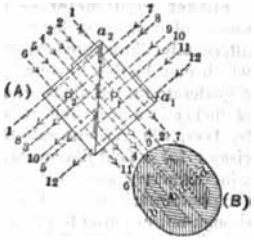


Fig. 3.

Lummer-Brodhun Sight Box. — The plan of this box is shown in Fig. 2. opaque diffusely-reflecting screen S receives light from the sources to be mpared and reflects it along the paths indicated by aid of the mirrors M–M d the prisms P_1–P_2. The prisms present to the eye a composite field in which e brightness of the two sides of S can be conveniently compared. Fig. 2 also ows the arrangement for equality-of-brightness working. The prisms are optical contact over an elliptical portion of their hypotenusal faces, and the mainder of one is cut away. The central portion of the field is illuminated direct transmission through the contact area, the outer portion by total lection from the face of the uncut prism.

For equality-of-contrast working the arrangement of the prisms is as shown Fig. 3. The hypotenusal face of P_2 is recessed over the area shaded in (B). at of P_1 is plane. Two thin glass absorbing strips a_1 and a_2 are set before the es of P_1 and P_2 as shown in the plan (A). By tracing the several paths licated it is seen that the field has the appearance of (B) and that the regions aded are darkened by the absorption of light in a_1 and a_2. In a state of balance and d appear equally bright and c and e equally dark in contrast. The gree of contrast created by a_1 and a is ordinarily about 8 per cent, this being accordance with Fresnel's formula. A method of securing less than 8 per nt would be to place a sheet of glass over the entire side of the cube and to rease the thickness of the glass (either by cementing two pieces together, by grinding) over the contrast field. A degree of contrast as low as 2 per nt has been secured by this method, which has been found satisfactory. Accuracy of adjustment and cleanliness of all parts are essential in photometers the Lummer-Brodhun type.

Comparison of Bunsen, Leeson, and Lummer-Brodhun Boxes. — unsen, Leeson and Lummer-Brodhun sight boxes should be so mounted as to rmit the complete reversal of the optical system about its axis of symmetry order that optical asymmetry may be corrected as explained above. The unsen and Leeson types are binocular and therefore less fatiguing in a long

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series of observations than the monocular Lummer-Brodhun more, they are the more readily balanced with slightly flicke Lummer-Brodhun contrast type excels in sensitiveness and gen steady lights of equal and slightly dissimilar color.

It may be stated, however, that the complete reversal systen in practical photometry, with the exception of measurement where the substitution method cannot be readily followed. I practical operators of photometric equipment, there is relative between steady and flickering light for the different types of ph

Flicker Photometer. — The flicker photometer affords th means of comparing light sources of distinctly unlike color. alternately illuminated by two such sources displays a flicke which may be due to color dissimilarity or to difference in bri a moderate rate of alternation the color sensations blend and th of flicker is a true indication of equal brightness, as conclusi by Ives, who recommends the following conditions as suited cision: (*a*) a field illumination of 25 meter-candles; (*b*) a pho 2 in. diameter; and (*c*) a background field about 25 in. in diame the photometric field and about equal to it in brightness. The though not essential to precision, is an aid to comfort.

Reference should also be made to the work done with the flicker photometer, which has a very ingenious eyepiece, made be attached to the contrast type of Lummer-Brodhun photo contrast glasses removed. The approximate specifications are The flicker field shall subtend an angle of approximately 2 from the eyepiece. The field shall have an effective brightness for all loss of lens absorption and reflection of 2½ milli-lamberts, and the flicker field is to be surrounded by an illuminated field of approximately the same brightness, the pupil aperture to be 5 millilamberts in diameter.

Bechstein Flicker Photometer (Fig. 4). — This photometer employs a train of lens and prism oscillating before a fixed diffusing wedge. The field of view consists of a circle and ring, alternately illuminated by the respective sides of the wedge as the lens system revolves. The highest sensitiveness exists at the lowest speed at which the flicker can be made to disappear.

Wild Flicker Photometer (Fig. 5). — The Wild flicker photometer is the simplest of this class. It consists of a disk *D* of white diffusing paper, one half of which is made impregnation. This disk is revolved about an axis slightly a path of light and a mirror *M* reflects one side of the disk to the sight tube *T*. A high degree of precision is claimed by Wild for this device.

Color-equalizing Filters. — The simplest method of comparison for lights of dissimilar color is to employ a Lummer-Brodhun photometer in connection with a set of glass filters of graded tints, selecting one which renders the light of the standard lamp equal in color to that of the lamp under meas absorption of each screen for the light of the standard lamp mus by means of the flicker photometer, but the inconvenience of instrument is limited to the process of calibration.

Sector Disk. — The sector disk affords a most convenient me

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he intensity of the light received from an illuminant on the photometric screen. t consists of one or more disks with sector apertures revolving on a common xis. By advancing one disk with respect to the other the net aperture may be ltered at will. By Talbot's law the intensity of transmitted to incident light quals the ratio of the total angular opening to 360 degrees. The sector disk as the advantage over other absorbing media in that it is adjustable, is not ffected by time, and is independent of color.

Photometric Bar. — The devices above described are best suited for use in onnection with a photometric bar or bench, which should be level and straight, nd preferably greater than 100 inches in length. A plan f the layout is shown in Fig. 6. For convenience the ight box and at least one of the lamps should be mounted n movable carriages. The bench should be provided ith a series of screens *D* of dead black material having raded apertures along the photometric axis and with olid screens at the ends. These screens should completely occlude from the ight box all extraneous light, and should protect the eye of the operator from he direct light of the lamps. If these conditions are met the photometric oom need not be blackened. The sight box should have a dark background, owever, and all light in the room should be well diffused. The bar should e provided with a scale of equal divisions and a scale reading directly the ratio f the inverse squares of the distances from the ends of the bar. For use with standard lamp of definite value in a fixed position a direct reading scale of andle-power is readily obtained from the ratio scale.

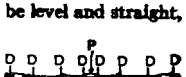


Fig. 6.

Connections for Testing Incandescent Electric Lamps. — In testng incandescent electric lamps the effects of voltage fluctuation must be reduced o a minimum. A storage battery or special generator of very close regulation hould be employed if possible. In practically all cases double circuit phoometers are used, and the simpler the wiring the better.

Manipulation of Photometric Bar. — Direct comparison between the est lamp and the standard may be made with the two in fixed positions by movng the sight box to a point of balance. In this case half the observations hould be made with the sight box reversed. For the substitution method a xed socket is provided at one end of the scale. The second socket and the ight box are on movable carriages coupled at a fixed distance. A well-seasoned mp is placed in the movable socket and adjusted to a suitable voltage, which s subsequently held constant. The standard lamp is placed in the fixed socket nd a balance secured by setting the movable carriages. The standard lamp s then removed and test lamps substituted in turn, a balance point being bserved for each. The intensity of each test lamp equals that of the standard nultiplied by the direct ratio of the squares of their distances from the screen t the times of balance. Reversals are unnecessary in the substitution method. The comparison lamp should be checked against the standard at intervals.

For further information on the *substitution method* see Wickenden, W. E., *Illumination and Photometry*, N. Y., pages 56 and 57.

MEASUREMENT OF PHOTOMETRIC DISTRIBUTION. — Mean orizontal intensity is measured with the lamp rotating about its vertical axis. pecial mountings, driven by motor or hand wheel, are provided for this purose. Rotators are made universal by provision for the turning of the lamp y definite angular steps about its luminous center in a vertical plane includng the photometric axis. The speed of horizontal rotation should be only sufficient to equalize differences in intensity.

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Mirror Rotators. — In testing the light distribution of arcs, heavy reflector

units, gas lamps, etc., which must remain in an upright position, mirror rotat are generally employed to direct the light from any desired vertical angle tow the photometer. A three-mirror device is shown schematically in Fig. 7. A two-mirror arrangement could also be used. In either case the lamp remains stationary, or is revolved about its vertical axis only, while the mirror system is turned by steps about the photometric axis. Numerous other devices for this purpose are described in standard works on photometry.

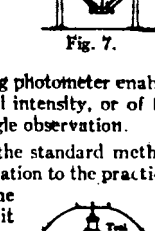


Fig. 7.

INTEGRATING PHOTOMETERS. — An integrating photometer enab the measurement of mean spherical or mean hemispherical intensity, or of total flux of light from an illuminant, to be made by a single observation.

Sphere Photometry. — Since the sphere is practically the standard meth of photometry, the following notes are important in their relation to the practi testing by this method. One type of sphere known as the Ulbricht Integrating Sphere is shown in Fig. 8, in which it will be seen that the apparatus consists of a hollow sphere whose inner surface is coated with a white material giving approximately true diffusion. In the following notes on sphere photometry, the type developed by the Electrical Testing Laboratories will be referred to.

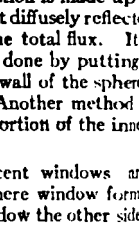


Fig. 8.

Sphere Theory.—The theory of the sphere photometer is that the illumination on any part of its interior surface when a lighted lamp is introduced into it at any location is made up two parts: (*a*) the direct light from the lamp; and (*b*) the light diffusely reflect from all parts of the sphere wall which is proportional to the total flux. It only necessary therefore to measure (*b*) and this may be done by putting translucent milk glass in a window contiguous with the inner wall of the spher (*a*) is screened off from the window by an opaque screen. Another method to measure (*b*) by viewing directly as the test surface a portion of the inn surface of the sphere.

Equipment. — **The Photometer.** — When translucent windows a used, the photometer head may be arranged so that the sphere window form one side of the photometer field and the comparison lamp window the other side

In the selection of a **comparison lamp** it is desirable that its construction should be as nearly perfect as possible with the filament lying in a single plane preferably without an anchor support or with supports such that variabl cooling may be obviated.

In connection with the **screen** practice has shown that the best position fo the screen inside the sphere is two-thirds the distance from the lamp to th window. This screen should be the smallest that will adequately screen th largest lamp.

The lumen **scale** is computed with relation to its location from the compari son lamp window. This position is fixed and must not be changed.

The **slide aperture** used in conjunction with the 40-inch sphere as developed by the Electrical Testing Laboratories is proportioned to the scale and is mad adjustable.

Photometer Calibration. — Slide Apertures. — When the photometer is calibrated the apertures are adjusted so that a continuous range is given for the measurement of lamps from 10 to 1000 watts. The size of the lamp bulb and base are likely to introduce discrepancies, however, which prevent the use of this range in its entirety with one setting.

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As far as **color** is concerned, for the photometry of **Mazda *B*** lamps the comparison lamp should be operated at such a temperature or efficiency as to produce a color match with the average size of lamp. In most cases the sphere coating is slightly selective, absorbing more light toward the blue end of the spectrum, therefore the comparison lamp may be operated at a somewhat lower temperature than the test lamp and still give a good color match and prolong the life of the comparison lamp.

When the color match has been secured, the **intensity** may be adjusted by varying the glass either in the comparison lamp window, sphere window or both. All the glasses should be non-selective in so far as practicable. The brightness of the field for best sensibility should be equal to or slightly brighter than the immediate surroundings. In a dark room the average should not be less than 5 millilamberts or the equivalent of three foot-candles on a white blotter.

As to **filters** for the photometry of Mazda C lamps, or other lamps where a color difference is involved, glass light filters may be used to correct the color of the test lamp to that of the comparison lamp or vice versa. Theoretically the color of the comparison lamp should remain unchanged and the filter should be placed between it and the window. Under these conditions the transmission of the filter will remain fixed, regardless of the color of the test lamp. However, as a practical matter, it is more convenient to change the color of the light from the test lamp, because Mazda C lamps are usually high in candle-power to begin with, and the filter reduces the intensity of the test surface and also changes the color. Therefore it is preferable to allow the color of the comparison lamp to remain unchanged as the transmission factor of the filter will remain constant regardless of the color of the test lamp. The filter should be placed between the prism and the window and not between the lamp and the window for the reason that light travels more rapidly through air than through glass. Should it be placed between the lamp and window it would be equivalent to increasing the distance between the lamp window thus introducing error. Also the distance between the filter and window should be sufficient to reduce the inter-reflection to a negligible quantity, two inches is usually sufficient. However, this applies only when the transmission of the filter has been determined independent of the photometer, namely, not calibrated in place in the photometer.

Regarding **alignment**, all optical parts, track and comparison lamp carriage should be kept in alignment. A non-uniform field is an indication of poor alignment or soiled test plate. The prism is screened with a small diaphragm but slightly larger than the field so that a small shift in the prism may cause a dark shadow on the field.

In selecting a **coating** for the sphere, a number of points must be borne in mind. The surface must have good diffusing qualities; it must be reasonably non-selective in its absorption; it must have a relatively high reflection factor and it must be permanent in color. These qualifications necessitate a pure white pigment with a colorless binder. A number of experiments have been conducted using zinc oxide, lead oxide, magnesium carbonate and the like, with binders of cellulose, sodium silicate, white shellac, and the like. The Bureau of Standards has developed a formula for a coating which has been found very satisfactory though difficult to make and apply. For all practical purposes a good grade of calcimine carefully applied with a wide camel's hair brush makes a reasonably good coating easily applied and always available. A little Prussian blue mixed with the calcimine will somewhat lower its reflection factor but will make it less selective.

Possible Reasons for Erroneous Results. — Bulb absorption. — The substitution method should be adhered to even more rigidly in the sphere

than on the bar photometer. A discolored or tinted bulb may absorb some o the reflected light which it intercepts thus lowering the photometer setting This is not an error though it may render an erroneous result. To photomete a lamp of this character, if the substitution method cannot be applied, a checkin lamp may be introduced into the sphere and measured, first alone and secon with the discolored or tinted lamp cold. The difference in reading represent the per cent of the reflected light absorbed by the latter. In making thes measurements, the direct light should be screened off from the discolored o tinted lamp. A simple method is to place the two base to base with the tes lamp in the regular socket.

A change in the size or shape of a bulb or base of the test lamp may give a wrong reading. The proper standard lamp or the use of the method describe for measuring tinted lamps may be used with good results.

As to the **coating,** it should be kept in mind that the inside surface of th sphere under the best of conditions will collect dust and this accumulation tend to settle in the lower half of the sphere with denser accumulation in the botton of the sphere. This may change the character of the light distribution betwee standard lamps and the lamps tested and give fallacious results. The solutio of the difficulty is properly to maintain the surface by frequent cleanings o recoatings.

Undue voltage drop in the **lamp socket** contact may give rise to incorrec results. A double center contact should be employed and the shell of the socke kept clean.

Screening. — Photometer. — Stray light reaching the test plate either from an extraneous source or reflected from the photometer lamp may give an incorrect answer. To test for stray light, the test plate should be removed and the eye or a mirror substituted in order to see if light from any source other than the comparison lamp may reach the window. A perfectly protected test plate should not be visible from any position from which light may come other than the comparison lamp.

In screening the **sphere** it must be remembered that it is only the reflected and not the direct light that is to be measured, therefore, it is well to be certain that the screen in the sphere is performing its function. A hole should be provided in the sphere so that the shadow cast by this screen may be seen when the test lamp is in place.

An improperly located **scale** will give fallacious results but it is easily discovered and remedied. A gauge with a forked end to span the comparison lamp and reach the comparison lamp window should be a part of the equipment of every sphere.

Extension of Range. — If lamps are to be tested that are beyond the limits of the scale, the range may be extended in two ways. If the range is to be changed temporarily and but slightly, the comparison lamp voltage may be raised or lowered until the lamps can be read on the scale. Standard lamps are then read and the factor which is obtained, applied. The range may be considerably extended by changing the glass in the comparison lamp window. If the brightness of this window is to be decreased, one thickness of denser opal glass (or several thicknesses) may be employed. On the other hand, if it is to be increased, several thicknesses of ground glass may be substituted. In any case, the distance from the scale to the window should be measured from the first diffusing surface.

Verification. — A slight dust accumulation on the sphere window may cause the light emitted through the slide apertures to vary. If the substitution method is not adhered to, it is necessary to verify these apertures from time to

time. This can be done by using the largest opening as standard and reading on the other scales in turn. If they are not in agreement, the substitution method should be used throughout. Simple and accurate methods of determining the position of the scale, with a moving comparison lamp, is available with this type of photometer.

Standard Lamps. — A very important part of the sphere equipment is a complete range of standard lamps. There should be a sufficient number of lamps to permit the use of the substitution method and the extent to which the substitution method must be followed will depend largely upon the grade of electrical instruments used.

The qualifications for a standard lamp demand that it must pass a most rigid inspection for appearance in every particular. The construction may differ considerably from the same type of commercial lamp, for instance, lamps where copper supports are employed must be so made that each clamp is tight in order to obviate a variable cooling effect. Where spring supports are used, they must be such that too much tension is not placed upon the filament, at the same time they must be tight enough to prevent locked filaments. It is hardly necessary to mention the vacuum for type B lamps and the proper treatment of the type C lamps as any slight defect will impair the constancy of the standard.

Standardization values may be relied upon only for a limited period of time, therefore, lamps should be verified every three months if they are in current use. If they are used only occasionally they may be returned less frequently. To prolong the life as much as possible without materially changing the color, lamps are standardized at slightly lower than rated efficiency. If lamps are subjected to a higher voltage than labelled it is readily seen that the life will be shortened and the standardization values changed. It is good practice, therefore, always to put resistance in the circuit when changing lamps.

PORTABLE PHOTOMETERS. — Weber Photometer. — Portable photometers exist in great variety and have for their purpose the measurement of illumination and of the intensity of light sources in place. The great majority are modifications of the Weber photometer, shown schematically in Fig. 9. This comprises two cylindrical tubes of blackened interior, one fixed and the other attached to it at right angles by means of a sleeve to allow rotation. A Lummer-Brodhun prism device is placed at the junction of their axes, and permits the brightness of two translucent glass plates P_1 and P_2 to be compared at the eyepiece E. P_1 is illuminated by an external source I_1 at a distance d_1. P_2 is movable along the tube by a knurled head and is illuminated by a small standard lamp L mounted in a convenient housing. Assuming both plates to be illuminated by light incident normally at a state of balance, then

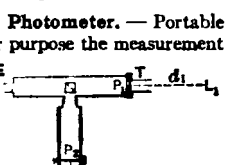


Fig. 9.

$$I_1 = \frac{I_2 T_2}{T_1} \times \frac{d_1^2}{d_2^2},$$

where T_1 and T_2 are the respective brightness coefficients of the two plates. A calibration for intensity measurements is readily obtained by the use of a standard lamp as I_1 and by observing the scale readings d_2 giving a balance with various values of d_1, keeping I_2 constant.

Two methods are available for the measurement of illumination. In the first the terminal tube T is removed and a flush test plate of depolished milk glass fitted in its place. This test plate is placed in the position where the illumination is to be tested and the instrument balanced as usual.

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For the second method of illumination measurement the terminal tube is n removed, but the plate P_1 is omitted. A large, white diffusely reflecting card placed in the position where the illumination is to be tested and the tube pointed in its direction so that the entire cone of light entering T arises fro the test tube. So long as this condition is met the inclination and distance T is not important.

The first method is preferable where it is possible to make the attached te plate coincide with the position of the test. In the second method it is difficu to avoid interference with light which should reach the test plate.

Sharp-Millar Photometer. (Fig. 10). — This photometer is a modifie Weber instrument which is extensively used in America. It comprises a elongated wooden box divided into two compartments, one of which contains a fixed Lummer-Brodhun photometric cube and the other a lamp carriage movable along the box by turning a knurled head H. Observations are made at E at one side of the box. The two compartments are separated by a ground-glass window whose brightness is balanced against illumination from an outside source admitted through an elbow tube T. Stray light in the lamp compartment is screened from this window by a series of diaphragms with centra apertures. The elbow tube T is fitted on a collar and may be turned to an desired inclination. At the elbow is a circular, reversible plate one side of whic is a mirror for measurements of illumination and the other a white diffusin surface for measurements of candle-power. In the former case the end of th tube is fitted with a flush plate of depolished milk glass. The range of th photometer is controlled by a pair of glass absorbing screens mounted in th compartment with the Lummer-Brodhun cube. These plates are respectivel of high- and low-absorbing power. They may be turned so that either one ma be used to reduce the illumination of either part of the field. But one may b employed at a time. In this way a range from 0.004 foot-candle to 2000 foot candles may be secured. In the most recent design the need of a voltmete or ammeter to keep the standard lamp constant is obviated by a small Wheat stone bridge arrangement with a telephone receiver, whereby the lamp may b kept at constant hot resistance. The Sharp-Millar photometer may be use with a detached test plate similar to that described for the Weber photometer

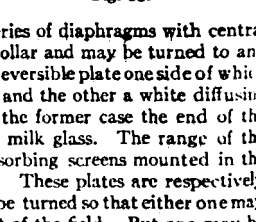


Fig. 10.

Another type of portable photometer which has come into fairly wide use i that known as the Macbeth Illuminometer. This instrument has certain fea tures which differ from the Sharp-Millar type, although in principle the two instruments are fairly similar.

COLORIMETRY. — The Ives colorimeter is an instrument for tri-chro matic color analysis. (*See Vision, Laws of.*) It consists essentially of an oblong box, at one end of which are placed four slits, one clear, and the three others equipped respectively with red, green and blue screens. By means of levers the openings of the three colored slits can be altered to read by scales from 0 to 100. By rotating a wheel of lenses the three colors are mixed. The observer views a divided field, one part consisting of the mixture of the three primary colors and the other of the color to be matched as viewed through the clear slit. To make a measurement, the three colored slits are opened until white is matched, and the scales are set to read 100 for each color. Then any color matched by moving the levers can be read off in terms of the per cent of red, green and blue necessary to match white. The precision of the instrument is from 2 to 5 per cent under favorable conditions.

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ING POWER OF SURFACES.— See section on *Reflection of* rticle on *Photometric Quantities*.

TIONS IN PHOTOMETRIC OBSERVATIONS.— The eyes er should be constantly shaded from bright light to maintain their in a state of dark adaptation. For best photometric sensibility a ation of about 2 foot-candles is desirable. At low intensities the t (see *Vision, Laws of*) may prove disturbing. Should a daylight e used, a field or screen brightness far in excess of 1.7 millilamberts y be advisable but necessary.

on of photometric settings may often be improved by a process down between points equally out of balance. Many good photo- ject their first observation in a set as untrustworthy. Not more ures in the result are significant.

ter bar need not be more than 18 to 20 inches in length. The a large unit to the screen should not be less than about ten r-all maximum dimension of the unit under test.

e of electric lamps, or current, in the case of series lamps, should be the most accurate device obtainable. In life tests of incandescent egulation of voltage is of the utmost importance and a sensitive, gulator is most desirable. In tests of illuminants in place, the nt or power, or the gas consumption and pressure should be ascer- ecorded if possible. In tests of gas illuminants the volume con- l be reduced to the corresponding volume at a temperature of barometric pressure of 30 inches.

RAPHY. — Palaz-Paterson, *Industrial Photometry;* Liebenthal, *Photometrie;* Johns Hopkins University, *Lectures on Illuminating* Vol. 1, Baltimore, 1910; Barrows, W. E., *Light, Illumination and* Vickenden, W. E., *Illumination and Photometry, Phil. Mag.*, Vol. 24. *actical Electric Illumination; Illuminating Engineering Practice;* . Illum. Eng. Lectures, N. Y., 1917; Harrison, W., *Electric Light-* n, O. J., *Electric Lighting.* Numerous papers in *Trans. Ill. Eng.* . *Elec. Wld.; and Bul. Bur. Stand.*

LUE OF.— The letter π is used to represent the ratio of the of a circle to its diameter; it is an incommensurable quantity. Its 59265. . . . The value 3.1416 is sufficiently accurate for all oses, and for rough calculations the value 22/7 is convenient. The ors frequently occur:

.14159	$\frac{\pi}{4} = 0.785398$	$\frac{1}{2\pi} = 0.159155$
.28319		
.42478	$\frac{\pi}{6} = 0.523599$	$\frac{1}{4\pi} = 0.079578$
.56637		
57080	$\frac{4\pi}{3} = 4.18879$	$\pi^2 = 9.86960$ $\pi^3 = 31.00628$
04720	$\frac{1}{\pi} = 0.318310$	$\sqrt{\pi} = 1.77245$ $\sqrt[3]{\pi} = 1.46459$

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PIPES AND PIPING. — (*See also Boilers; Electrolysis of Grounded Structures; Hydraulics, Principles of; Power Stations; Valves.*) In the following table is given a list of the metals ordinarily used for steam, gas and water pipes, together with their average weight per cubic inch, their tensile strength and the expansion per 100 feet for various temperature differences. The expansions are based on data given in Gebhardt's *Steam Power Plant Engineering*.

TENSILE STRENGTH, WEIGHT AND EXPANSION OF PIPE MATERIALS

Material	Lb. per cu. in.	Tensile strength, lb. per sq. in.	Expansion (in. per 100 ft.) Temp. rise above 60° F.				
			100°	200°	300°	400°	500°
Brass, wrought	0.30	50,000	1.15	2.41	3.80	5.38	7.11
Copper, wrought	0.32	30,000	1.08	2.26	3.56	5.05	6.66
Iron, cast	0.26	18,000	0.72	1.50	2.38	3.36	4.44
Iron, wrought	0.28	50,000	0.79	1.65	2.61	3.70	4.89
Lead	0.41	1600 to 2400	....	....	....	....	....
Steel, mild	0.28	65,000	0.79	1.65	2.61	3.70	4.89

The material for steam pipe, whether high or low pressure, is now almost uniformly open-hearth steel. This may be made by the acid or basic process but Bessemer pipe or wrought-iron pipe should not be used if the best results are to be obtained. The use of Bessemer-steel pipe brings in difficulty in flanging and bending is usually uncertain at the welds. It has in its composition rather more phosphorus and sulphur than is considered good when severe strains are to be placed on the material. Wrought-iron pipe, when it can be obtained may be very good for certain uses but it is almost impossible to flange a piece of wrought-iron pipe satisfactorily, and its use is now confined mainly to unimportant work at localities close to the place where the pipe is made. Steel pipe when used for oil or salt water is often galvanized and its thickness should be proportioned to meet the pressures in use.

Where warm water is to be distributed, cast-iron pipe has been and is the standard. Cast-iron pipe, when properly made, has proved to be the best for large and small water mains for either low or high pressures. Where the water pipe is small or where many bends are required, or where the heat and wear are excessive, bronze pipe has been substituted for cast-iron with very good results. The smaller sizes of pipe used in oiling systems are almost invariably made of brass. The use of copper pipe for steam work has been almost entirely superseded, the introduction of superheated steam with the resulting action of the high temperature on the copper rendering it unfit for such employment. There are many stations in which nothing but open-hearth steel and cast-iron piping are used and it may be noted that this practice is increasing and these materials will be the standard for the future.

DIMENSIONS AND WEIGHT OF COMMERCIAL PIPE. — The size of iron and steel pipes is usually specified in terms of the "nominal" inside

he actual inside diameter is usually greater than the "nominal," ge difference being the greatest for small sizes. The thickness of ght per lineal foot of a given size of pipe varies over a considerable to processes of manufacture. Manufactures specify that "full may have a variation of from 5 per cent above to 5 per cent below table weight, but "merchant pipe," which is the ordinary pipe obbers and manufacturers, is almost invariably from 5 to 10 per he nominal weight.

specifications for pipe, engineers should be careful to state what is desired, whether "merchant," full weight, or extra strong, and cast-iron pipe the class according to the table below.

MENSIONS AND WEIGHT OF CAST-IRON PIPE

Class A		Class B		Class C		Class D	
Thickness, in.	Lb. per ft.	Thickness, in.	Lb. per ft.	Thickness, in.	Lb. per ft.	Thickness, in.	Lb. per ft.
0.39	14.5	0.42	16.2	0.45	17.1	0.48	18.0
0.42	20.0	0.45	21.7	0.48	23.3	0.52	25.0
0.44	30.8	0.48	33.3	0.51	35.8	0.55	38.3
0.46	42.9	0.51	47.5	0.56	52.1	0.60	55.8
0.50	57.1	0.57	63.8	0.62	70.8	0.68	76.7
0.54	72.5	0.62	82.1	0.68	91.7	0.75	100.0
0.57	89.6	0.66	102.5	0.74	116.7	0.82	129.2
0.60	108.3	0.70	125.0	0.80	143.8	0.89	158.3
0.64	129.2	0.75	150.0	0.87	175.0	0.96	191.7
0.67	150.0	0.80	175.0	0.92	208.3	1.03	229.2
0.76	204.2	0.89	233.3	1.04	279.2	1.16	306.7
0.88	291.7	1.03	333.3	1.20	400.0	1.37	450.0
0.99	391.7	1.15	454.2	1.36	545.8	1.58	625.0
1.10	512.5	1.28	591.7	1.54	716.7	1.78	825.0
1.26	666.7	1.42	750.0	1.71	908.3	1.96	1050.0
1.35	800.0	1.55	933.3	1.90	1141.7	2.23	1341.7
1.39	916.7	1.67	1104.2	2.00	1341.7	2.38	1583.3
1.62	1283.4	1.95	1545.8	2.39	1904.2	....	.....
1.72	1633.4	2.22	2104.2	....	.....	....	.....

orking pressures recommended for the four classes are:

AFE WORKING PRESSURES, CAST-IRON PIPE

f Pressure	A	B	C	D
quare inch.....	43	86	130	173
er, feet.....	100	200	300	400

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Cast-iron Pipe. — The dimensions and weights given above a the catalogue of the U. S. Cast-iron Pipe and Foundry Co. (1908). are figured on the basis of a pipe length of 12 feet, and include part of weights of standard sockets.

Welded Pipe. — The first table following is based on Briggs' sizes up to 10 inches, and upon the National Tube Co.'s Stand inches (1910). Weights per foot, up to and including 15 inches inte are based upon a length of 20 feet including the coupling; weig larger sizes are for plain end pipe.

The second table gives the dimensions of "Extra Strong" Extra Strong" welded tubes (*National Tube Co., 1902*).

DIMENSIONS AND WEIGHT OF WELDED PIP

Size, nominal internal diam., in.	Diameter in inches		Thickness of metal, in.	Number of threads per in.
	Actual external	Approx. internal		
⅛	0.405	0.269	0.068	27
¼	0.540	0.364	0.088	18
⅜	0.675	0.493	0.091	18
½	0.840	0.622	0.109	14
¾	1.050	0.824	0.113	14
1	1.315	1.049	0.133	11½
1¼	1.660	1.380	0.140	11½
1½	1.900	1.610	0.145	11½
2	2.375	2.067	0.154	11½
2½	2.875	2.469	0.203	8
3	3.500	3.068	0.216	8
3½	4.000	3.548	0.226	8
4	4.500	4.026	0.237	8
4½	5.000	4.506	0.247	8
5	5.563	5.047	0.258	8
6	6.625	6.065	0.280	8
7	7.625	7.023	0.301	8
8	8.625	7.981	0.322	8
9	9.625	8.941	0.342	8
10	10.750	10.020	0.365	8
11	11.750	11.000	0.375	8
12	12.750	12.000	0.375	8
....	14.000	13.250	0.375	8
....	15.000	14.250	0.375	8
....	16.000	15.250	0.375	8
....	18.000	17.250	0.375	....
....	20.000	19.250	0.375	....
....	22.000	21.250	0.375	....
....	24.000	23.250	0.375	....

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NSIONS OF "EXTRA STRONG" AND "DOUBLE EXTRA STRONG" WELDED TUBES

	Actual outside diam., in.	Thickness, extra strong, in.	Thickness, double extra strong, in.	Actual inside diam., extra strong, in.	Actual inside diam., double extra strong, in.
	0.405	0.100	.....	0.205	.....
	0.54	0.123	.....	0.294	.....
	0.675	0.127	.....	0.421	.....
	0.84	0.149	0.298	0.542	0.244
	1.05	0.157	0.314	0.736	0.422
	1.315	0.182	0.364	0.951	0.587
	1.66	0.194	0.388	1.272	0.884
	1.9	0.203	0.406	1.494	1.088
	2.375	0.221	0.442	1.933	1.491
	2.875	0.280	0.560	2.315	1.755
	3.5	0.304	0.608	2.892	2.284
	4.0	0.321	0.642	3.358	2.716
	4.5	0.341	0.682	3.818	3.136

l Pipes. — Large pipes are frequently made of sheets of boiler steel ed joints, with longitudinal, circumferential or spiral seams. The tables give the necessary data regarding dimensions, rivets, etc. able is taken from a catalogue of the Abendroth & Root Mfg. Co.

T IRON AND RIVETS REQUIRED FOR RIVETED PIPES

ft. of iron re- o make 100 lin. ed and formed hen put together			No. sq. ft. of iron required to make 100 lin. ft. punched and formed sheets when put together			
Width of lap in in.	Square feet	Approx. No. of rivets 1 in. apart required for 100 lin. ft. punched and formed sheets	Diam. in in.	Width of lap in in.	Square feet	Approx. No. of rivets 1 in. apart required for 100 lin. ft. punched and formed sheets
1	90	1600	14	1½	397	2800
1	116	1700	15	1½	423	2900
1½	150	1800	16	1½	452	3000
1½	178	1900	18	1½	506	3200
1½	206	2000	20	1½	562	3500
1½	234	2200	22	1½	617	3700
1½	258	2300	24	1½	670	3900
1½	289	2400	26	1½	725	4100
1½	314	2500	28	1½	779	4400
1½	343	2600	30	1½	836	4600
1½	369	2700	36	1½	998	5200

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THICKNESS AND WEIGHT PER FOOT OF SHEET IRON

No. of gauge, B.W.G.	Thickness, in.	Weight in lb., black	Weight in lb., galvanized	No. of gauge, B.W.G.	Thickness, in.	Weight in lb., black	Weight in lb., galvanized
26	0.018	0.80	0.91	18	0.049	1.82	2.16
24	0.022	1.00	1.16	16	0.065	2.50	2.67
22	0.028	1.25	1.40	14	0.083	3.12	3.34
20	0.035	1.56	1.67	12	0.109	4.37	4.73

Wooden Stave Pipes are usually built up in place. Staves of redwood, fir, yellow pine, and spruce are used. The staves range from 1¼ to 2½ inches in thickness and from 6 to 8 inches in width; these are held in place by steel bands ranging from ⅜ to ¾ inch in diameter. The interior surfaces of the staves wear smoother by the action of the flowing water and do not become fouled. Stave pipes have been installed in sizes ranging from 18 to 144 inches in diameter, and for heads up to 300 feet.

FORMULAS FOR WEIGHT, CIRCUMFERENCE, SURFACE, CONTAINED VOLUME AND SAFE PRESSURE. — Let

A = external surface per lineal foot in square feet,
C = external circumference in inches,
D = internal diameter in inches,
D_0 = external diameter in inches,
f = factor of safety,
H = safe head in feet of water,
P = safe pressure in pounds per square inch,
S = tensile strength in pounds per square inch,
T = thickness of wall in inches,
V = volume of contents (water, steam or gas) per lineal foot in cubic feet,
w = specific weight of metal in pounds per cubic inch,
W = weight of metal per lineal foot in pounds.

Then

$$A = 0.262\,D_0, \qquad C = 3.14\,D_0, \qquad D_0 = D + 2\,T,$$

$$H = \frac{4.62\,ST}{Df}, \qquad P = \frac{2\,ST}{Df},$$

$$T = \frac{D_0 - D}{2} = \frac{DfP}{2\,S} = \frac{DfH}{4.62\,S},$$

$$V = 0.00545\,D^2, \quad W = 9.42\,w\,(D_0^2 - D^2) = 37.7\,wT\,(D + T).$$

The values of the specific weight w and tensile strength S are given in the table at the beginning of this article. The tensile strength of riveted pipe is about 70 per cent of the tensile strength of the metal.

JOINTS. — Pipe joints have been a great source of trouble in the past and the various kinds and "standards" have been as many almost as there were individual engineers. For low-pressure pipe work the screwed joint with the standard pipe thread and cast-iron flanges has been and is the standard for the best work. For pressures above 100 lb., however, another type of joint should

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e adopted if the best work is desired. For this purpose there has been no oint found better than the so-called Van Stone joint. This is made by flanging he end of the pipe against the outside of a steel or cast-iron flange. There re many varieties of welded flanges in which the flange is welded directly to he pipe, but these do not seem to have been as popular or as good in construc- ion as the so-called Van Stone, although many people use them. All welded anges have the disadvantage that they cannot be turned on the pipe, making reat care necessary to avoid mistakes in drilling them.

The best joints are made by grinding the seats to a perfect surface and then olting them together without a gasket. This, however, takes a high-grade nechanic and has been satisfactory only when made in the proper manner. nstead of grinding the faces, it is now considered at least as good to fine-tool inish them and insert a gasket which in the best work has been made of very oft steel approximately 1/100 inch thick. Duralite and other indurated fibers nake good gaskets. Copper gaskets appear to deteriorate very rapidly in this osition and are not used on high-pressure work as much as formerly. The ongue-and-groove joint cannot be recommended for steam work as it is almost mpossible to bring two joints to the same degree of tightness. For the lower team pressures copper gaskets work very nicely and are now standard. These re usually stamped with corrugations which flatten out when the bolts are ightened up, assuring a surface practically the whole width of the face. For xhaust work rubber with wire insertion such as the "Rainbow" is mostly used. For water, whether hot or cold, the "Common Sense" or other babbitt com- position gaskets are quite satisfactory. The gasket made up of a soft lead ring with a copper wire ring outside of it has also been largely used with very good results and "Rainbow" gaskets are satisfactory when the pressures are not too high.

PIPE FITTINGS. — For low-pressure work, either steam, exhaust or water, the Master Steam Fitters' Association has adopted a standard of pipe fittings which is used practically throughout the United States. It is only for pressures higher than 300 pounds that special fittings are required. Up to 200 pounds steam pressure with no superheat, cast iron or gun iron forms the ideal material for pipe fittings and is practically the only material in use. With the advent of superheated steam, however, the cast-iron fittings soon proved themselves to be useless with the high heats and semi-steel and steel fittings were tried with the best of results. To-day no plant using superheated steam installs cast-iron fittings for high-temperature work. All fittings should be provided with proper means of draining and drainage pockets or outlets should be placed at the lowest points for the attachment of the drainage system.

For dimensions and weights of various pipe fittings see *Kent's Mechanical Engineers' Pocket Book*. See also article in this book on *Valves*.

PIPE COVERINGS. — To prevent loss of heat by radiation, steam and feed-water pipes are usually protected with a cover, 1 inch or more in thickness, of loose non-conducting material. About 3 B.t.u. per square foot per hour per degree difference in temperature is radiated from a bare pipe under ordinary conditions. By the use of any good commercial covering from 75 to 85 per cent of this loss may be prevented. Pipe covering is usually applied in sections, moulded to fit the pipe, and held in place by bands. The covering for fittings and valves is usually applied in plastic form.

Cost of Pipe Covering (Pre-war figures). — Eighty-five per cent magnesia 1 inch thick costs in the neighborhood of 30 cents per square foot in place. In general such covering costs about one-half list price including labor. One writer states that one man will cover 100 feet of straight pipe

or 40 fittings per day up to 4-inch pipe size. Above 4 inch the cost pe 100 feet of pipe length will be greater owing to the increased labor of hand ling.

FLOW OF WATER THROUGH PIPES. — The pressure required t force a stream of water through a pipe is usually expressed in terms of the heigh of a column of water which would produce a static pressure equal to this pressur A pressure of

1 pound per square inch = 2.31 feet of water column,
1 foot of water column = 0.433 pound per square inch.

Friction and Velocity Head. — The head required to overcome th resistance of a pipe is called the "friction head," and for a given pipe an velocity of flow is proportional to the length of the pipe. The head require to overcome the resistance at the entrance to a pipe is called the "entry head; in the case of long pipes the entry head is negligible in comparison with th friction head. In addition to these two heads, a certain pressure, and therefor a corresponding head, is required to produce any change in the velocity of flow as, for example, when water enters a pipe from a reservoir. This velocit head is equal to $\frac{V_1^2 - V_2^2}{64.4}$, when the velocity changes from V_1 to V_2 feet pe second. A decrease in velocity gives rise to a *negative* velocity head. In lon pipes the velocity head is negligible.

Hydraulic Grade Line. — Imagine a horizontal line drawn over pipe line from a reservoir, and let this horizontal line be at the same elevatio as the surface of the reservoir. From each point of this horizontal line dro perpendiculars equal in length to the loss of head between this point an the reservoir. The locus of the foot of these perpendiculars is called th "hydraulic grade line." In a pipe leading from a reservoir no part of th length of the pipe should be above the hydraulic grade line. If the pipe ha vertical curves, valves should be provided at the high points to permit th escape of the air which tends to collect at the top of such curves, otherwis the pipe may become "air-bound," i.e., water will not flow although the supply is higher than the outlet.

Formulas Connecting Velocity, Discharge, and Head. — Various form ulas have been proposed to express the relation between velocity, discharge and head. Let

d = diameter of pipe in inches,
D = diameter in feet,
H = loss of head in pipe in feet of water,
L = length of pipe in feet,
p = loss of pressure in pipe in pounds per square inch,
Q = discharge in cubic feet per second,
V = velocity of flow in feet per second.

Unwin gives the following formula:

$$V = 4.012\sqrt{\frac{DH}{fL}},$$

where f is the coefficient of friction. This coefficient depends upon the smooth ness and cleanness of the pipe and also upon whether the pipe is straight or crooked, and upon the velocity. (*See Kent's Mechanical Engineers' Pocket Book.*) Rankine gives the following formula for f for smooth, clean, straight pipe:

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$$f = 0.005\left(1 + \frac{1}{12\,D}\right).$$

This formula is approximate only, since it does not take into account the velocity of flow. It is sufficiently accurate, however, for velocities up to 6 feet per second.

Combining these two formulas the following are obtained:

$$V = 16.4\,d\sqrt{\frac{H}{L\,(d+1)}} = 25\,d\sqrt{\frac{p}{L\,(d+1)}},$$

$$V = 57\,D\sqrt{\frac{H}{L\,(D+0.083)}} = 87\,D\sqrt{\frac{p}{L\,(D+0.083)}},$$

$$Q = 0.00545\,d^2V = 0.089\,d^3\sqrt{\frac{H}{L\,(d+1)}} = 0.136\,d^3\sqrt{\frac{p}{L\,(d+1)}},$$

$$Q = 0.785\,D^2V = 44.7\,D^3\sqrt{\frac{H}{L\,(D+0.083)}} = 68\,D^3\sqrt{\frac{p}{L\,(D+0.083)}}.$$

When the pipe is not completely filled with water, the same formulas hold provided d and D are taken as 4 times the hydraulic radius. The "hydraulic radius" is defined as the ratio of the area of the cross section of the water to that portion of the perimeter of the pipe in contact with the water.

These formulas apply approximately to any kind of clean, straight pipe, provided the interior surface is smooth. The formulas involving the head H also apply approximately to any kind of liquid or gas, provided H is taken as the height of a column of the given liquid or gas which will produce a static pressure equal to the fall in pressure in the pipe. The coefficients in the formulas involving the drop of pressure p should then be multiplied by $\sqrt{\frac{62.4}{w}}$, where w = weight in pounds of 1 cubic foot of the given liquid or gas, and 62.4 = weight in pounds of 1 cubic foot of water.

These formulas are for *new, clean, straight pipes.* For cast-iron pipes that have been in service a number of years the loss of head will be larger on account of corrosion and incrustation, and the value of H in the formulas should be multiplied under average conditions by the factors opposite; but they must be used with much discretion, for some waters corrode pipes much more rapidly than others.

10 years	1.3
20 "	1.6
30 "	2.0
50 "	2.6
75 "	3.4

The same figures may be used for wrought-iron pipes which are not subject to a frequent change of water.

From the above formulas for velocity the loss in head due to pipe resistance is

$$H = \frac{LV^2\,(d+1)}{270\,d^2} = \frac{LV^2\,(D+0.083)}{3250\,D^2}.$$

William Cox (*Amer. Mach.*, 1893) gives the following formula for pipes over 6 inches in diameter:

$$H = \frac{L\,(V^2 + 1.25\,V - 0.5)}{300\,d}.$$

The Pelton Water Wheel Co. advocates the following formula for riveted pipe for pipes over 6 inches in diameter:

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$$H = \frac{L(V^2 + 1.25V - 0.5)}{250d}.$$

Effect of Curves and Valves.—The resistance of curves and valves may be allowed for approximately by taking for L in the above formulas the actual length of the pipe plus a length equal to

$$\frac{kd^2}{d+1} \text{ feet, or } \frac{KD^2}{D+0.083} \text{ feet,}$$

for each curve or valve, where k and K have the following values:

	45° angle	90° angle	Gate valve	Globe valve	Angle valve
$k =$	0.8	4.2	0.8	8.1	12.4
$K =$	9	49	9	96	148

These coefficients are based on data given by Gebhardt (*Steam Power Plant Engineering*). Variations of 100 per cent or more from the values given may be expected, depending on the radius of the bends and design of the valves.

According to Briggs the effect of each right-angle bend is equivalent to increasing the length 40 diameters, and the effect of each globe valve is equivalent to increasing the length 60 diameters.

Water-Hammer. — From the formula given by Prof. I. P. Church the pressure developed by the instantaneous closing of a valve in a water pipe is

$$P_i = \frac{63.5V}{\sqrt{1 + \frac{300{,}000d}{MT}}} \text{ pounds per square inch,}$$

where M = modulus of elasticity of the pipe material and the other symbols are as above.

FLOW OF AIR AND GAS THROUGH PIPES. — (*See also preceding section.*) Let

d = internal diameter of pipe in inches,
L = length of pipe in feet,
p = fall of pressure in the pipe in pounds per square inch,
Q = discharge in cubic feet per second,
V = linear velocity in feet per second,
w = weight of 1 cubic foot of air or gas in pounds.

Then from Unwin's formula, using the same coefficients as for the flow of water, *when the fall of pressure is small,*

$$V = 198d\sqrt{\frac{p}{wL(d+1)}}. \quad (1)$$

$$Q = 1.08d^2\sqrt{\frac{p}{wL(d+1)}}. \quad (2)$$

For air: $w = \frac{2.70P}{460+t}$; for any other gas: $w = \frac{2.70GP}{460+t}$,

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where P = absolute pressure in pounds per square inch and t = temperature in degrees F and G = the specific gravity of the gas referred to air as unity. For ordinary illuminating gas $G = 0.65$.

Various authorities give different values of the numerical coefficients in the formulas for V and Q (*see Kent's Mechanical Engineers' Pocket Book*). The values given above, which are the same as for the flow of water ($w = 62.4$), are sufficiently accurate for rough calculations. The formula for Q may also be written

$$Q = Cd^2\sqrt{\frac{dp}{wL}}, \qquad (3)$$

where $C = 1.08\sqrt{\frac{d}{d+1}}$, corresponding to the coefficient 1.08 in equation (2).

C is frequently taken as unity for all sizes of pipes.

When the *fall of pressure is large*, the above formulas for Q give approximately the quantity per second at the *average* pressure in the pipe, provided the weight per cubic foot is taken corresponding to this *average* pressure. Or, putting P = the pressure in pounds per square inch at the *outlet* of the pipe, and w = weight per cubic foot at this pressure P, p being the fall in pressure, then the discharge in cubic feet per second at the pressure P is approximately (from equation 2)

$$Q = 1.08\,d^2\sqrt{\frac{p\,(P+0.5\,p)}{PwL\,(d+1)}}.$$

For d large compared with unity, $\frac{d}{d+1}$ may be taken sensibly equal to unity, and this expression may be written

$$Q = 1.08\,d^2\sqrt{\frac{p\,(P+0.5\,p)\,d}{PwL}}.$$

For $P = 14.7$ pounds per square inch, and $t = 60°$ F., then for air

$$Q_a = 1.02\,d^2\sqrt{\frac{p\,(P+0.5\,p)\,d}{L}}, \text{ cubic feet per second,}$$

and for illuminating gas of 0.65 specific gravity,

$$Q_g = 1.26\,d^2\sqrt{\frac{p\,(P+0.5\,p)\,d}{L}} \text{ cubic feet per second.}$$

Instead of the coefficients 1.02 and 1.26 the following values correspond to the coefficients in the formulas used by the authorities named:

	Instead of 1.02	Instead of 1.26
Wm. Cox (*Am. Mach.*, 1902)	0.95	1.18
J. E. Johnson (*Am. Mach.*, 1899)	0.96	1.19
E. A. Rix (*Pac. Coast Gas Assoc.*, 1905)	1.05	1.30

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Effect of Bends, Valves, etc. — The Norwalk Iron Works Co. give th following table; radius of elbow and length of pipe are both expressed in term of the pipe diameter:

Radius of elbow.....	5	3	2	1½	1¼	1	¾	½
Equivalent lengths of straight pipe.....	7.85	8.24	9.03	10.36	12.72	17.51	35.09	121.2

W. L. Saunders (*Compressed Air*, 1902) gives the following figures for the lengt of pipe in feet equivalent to each of the items listed:

Diam. of pipe, in..	1	1½	2	2½	3	3½	4	5	6	7	8	1
Globe valves.....	2	4	7	10	13	16	20	28	36	44	53	7
Elbows and tees..	2	3	5	7	9	11	13	19	24	30	35	4

FLOW OF STEAM. — The formulas given in the preceding section appl only approximately to the flow of steam. Putting v = volume of 1 pound c steam in cubic feet (*see tables under Steam*), the above formula for flow i cubic feet per second becomes

$$Q = 1.08\, d^2 \sqrt{\frac{vp}{L\,(d+1)}},$$

and the corresponding flow in pounds per second is

$$W = 1.08\, d^2 \sqrt{\frac{p}{vL\,(d+1)}}.$$

G. H. Babcock, in *Steam*, gives the flow in pounds per minute as*

$$W = 87 \sqrt{\frac{w p d^5}{L\left(1 + \frac{3.6}{d}\right)}}.$$

The corresponding flow in cubic feet per second may be written

$$Q = 1.45\, d^2 \sqrt{\frac{p}{wL\,(d+3.6)}}.$$

For a given drop in pressure this formula gives a less flow for pipes under 2 inche in diameter and a greater flow for pipes over 2 inches in diameter than is given by the corresponding formula for air or gas.

Size of Steam Mains. — Formerly steam mains of 18 to 24 in. in diameter were considered necessary in small stations and the radiation owing to the poor quality of pipe covering then used was enormous. At the present time very few mains are put in of larger size than 14 in. I. D. and in some cases a 10 or 12-in. main is considered sufficient. The drop in pressure between boiler and prime mover is considerably larger than formerly but the actual heat loss due to friction and radiation is very much less than it was. This reduction in pipe sizes also brought in great economies in the upkeep cost of the steam lines as with the high pressures carried at the present day it would be almost impossible to keep a 20 in. or 24-in. main tight under the conditions of actual service.

* w is pounds per cubic foot at entrance pressure.

For years a standard practice for the speed of steam in steam lines was 4000 ft. per minute as the minimum, 6000 as the average and 8000 as the maximum. This was considered the standard in the days when 125 pounds steam pressure was carried without superheat. At the present time with 200 pounds pressure and superheat which may extend as high as 200° F. above the saturation temperature, the minimum steam speeds are much higher and very few engineers are using as the minimum speed less than 8000 ft. per minute, the maximum in some cases running as high as 18,000 ft. with no bad results.

Many formulas have been used for determining pipe sizes for steam engines, but most of them are now obsolete. In "Power" for January 19, 1915, F. W. Salmon presents results secured by plotting the necessary data from a large number of successful plants.

Let A = area of pipe bore in square inches,
d = diameter of pipe bore in inches,
W = average pounds of steam per hour,
C = a constant for a given pressure in the pipe,

K = a constant $= \frac{\pi \times C}{4}$,

then

$$W = A \times C = d^2 \times K,$$

or

$$d^2 = \frac{W}{K}.$$

The values of C and K are given in the following table.

Vacuum, in. of Hg	C	K	Gage pressure lb. per sq. in.	C	K
28	50	39.2	80	267	210.0
26	84	66.0	100	275	216.0
24	105	82.5	125	284	223.0
22	122	95.7	150	291	229.0
20	134	102.0	175	298	234.0
18	144	113.0	200	304	239.0
16	151	118.6			
13	162	127.0			
6	176	138.0			
0	187	147.0			

EXPANSION OF PIPE. — The coefficient of expansion for ordinary steam pipe is about 0.000006 of its length for each degree F. A rough and ready rule is to allow ½ in. for every 100 ft. for every 100° F. difference of temperature. All pipe lines should be laid out to take care of this expansion, and to this end large radius bends should be employed wherever possible. It is usual to cut the pipe so it will be the right length when it is hot, making up the joints and pulling them together, so that an initial stress is put in the cold pipe. When the pipe becomes hot, this stress disappears and the pipe will then be in equilibrium. Suitable hangers should be provided every 10 or 12 ft. to support the pipe in its proper place. These may consist of a band around the pipe with a

rod hanger from some of the floor beams overhead, or the pipe may be s
from below on a roller. Anchors should also be provided at certain
that the direction of expansion may be controlled. On very long line
expansion joints become necessary, or the corrugated-steel expansion j
be used.

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POLES FOR OVERHEAD LINES. — (*See also Cross Arms; Distribution Lines; Insulator Pins; Insulators; Transmission Lines.*) The following is a brief table of contents of this article:

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Methods of Specifying Pole Dimensions. — A pole for supporting an overhead line is usually specified by its *total* or "nominal" length and by the diameter of its top; e.g., a 40-ft 7-in. top pole. When set, the distance a pole stands above the surface of the ground is less than the nominal length by the amount it sets in the ground. Poles are standard in lengths which are multiples of 5 feet. The ordinary range of length is from 30 to 60 feet.

The top of a pole is sometimes specified by inches circumference instead of by diameter. Poles are standard in diameters which are even multiples of one inch. The ordinary range of top diameter is from 7 to 8 inches except on the Pacific Coast, where from 8 to 10 inches is common.

Taper of Poles. — The taper of various kinds of poles, specified as the difference, measured in inches, between two circumferences 10 feet apart, is given as follows in *Forest Service Bull. No. 84:* Chestnut (Maryland), 3.8 to 4.0; Northern white cedar (Michigan), 5.2; Western yellow pine (California), 4.0; Lodgepole pine (Montana), 3.0; Loblolly pine (Texas), 2.4; Western red cedar (Washington), 3.5. Trees grown upon a high elevation have a greater taper in the trunk than trees grown lower down.

WOODS USED FOR POLES AND CROSS ARMS. — (Based on publication of the Forest Service, see *Bibliography.*) Of the timbers used for poles, chestnut and northern, southern and Idaho cedar easily rank first. Longleaf and shortleaf pine, red cedar, cypress, redwood, locust, catalpa and several of the oaks are used, but in much smaller numbers, and their employment is generally confined to the region of their growth. Still other timbers are used, but in numbers insignificant in comparison with those mentioned above.

For cross arms, longleaf, shortleaf and loblolly pines of the South and Norway pine of the North are most largely used, while the demand for cedar, cypress, spruce and red fir is but little less. Again, as in the case of pole timbers, a third group may be formed of those timbers used in small numbers and very locally.

In 1915, of the 4,077,964 poles purchased in the United States, 61.8 per cent were cedar, 16 per cent were chestnut, the remainder being oak, pine, cypress, etc.

Desirable Timber for Poles. — The several qualities which timber must possess to adapt it to use for poles are stated to be: Durability in contact with the soil, minimum weight, straightness coupled with relatively small size and little taper. The wood must be soft, so that the spikes of a climber may enter readily and at the same time it must have strength to support considerable

weight. These qualities are admirably combined in cedar and in juniper, which commercially is a cedar; no other woods possess so many.

Uncertainties in Names of Timber Trees. — The terms cedar, pine, etc used in describing poles and cross arms and even the apparently more exact terms, such as white cedar, yellow pine, etc., each cover several kinds of trees and have different meanings in different localities.

There are at least eight pines (of the thirty-five native ones) in the market some of which so closely resemble each other in their minute structure that they can hardly be told apart; and yet they differ in quality and should be used separately, although they are often mixed or confounded in the trade.

Referring to the use of yellow pine as the material for cross arms the Committee on Overhead Line Construction of the N. E. L. A., says: "Yellow pine is understood to cover what is commonly known as longleaf pine. It is understood that the term is descriptive of quality rather than of botanical species." Forestry Bulletin No. 10 states: " 'Yellow pine,' is applied in the trade to all the Southern lumber pines; in the Northeast it is also applied to the pitch pine; in the West it refers mostly to bull pine. 'Yellow longleaf pine,' 'Georgia pine,' chiefly used in advertisement, refers to longleaf pine."

Timbers Ordinarily Used for Poles and Cross Arms. — The principal timber trees from which poles and cross arms are obtained are briefly described below in accordance with the names used in the publications of the Forest Service.

Chestnut. — Chestnut ranks next to the cedars in the quantity of poles used. The reported number purchased in 1909 was 608,000. The sapwood is very narrow, usually from about ⅛ to ⅜ of an inch wide. Chestnut is widely distributed throughout the entire Appalachian mountain region. A small territory embracing parts of Pennsylvania, Maryland, Virginia and West Virginia furnishes nearly all the chestnut poles. Chestnut is not so straight as cedar and is liable to be knotty. It has greater strength, but this advantage is more than counterbalanced by its greater weight, which prohibits long shipments.

Northern White Cedar or Arborvitæ. — This species is very commonly used for poles throughout the central and eastern portion of the United States. The principal source of supply is in the states bordering the Great Lakes. It makes a very desirable pole on account of its durability but is high-priced. The sapwood varies from ½ to 1 inch in thickness. A very large portion of northern white cedar poles have unsound butts. Northern white cedar, common in the northern woods of New England, New York and the Lake States, occurs as far south as North Carolina and Tennessee, but only in the mountains where the elevation is sufficiently great to permit northern species to thrive.

On account of its strength, lightness, durability and form it is the most desirable pole timber. Arborvitæ is extremely slow in growth. The sapwood zone is narrow at the butt and gradually widens as the top is approached. The average time it takes to produce a 30-foot arborvitæ pole is about 190 years.

Southern White Cedar. — The number of southern white cedar poles purchased in 1909 was 44,000. The woods known under the general name of "cedar" comprise a number of distinct species which differ in their durability, the white cedar of the southern swamps being somewhat less durable than the cedar of the Lake States. The sapwood, which is usually from ½ to 1 inch wide, decays very quickly. Southern white cedar, though sometimes found as far north as southern Maine, is of commercial importance chiefly south of Delaware and New Jersey.

Red Cedar. — A small to medium-sized tree scattered through the forests, or, in the West, sparsely covering extensive areas (cedar brakes). The

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red cedar is the most widely distributed conifer of the United States, occurring from the Atlantic to the Pacific and from Florida to Minnesota, but attains a suitable size for lumber only in the Southern and more especially in the Gulf States.

Juniper. — The term Juniper is commonly used by telephone men for southern white cedar; the term also is applied to red cedar. Juniper poles come from Virginia, the Carolinas and other South Atlantic States.

Western Red Cedar. — The light and durable western red cedar is much used for poles on the Pacific coast and throughout the Northwest. Also it competes to a certain extent with northern white cedar in the East, its form and size making it especially desirable for the larger classes of poles. The principal points of production are northern Idaho and western Washington. The relative durability of western red cedar and northern white cedar under similar conditions is not known, and the testimony by pole users on this point is somewhat contradictory.

Cypress. — The cypress is a large deciduous tree, occupying much of the swamp and overflow land along the coast and rivers of the Southern States. Cypress is usually considered a durable wood, and the heartwood is, in fact, one of the most durable of our native species. The sapwood, however, decays quickly and this seriously weakens the pole. The width of the sapwood on pole-size trees is from ¾ of an inch to 1¼ inches. Cypress frequently is too large for use as a pole and has greater value for lumber. Even when its general diameter is small enough the butt will often be so big that it adds too much weight.

Longleaf Pine. — Large tree; forms extensive forests and furnishes the hardest and strongest pine lumber in the market. Coast region from North Carolina to Texas. The longleaf pine is strikingly heavy, hard and resinous, and usually very regular and narrow ringed, showing little sapwood, and differing in this respect from the shortleaf pine and loblolly pine, which usually have wider rings and more sapwood, the latter excelling in that respect.

Shortleaf Pine. — Resembles loblolly pine; often approaches in its wood the Norway pine. The common lumber pine of Missouri and Arkansas, North Carolina to Texas and Missouri.

Loblolly Pine. — Large-sized tree; forms extensive forests; wider-ringed, coarser, lighter, softer, with more sapwood than the longleaf pine, but the two often confounded. This is the common lumber pine from Virginia to South Carolina and is found extensively in Arkansas and Texas, Southern States, Virginia to Texas.

This pine is not durable when used as a pole unless treated with preservatives, but because of its cheapness and ease of impregnation is very desirable if preservative treatment is contemplated. Its distribution, ease of reproduction and rapidity of growth insure a steady and cheap supply. When this timber is used it is necessary to treat the entire pole instead of only the butt, especially in the warmer and more humid localities of the South.

Norway Pine. — Large-sized tree; never forming forests, usually scattered or in small groves, together with white pine; largely sapwood and hence not durable. Minnesota to Michigan; also in New England to Pennsylvania. The Norway pine, which may be confounded with the shortleaf pine can be distinguished by being much lighter and softer. It may also, but more rarely, be confounded with heavier white pine, but for the sharper definition of the annual ring, weight and hardness.

Western Yellow Pine. — Western yellow pine is used for poles to a limited extent in certain parts of the Southwest, where the high cost of more

durable pole timbers makes it necessary to find a cheaper substitute. The li of this timber, untreated, is very short. In the upper part of the San Joaqu Valley of California, where a study of this species was made, untreated pine pol last only two or three years; but since the wood when not exposed to the s is fairly durable, it is believed that a butt treatment with a good wood preserv tive will result in a pole that will give good service. A butt-treated pine po costs considerably less than an untreated cedar pole in this locality.

Lodgepole Pine. — Lodgepole pine is cut to a limited extent for pole It grows at high altitudes in the Rocky Mountains. It decays quickly in conta with the soil, but is durable when not so exposed. The tree grows tall an straight, with very little taper and makes a well-shaped pole. In certain par of the West, where there are large bodies of fire-killed lodgepole that rema standing for many years, sound and thoroughly seasoned, conditions for effecti treatment are excellent. If given a butt treatment, this dead timber makes durable pole, and in many localities the cost of the pine pole plus the cost of t treatment is less than that of the Idaho cedar untreated. The sapwood of pol sized timber may be an inch or an inch and a quarter thick.

DEFECTS IN WOOD USED FOR POLES AND CROSS ARM — (*See also Timber.*) The following are the defects in timber which are fr quently referred to in specifications for poles and cross arms.

Pith. — The pith of a tree is the central core about which the annu rings are formed. It goes through the tree from top to bottom and branch into the limbs. The pith is quite thick, usually ⅛ to ⅓ inch in Norway pine ar in the southern species, though much less so in white pine and is very thin ¼ to 1/16 inch in cypress, cedar and larch. The pith of the tree is the weakest pa on account of the many knots which it invariably and necessarily contains.

Sapwood. — The sapwood of a tree is a zone of wood next to the bar 1 to 3 or more inches wide and containing 30 to 50 or more annular rings (i coniferous trees). It is of lighter color than the inner, darker part of the l which is the heartwood. Sapwood changes to heartwood as the tree grows.

The width of the sapwood is small for longleaf and white pine and great f loblolly and Norway pines. In old trees of longleaf pine the sapwood form about 40 per cent of the merchantable log, while in the loblolly and in all youn (coniferous) trees the bulk of the wood is sapwood.

Sapwood, being the normal condition of the outer rings of a tree, is not "defect" in poles, where the whole cross section of the tree (except bark) is use Being weaker and more liable to decay it is considered a "defect" in pins an cross arms, which are better if made from the heartwood only.

Cup-Shakes. — These are cracks extending circumferentially at one o more places, caused by the separation of the annual rings.

Doatiness. — This is a speckled stain found in beech, American oa and other timber, due to incipient decay. It is produced by imperfect season ing or by exposure for a long period to a stagnant atmosphere.

Heart-Shakes. — These are splits or clefts occurring in the center of th tree. They are common in nearly every variety of timber and are very seriou when they twist in the length, as they interfere with the conversion of the tre into boards or scantlings. They sometimes divide the log in two for a few fe from the end.

Star-Shakes. — When several heart-shakes occur in one tree they a called star-shakes from the appearance produced by their radiation from th center.

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Wind-Cracks. — Shakes or splits on the sides of a balk (a log which has been squared off) of timber, caused by shrinkage of the exterior surface, are called wind-cracks.

Dry Rot. — Dry rot is a special form of decay in timber caused by the growth of a fungus which spreads over the surface like a close network of threads, white, yellow or brown, and causes the inside to perish and crumble. Causes which render timber favorable to the growth of this fungus are; large proportion of sapwood; felled at wrong season when full of sap; if cut down in the spring or fall of the year instead of in midwinter or midsummer, when the sap is at rest; stacked for seasoning without sufficient air spaces being left; fixed before thoroughly seasoned; painted or varnished while containing moisture. (Six preceding definitions from *Carpentry and Joinery* by *Paul N. Hasluck.*)

Sound Knot. — A sound knot is one which is solid across its face and which is as hard as the wood surrounding it; it may be either red or black, and is so fixed by growth or position that it will retain its place in the piece.

Loose Knot. — A loose knot is one not firmly held in place by growth or position.

Pith Knot. — A pith knot is a sound knot with a pith hole not more than one-fourth of an inch in diameter at the center.

Encased Knot. — An encased knot is one which is surrounded wholly or in part by bark or pitch. Where the encasement is less than one-eighth of an inch in width on both sides, not exceeding one-half the circumference of the knot, it shall be considered a sound knot.

Rotten Knot. — A rotten knot is one not as hard as the wood it is in.

Pin Knot. — A pin knot is a sound knot not over one-half inch in diameter.

Spike Knot. — A spike knot is one sawn in a lengthwise direction. The mean or average width shall be considered in measuring these knots.

Pitch Pocket. — A pitch pocket is an opening between the grain of the wood containing more or less pitch or bark.

Pitch Streak. — A pitch streak is a well-defined accumulation of pitch at one point in the piece. When not sufficient to develop a well-defined streak, or where the fiber between grains — that is, the coarse-grained fiber, usually termed "spring wood" — is not saturated with pitch, it shall not be considered a defect.

Wane. — Wane is bark, or lack of wood from any cause, on edges of timber.

Shakes. — Shakes are splits in timber which usually cause a separation of the wood between annual rings.

Checks. — Checks are splits in timber, which usually cause a separation of the wood across annual rings. (Last twelve definitions are those used in the timber-test work of the Forest Service in describing defects. *Forest Service Circular 38, Revised.*)

Wind Shake. — A crack or incoherence in timber produced by violent winds while the timber was growing.

Wind. — A turn or bend. A piece of timber is out of wind when it is perfectly straight or flat.

Warped. — Twisted out of shape by seasoning.

Cat-Faces. — Old wounds, partially overgrown, leaving a long, narrow, dead surface exposed.

VOLUME AND WEIGHT OF POLES. — A quick way to find the approximate volume of a pole is to multiply the area of the circle at the center of gravity

by the length of the pole. The formula for the volume, considering a pole as frustrum of a cone is

$$v = \frac{\pi}{1728}(d_1^2 + d_1 d_2 + d_2^2)h,$$

where v = volume in cubic feet; d_1 = diameter at butt in inches; d_2 = diamet at top in inches; h = length of pole in feet.

The following table gives the volume of some standard poles:

Kind of pole	Nominal size		Volume, cubic feet
	Diameter, inches	Length, feet	
Chestnut	7	30	20.0
Southern white cedar	7	30	20.8
Northern white cedar	7	30	17.6
Western red cedar	8	40	27.3
Western yellow pine	8	40	26.0

The weight of a pole may be found by multiplying its volume in cubic f by its weight per cubic foot. The following table gives the weight per cubic fo

WEIGHT PER CUBIC FOOT OF POLES

Kind of pole	When cut		When seasoned	
	Weight,* pounds per cubic foot	Moisture, per cent of dry weight	Weight,* pounds per cubic foot	Moisture per cent o dry weigh
Southern white cedar	38.9	88	25.0	21
Chestnut (N. C.)	56.5	101	43.2	54
Chestnut (N. J.)	51.8	85	42.2	50
Chestnut (Pa.)	54.0	92	40.7	45
Chestnut (Md.)	56.4	86	44.9	48
Northern white cedar	34.2	90	22.9	27
Western red cedar	42.4	133	23.5	29
Western yellow pine	66.6	154	30.3	16

* Including contained moisture.

SEASONING.— Poles should be seasoned because it increases their resis ance to decay, increases their strength and decreases their weight. The streng of partially seasoned timber, other things being equal, increases as the amou of moisture it contains decreases. Thoroughly seasoned timber of small siz is sometimes three or even four times as strong as the same timber, when gree Seasoning of poles reduces their weight, commonly from 16 to 30 per cent, a even more for some species, with a corresponding decrease in the cost of tran portation. Thorough seasoning is essential if the poles are to be treated wi preservatives. The percentage of moisture in a pole when cut varies with t season when cut as shown in the table at top of p. 1149.

In general, poles cut during the spring and summer lose weight most rapidl Poles cut during autumn and winter lose weight less rapidly, but more regular

seasoning may be detrimental to the timber by causing excessive Shrinkage of poles during seasoning is very slight and does not er cent on the circumference.

URE CONTENT WHEN CUT, PER CENT OF DRY WEIGHT

Kind of pole	Spring	Summer	Autumn	Winter
white cedar (N. C.)	68	77	87	88
(N. C.)	97	91	95	101
(N. J.)	81	83	81	85
(Pa.)	89	92	88	88
(Md.)	83	84	85	86
white cedar (Mich.)	77	82	79	90
ed cedar (Cal.)	...	133	...	...
ellow pine (Cal.)	149	147	145	154

e in months required for poles cut at different periods of the year o approximately air-dry weight is as follows:

TIME REQUIRED FOR SEASONING

nd of pole	Spring	Summer	Autumn	Winter	Moisture content* seasoned
	Months	Months	Months	Months	Per cent
(Md.)	5	4	8	7	55
white cedar					
	3	3	8	5	26
white cedar					
	12	9	7	6	37
red cedar (Cal.)	....	....	....	....	43
yellow pine (Cal.)	5	3	9	6	25

verage amount of moisture remaining in the poles after seasoning as above in the weight of the dry wood.

ING. — If the top of a pole is left flat rain water will not run off d will penetrate the pole by following the grain, causing early decay e top. Poles are accordingly "roofed" by cutting the top to give an rface which is sometimes conical but usually is merely two inclined eting in a horizontal ridge. The angle of the planes with the horizontal 45 degrees. Where a bracket is to be bolted to top of pole a flat strip 1 inch in width is sometimes left, instead of a sharp ridge, in order to e material in the pole top where the strain from the upper bracket s. Roofs should be painted to close the grain which is porous, in order t the entrance of water.

SRVATIVE TREATMENT. — The forest service estimate that it 90 years to grow a 30-foot cedar pole whose average life, when set in the its natural state, does not exceed 15 years. They also find that of the poles in use have to be replaced annually. Taking into account er of poles in use, they conclude that the enormous demand must soon

deplete the supply and have made extensive experiments on preservative treatment as a means of conserving the pole supply.

Preservative treatments are used to increase the resistance of poles to decay. The advantages of such treatment are:

1. It increases the life of the pole.
2. It makes possible the use of smaller poles as less allowance need be made for decay.
3. It makes possible the use of species of timber not naturally durable.

The butt of the pole near the ground line is most subject to decay and treatment of the butt alone is usually deemed sufficient. In some of the Southern states the whole pole is subject to decay, in which case the whole pole is treated.

Cause of the Decay of Timber. — Decay of wood is due to low forms of plant life called fungi. The germs of decay are not inherent in the wood. The wood-destroying fungi start from the outside, either from adjacent rotten wood or by spores, which correspond to seeds, being carried by the wind and deposited on the surface. While the fungi from these spores begin at the "outside" of the wood, this surface must be understood to include all holes or cracks which the spores may enter.

Fungi require for their growth and development air, heat, moisture and food. Warmth, preferably between 60° and 100° F., favors decay. Cold retards it and temperatures above 150° F. prevent it. Under water or deep under the surface of the ground where the air is excluded, decay does not take place. Ordinarily wood which is seasoned until it is air-dry does not contain sufficient moisture to support the growth of fungi.

Preservatives. — The best method of checking the growth of fungi is to deprive them of food. This can be done by injecting poisonous substances into the timber. These substances are called preservatives. Of the many antiseptics which have been proposed for the preservation of timber only four have been largely used with success in the United States. These are creosote, zinc chlorid, corrosive sublimate and copper sulphate. Copper sulphate has fallen into almost total disuse. At present creosote and zinc chloride, pure or in mixture, are the only preservatives which are in general use.

Corrosive Sublimate (Bichlorid of mercury). — This is used in the so-called "kyanizing" process. This process consists in steeping the timber in a dilute solution of corrosive sublimate long enough to insure thorough penetration.

Zinc Chloride. — Zinc chloride is an excellent antiseptic; it is obtained by dissolving metallic zinc in hydrochloric acid. This is further diluted by water before it is used for wood preservation. Zinc chloride is much cheaper than creosote, and since it is shipped in the form of a solid the freight charges are considerably less. Zinc chloride is soluble in water, being in fact, injected into the timber in water solution and so when timber treated with it is exposed to moisture the leaching out of the salt is only a question of time. Hence zinc chloride is most commonly used in comparatively dry situations.

Creosote. — Creosote is a by-product of coal tar, which is produced at most plants for the manufacture of illuminating gas and at by-product coke-oven plants. Wood tar, when distilled in a similar manner, gives "wood creosote," which like that derived from coal tar, possesses strong antiseptic properties. There is also on the market a so-called creosote, a by-product of water-gas tar or tar manufactured from kerosene oils, which, for wood preservation, is probably inferior to the true creosote. In general, however, by "creosote" is meant the dead oil of coal tar.

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Creosote is not a single chemical compound but a mixture of a number of compounds. Not only does the relative proportion of the several constituents vary, but some may be absent or other compounds, not normally constituents of creosote, may be present. Creosote proper is the fraction of oil passing over between 240° C. and 270° C. during the first distillation of the crude coal tar. In practice, however, many of the creosote oils of commerce contain considerable amounts of materials having boiling points higher than 270° C. and lower than 240° C. Some commercial creosotes are rather thin oils, some are almost entirely solid with naphthalene and some are heavy oils with a large proportion of high-boiling constituents.

An analysis of creosote in well-preserved timbers (*Forest Service Circular 98*), led to the conclusions that light oils, boiling below 205° C., will not remain in timber, but that heavy oils, containing a high percentage of anthracene oil, will remain almost indefinitely and protect the wood from decay and boring animals.

The cost of creosote in carload lots (including transportation) is (1921) about 40 cents per gallon for points east of the Mississippi River and in the vicinity of the Gulf ports west of the Mississippi. West of the Rocky Mountains the cost is about 50 cents per gallon. A gallon of creosote is estimated to be 8½ to 9 pounds.

Patented Preservation. — There are many other patented substances known by various names, but most of them have for their base creosote or zinc chloride.

Carbolineum. — Carbolineum, like creosote, is derived from the distillation of coal tar. The compounds included in carbolineum are derived from the coal tar at a higher temperature of distillation and are therefore somewhat different.

Crude Petroleum. — Crude petroleum has been experimented with but there is little definite knowledge of its value as a wood preservative.

Methods of Treatment. — The methods of applying the preservatives to the pole are the brush treatment, open tank treatment and pressure tank treatment.

The brush treatment is applied to a part of the butt at the ground line, the open-tank treatment to the whole butt and the pressure-tank treatment to the whole pole.

The brush treatment is least expensive and gives the least protection and the pressure tank is most expensive and gives the most protection.

For a full description of these methods of treatment and estimates of cost see *U. S. Forest Service Circulars, Nos. 84, 147, etc.*

An estimate in 1921 for a two-coat brush treatment of the butts with creosote is approximately 50 cents per pole. Another way in which this may be figured is on the basis of the amount of creosote and the amount of labor required to treat one pole, as follows: It takes 2 to 3 pounds of creosote (¼ to ⅓ pound per square foot of surface treated) for one pole, and an efficient man about ½ hour to apply it. The cost of open-tank treatment of the butt with creosote varies from $2 for a 25-foot 7-inch pole to $13 on a 60-foot 8-inch pole. This cost mounts rapidly for large poles because the butt is not only of greater diameter but a greater depth has to be treated.

LIFE OF POLES. — Statistics compiled by the National Electric Light Association give the following figures for the average life of *untreated* poles; the figures for *butt-treated* poles are according to estimates by the U. S. Forest Service.

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Untreated	Years	Butt-treated	Years
Cedar	13.5	Chestnut	20
Chestnut	12.0	Western cedar	20
Cypress	9.0	Northern white cedar	22
Pine	6.5	Pine, in dry climates	20
Juniper	8.5		

Records of the German Postal and Telegraph Department covering 52 years show an average life of 20.6 years for creosoted pine poles.

SPECIFICATIONS FOR POLES. — In the report of the Committee on Overhead Line Construction of the National Electric Light Association (abbreviated N.E.L.A.) are given very complete specifications for chestnut, eastern white cedar and yellow pine poles. Space does not permit of the incorporation of these specifications here; copies may be had from the National Electric Light Association, 33 W. 39th St., New York.

FORCES ACTING ON A POLE.—A pole is subject to the following forces:

(1) Vertical forces due to weight of pole, wires, sleet, etc., and to downward pull of guys.
(2) Lateral horizontal forces due to wind across line on pole, wire, sleet, etc.
(3) Longitudinal horizontal forces due to unbalanced pull of wires.
(4) Torsional forces due to unbalanced pull of wires.

A pole is strong as regards the vertical forces but weak for horizontal forces and the cross arms are weak for the torsional forces. The theory of good line work is, therefore, first to reduce the horizontal and torsional forces as much as possible by balancing the stresses and second to convert remaining unbalanced horizontal stresses into vertical stresses on the pole by the use of guys.

In practice the lateral horizontal force of the wind is one which cannot ordinarily be provided for by guys. Calculations for strength of poles, when made, are ordinarily limited to the effect of side wind.

Breaking of Pole by Cross Wind. — The principal forces tending to break a pole are wind pressures on pole and conductors when the wind blows transversely. These tend to break it by cross bending.

Let M_1 = moment of the wind on the pole,
M_2 = moment of the wind on the wires,
M = moment of resistance of the pole.

Then the condition that the pole shall not break is that

$$M_1 + M_2 < M.$$

The calculation of M_1, M_2 and M is given below.

Moment of Wind on Pole (M_1). — Moment at ground level due to wind pressure on pole is

$$M_1 = \frac{P_1 H_1^2 (D_1 + 2 D_2)}{72},$$

M_1 = moment at the ground in pound-feet,
P_1 = wind pressure in pounds per sq. ft. of projected area of pole,
H_1 = height of pole in feet,
D_1 = diameter of pole at ground in inches,
D_2 = diameter of pole at top in inches.

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mum bending moment due to horizontal forces at the top of the
arily assumed to be at the ground level; it is really a little below
and opposite the center of pressure of the resistance furnished by

ent of Wind on Wires (M_2). — Moment at ground level due to
e on the wires is

$$M_2 = \frac{P_2 H_2 nd\ (S_1 + S_2)}{24},$$

nent at the ground in lb.-ft.,
d pressure in pounds per sq. ft. of projected area of wires,
ht of wires above ground in feet,
ber of wires,
neter of wires (including ice) in inches,
= lengths of adjacent spans in feet.

es are of different diameters or at different levels the formula is to
each size and each level separately and moments summed.

FIBER STRESS AND BREAKING LOAD

imber	Test specimen	Fiber stress at elastic limit, pounds per square inch	Fiber stress at rupture,* pounds per square inch	Actual force at rupture, pounds
(1).....	2 by 2 by 30 in....	2600	4250	....
tern....	25-ft. pole.....	....	5000 (5)	1310 (3)
tern (4).	25- to 35-ft. poles..	....	....	2215
tern (4).	25- to 35-ft. poles..	....	....	1930
4).....	25- to 35-ft. poles..	....	....	3040
laine (2)	29- to 31.5-ft. poles.	....	3200 to 5600	1235 to 2650
laine (2)	.....	....	3600 (5)	....
Conn. (2)	29- to 31.5-ft. poles.	....	4500 to 9780	1540 to 3240
.....	.....	4430 (1)	7110 (1)	....
	.....	....	5000 (5)	....
e (1)...	2 by 2 by 30 in....	3080	5130	....
e (3)...	25-ft. pole.....	....	....	1330
(1).....	2 by 2 by 30 in....	5090	8630	....
(1).....	2 by 2 by 30 in	4360	7710	....
dense(5)	.....	....	6500	....
Cal. (1).	2 by 2 by 30 in	3180	5180	....
(5).....	.....	....	3600	....
lmann (3)	25-ft. pole.....	....	....	1405

ervice Cir., No. 213; green, clear pieces.
Winchester, *Elec. W., March 16, 1911;* top circumference 1[illegible] to 21[illegible] inches,
ound from 4 to 6 ft., force applied 22 ft. to 26 ft. above gro[illegible]
ervice Cir., No. 204: 7 in. top diameter, force applied at top
. & Tel. Co.: from 6 to 9 in. top diameter, force applied at top.
l Electrical Safety Code.
f Rupture.

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Moment of Resistance (M). — The moment of resistance or strength of a circular pole for cross bending is

$$M = \frac{f\pi D^3}{384} \quad \text{or} \quad = \frac{fD^3}{122}.$$

M = moment of resistance of the section considered in lb.-ft.,
f = fiber stress in pounds per sq. in.,
D = diameter of pole in inches.

The maximum allowable moment M is found by using the maximum allowable value for the fiber stress f.

Fiber Stress (f) **and Actual Tests of Strength.** — The table on page 1153 gives the value of the fiber stress for various kinds of timber and the actual breaking load from tests of a number of poles.

Weakest Point of a Pole. — A pole is approximately a truncated cone in shape. For a bending force applied at one end such a cone is weakest at the point where the diameter is ⅔ the diameter at the point (near the small end) where the force is applied. A pole with 8-inch diameter at the cross arm is, therefore, weakest where it is 12 inches in diameter and may be expected to break at this point provided this point is above the place where maximum bending occurs. If it is less than 12 inches in diameter at the point of maximum bending then the break may be expected here. This rule must be considered approximate as it neglects the fact that the pole is not homogeneous, i.e., outer annual rings are sapwood and inner are heartwood, and also neglects effect of knots, etc.

ATTACHMENT OF CROSS ARMS TO POLES. — Wooden cross arms are attached to wooden poles:

(1) By gaining the pole, see below.
(2) By one or two lag screws or bolts.
(3) By one or two cross-arm braces.

The forces at the point of attachment which these fastenings must resist are:

(1) A force vertically downward, equal to weight of cross arm, pins, insulators and wire (including sleet).

(2) A horizontal force parallel to axis of arm, equal to pressure of wind blowing across line on wires.

(3) A horizontal force at right angles to axis of arm: (a) toward pole or (b) away from pole and equal to difference in pull of wires on two sides of arm.

(4) A couple in a vertical plane parallel to arm, equal to difference in moments of weight on the two ends of arm.

(5) A couple in a horizontal plane parallel to arm, equal to difference in moments of wire pull on the two ends of arm.

(6) A couple in a vertical plane at right angles to arm, equal to difference in moments of wire pull (caused by pin leverage) in the two directions.

Framing and Hardware. — Typical framing and hardware for the three principal combinations of arms (single arms, double arms and buck arms on corner poles) are shown in Figs. 1, 2 and 3, respectively. These are standard framings of the Stone & Webster Engineering Corp. The arms shown are all 6 pin, but the framing would be the same, except for length of arm for 4-, 8- or 10-pin arms.

Gaining. — A gain is a notch cut in the side of a pole to receive a cross arm. The width (vertical dimension) of the gain should be just large enough for the cross arm. The depth of gain varies from ½ to 1 inch. With gains shallower than ½ inch the cross arm has insufficient support below and the flat bearing

surface at the back is inadequate unless the pole is of larger diameter than usual. Deep gains greatly weaken the top of the pole especially when double arms are used. Gains should be painted before arms are attached to prevent moisture entering the wood through the cut surface.

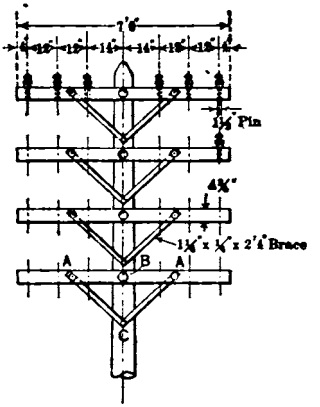


Fig. 1. Pole Top Framing, Single Arm

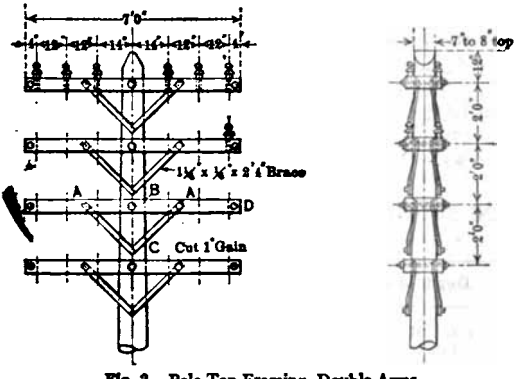


Fig. 2. Pole Top Framing, Double Arms

Specification for Framing. — Gaining shall be as follows:

Top of pole to center of top gain, 12 inches.

Center to center of gains, 24 inches.

Gains for buck arms shall be located centrally between gains for main arms.

Gains shall be cut not over 1 inch deep.

Arms shall be fastened to pole by one through bolt. Back of pole shall be flattened to give true bearing surface for washer under head of bolt. Each arm shall be braced by two braces fastened to back side of arm. Ends of double arms shall be separated by spacing blocks and shall be bolted together.

Specification for Hardware. — All hardware shall be galvanized iron.

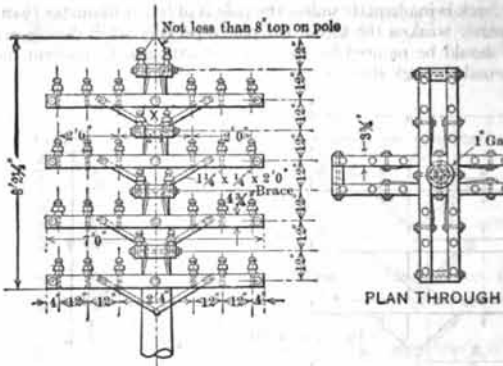


Fig. 3. Pole Top Framing, Corner Poles

Bolts. — Arms shall be fastened to pole with one ⅝-in. m
Double arms shall be fastened together by one ⅝-in. machine bolt
Above bolts shall have 6-in. thread to allow for variation in thickn
For fastening double arms to poles stud bolts having a nut at eac
be used. Braces shall be fastened to arms by ⅜-in. machine bolts.

Washers. — Square-cut iron washers shall be used at both e
fastening arms to poles and at both ends of bolts fastening double ar
Round-cut washers shall be used with machine bolts for fastening bra

Nuts. — Square nuts shall be used.

Braces. — Two braces shall be used on each arm. Bra
28 in. by 1¼ in. by ¼ in. except on corner poles, where 24 in. by 1¼
braces shall be used.

Lag Screws. — Braces shall be fastened to pole by ½ in.
screws.

DEPTH OF SETTING IN GROUND. — The following tab
depth of setting recommended by the National Electric Light Asso

Total length of pole, feet	Depth of setting, feet		Total length of pole, feet	Depth of se	
	Straight line	Curves and corners		Straight line	
30	5.0	6.0	60	7.0	
35	5.5	6.0	65	7.5	
40	6.0	6.5	70	7.5	
45	6.5	7.0	75	8.0	
50	6.5	7.0	80	8.0	
55	7.0	7.5			

GUYING OF POLES. — A guy is ordinarily composed of guy w
strain insulators, turnbuckles (sometimes) and guy stub or guy anc

Guy Wire. — Iron wires are used for guy wires but should alw
vanized (*see Galvanizing*). Solid wire was formerly common but st

is now generally used. Various sizes have been used but the bly the best. The N.E.L.A. specification for the two sizes em is:

e	Strands	Size of individual wires, B. W. G.	Ultimate breaking strength
ch			Pounds
	7	14	2300
	7	12	5000

ators. — Strain insulators are placed in guys to prevent the e guy wire, which is accessible to the public, becoming charged or contact with a conductor. Two strian insulators should be d about 5 feet from the pole and the other 8 feet above the

strain insulator are used. In one the insulation (usually im- is in tension, while in the other (usually porcelain) it is in com- ormer has the disadvantage that failure of the insulation causes e of the guy. The latter has the disadvantage that the insulator

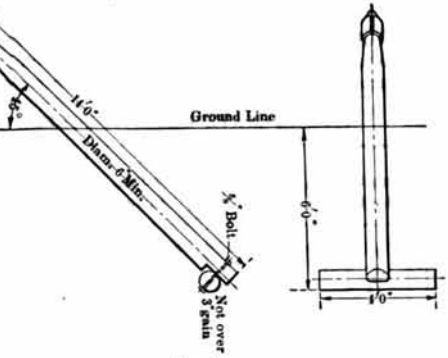


Fig. 4.

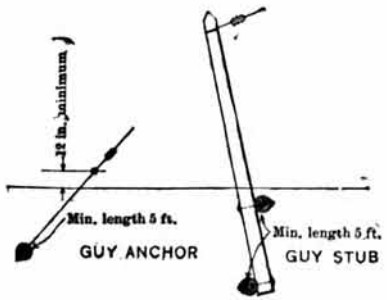


Fig. 5.

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may fail and the guy become charged without the failure being re The N.E.L.A. specification favors the latter type and requires strength of twice the strength of the guy wire and a wet flash ove of four times the line voltage.

Guy Stubs and Guy Anchors. — A common guy stub is sh This is made from parts of defective poles and is fastened togeth arm bolt. Fig. 5 shows another common form of guy stub and anchor.

There are also various forms of patented anchors which screw or are placed or driven into small holes and then expanded. The to economize labor of installation of standard anchors.

REPAIRING DECAYED POLES. — Where poles have bec the ground line by decay the strength may be restored by cutting butt and resetting pole, thus reducing its height by six to eigh reduction of height is not permissible, the pole may be stubbed b side of it a short pole or stub extending a few feet above ground t pole or the undecayed part above ground is bolted or otherwise f method does not look well and is unsuitable for city distributio been used for transmission lines. A more recent method is t decayed pole by a sleeve of concrete (usually reinforced) extend below the decayed portion. (*See Electrical World, April 1, 190 1913 for Orr patented process.*)

COST OF POLES. — The cost of wooden poles varies betw depending upon the part of the country in which they are pu following figures are rough approximations and are exclusive of f

APPROXIMATE COST OF POLES

Length, feet	Chestnut	Cedar, Iowa	Northern white ceda
25	$ 3.75*	$ 5.50*	.....
30	4.00*	10.00*	.....
35	6.25*	13.50*	.....
40	9.00†	17.00*	$8.00†
45	10.50†	22.00*	11.75†
50	16.75†	26.00*	14.50†
55	18.50†	40.00†	.....
60	14.50†	43.00†	.....

* 7-inch top.
† 8-inch top.

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OTENTIOMETERS. — (*See also Cells, Standard; Galvanometers; Resistors, Standard.*) A potentiometer is primarily an arrangement of resistances for the accurate comparison of two potential differences by balancing one against the other. In connection with suitable resistance standards (*see Resistors, Standard*) it may also be used for the accurate measurement of electric currents. The accessories for making ordinary d-c. measurements are a standard cell (*see Cells, Standard*) and a galvanometer (q.v.), and suitable keys or switches. For making a-c. measurements certain additional apparatus is required; see below under *Alternating Current Potentiometer*.

USES OF THE POTENTIOMETER. — For the calibration of current, voltage and power-measuring instruments, both d-c. and a-c., the potentiometer is the most accurate and satisfactory instrument available. A technical laboratory relies almost entirely upon the standard Weston (or Clark) cell and a set of standard resistances as its ultimate or primary standards, leaving the testing of the accuracy of these latter to a central standardizing bureau, such as the Bureau of Standards at Washington. It is, of course, convenient to have suitable "precision" ammeters, voltmeters and wattmeters as secondary laboratory standards but, as such secondary standards tend to "lose their calibration," they should be frequently checked against the standard cell and standard resistances by means of a potentiometer.

PRINCIPLE OF THE POTENTIOMETER (Figs. 1 to 3). — The potentiometer in its simplest form consists of a uniform wire stretched over a scale divided into a number of even parts, say 1500. A battery B (Fig. 1) having an e.m.f. of about 2 volts and a rheostat R are connected in series with this wire and two contact points A and S are provided, one contact S being movable. G is a galvanometer. At P there may be connected in will a standard cell or any other source of potential difference.

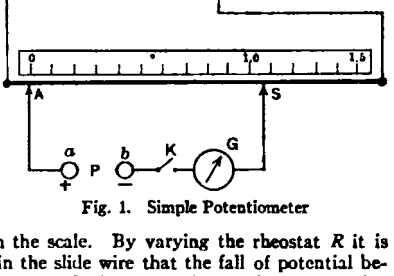


Fig. 1. Simple Potentiometer

At P is first connected a standard cell, say a Weston cell, having an e.m.f. of 1.01830 volts and the contact A is placed at and the contact S at 1.0183 on the scale. By varying the rheostat R it is possible to so adjust the current in the slide wire that the fall of potential between A and S due to the current from the battery B is exactly 1.0183 volts. This can be determined by closing the switch K; if R is properly adjusted there will be no deflection of the galvanometer. Care must be taken that the positive terminals of both B and the standard battery are connected to the same end of the wire.

To measure any other p.d. the standard cell is taken out of circuit and the terminals between which the p.d. is to be measured are connected to a and b respectively. The contact S is then moved until the galvanometer shows a balance. The corresponding position of the contact S, as read on the wire, then gives the value of this p.d. in volts.

Increase of Range by Use of Volt Box or Multiplier. — To measure voltages above 1.5 one must resort to the "volt box" or "multiplier," which is simply a standard high resistance, R_1 (Fig. 2) being provided with taps, so arranged that a definite fraction of the total drop can be measured on the poten-

tiometer. The unknown p.d. is connected at E, Fig. 2, the terminals a and b being the same as the like-lettered terminals in Fig. 1. The potentiometer reading would then be multiplied by 10 or 100 depending on the position of the switch D. The resistance R_1 must be sufficiently large so that the current taken by R_1 does not appreciably affect the value of the p.d. in the circuit being tested.

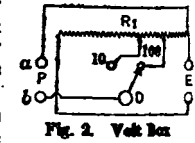


Fig. 2. Volt Box

Increase of Accuracy by Use of Additional Series Resistance. — The accuracy of measurement may be increased by inserting in series with the slide wire a known multiple of the resistance of, say, 1000 divisions of the slide wire. This is equivalent to increasing the length of the slide wire, and therefore, each division on the scale represents a correspondingly smaller fraction of a volt.

Current Measurement. — If it is desired to measure current, the drop across a known low resistance r is measured as shown in Fig. 3. The resistance r is usually so adjusted that its resistance between the potential terminals PP' is an even fraction of an ohm, in which case the potentiometer reads the current directly, with the exception of the proper pointing of the decimal. For instance, using a 0.01 ohm standard the potentiometer reading is to be multiplied by 100.

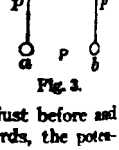


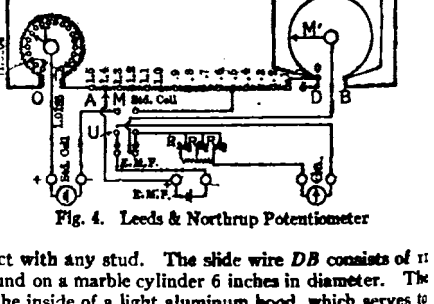
Fig. 3.

Caution. — In using any form of potentiometer a balance with the standard cell in circuit should always be obtained just before and after a balance with the unknown p.d. in circuit. In other words, the potentiometer current should always be checked both before and after a measurement.

TYPICAL DIRECT-CURRENT POTENTIOMETERS. — Potentiometers are made in such varied forms that it would take considerably more space than is available to describe them all. The most generally used direct-current types are the high-resistance "null" type, the low-resistance "null" type and the Brooks deflection type.

The Brooks potentiometer is particularly well adapted to the requirements of a large electrical engineering laboratory, where many instruments must be checked and kept in adjustment, and where it is imperative that the work be done with great speed, combined with a degree of precision ample for engineering work.

Low-resistance Null Type (Fig. 4). — A diagram of the connections of a Leeds and Northrup low-resistance null-type potentiometer is shown in Fig. 4.



wire and carries a scale from which the number of turns and the fraction of a turn can be easily read.

This potentiometer is designed for use with commercial "standard" Weston cells, which differ slightly in e.m.f. Each one, however, is accompanied by a certificate giving its e.m.f.

The switch T should be set at the stud corresponding to this stated e.m.f. In other words, the switch T is used for adjusting the potentiometer to the particular cell which is used. The rheostat R is then adjusted until no current flows through the galvanometer with the double-throw switch U thrown across the contacts marked Std. Cell.

In closing the galvanometer circuit close the keys K_3, K_2, and K_1 in the order stated. K_3 puts the galvanometer in series with a high resistance, K_2 puts the galvanometer in series with a medium resistance and K_1 puts the galvanometer in circuit without series resistance. If the potentiometer is considerably off balance this may thus be detected without causing a violent deflection of the galvanometer, and a closer balance obtained before the other keys are closed.

Range of Low-resistance Null Type. — With the rheostat R adjusted to give a perfect balance the current through the potentiometer is $\frac{1}{50}$ ampere, and the drop across each coil and across 1000 divisions of the slide wire is consequently 0.1 volt and across 1 division of the slide wire 0.0001 volt.

Range-lowering Device. — The shunt S serves as a range-shifting device, by which the range may be reduced to 0.1 the normal, one division of the slide wire in this case being equal to 0.00001 volt. This shunt has such a resistance that when the plug opposite K is shifted to the lower hole the drop over AD will be $\frac{1}{10}$ its previous value.

High-resistance Null Type (Fig. 5). — A diagram of the connections of a Wolff high-resistance null-type potentiometer is shown in Fig. 5. In this instrument the slide wire is dispensed with altogether. The double-dial switches are so arranged that the total resistance between the terminals B is constant and equal to 15,000 ohms irrespective of the position of the switches. The means whereby this is accomplished is evident upon tracing out the circuits in the diagram. By using this high resistance and keeping it constant, the effect of the contact resistances in the various switches is rendered negligible. The adjustments are made in the same manner as for the simple slide-wire potentiometer, except that instead of moving a sliding contact along a wire, one manipulates the various dial switches. The potentiometer circuit proper and all necessary keys and switches, are provided in this instrument. The accessories necessary for making measurements up to 1.5 volts are a regulating rheostat of about 5000 ohms total resistance, a standard cell, a suitable galvanometer and two cells of storage batteries or other source of e.m.f. of about 4 volts.

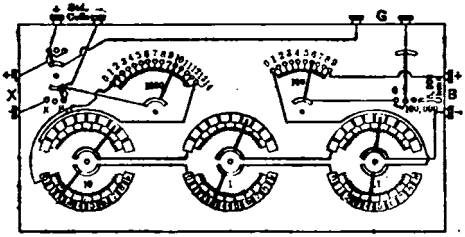


Fig. 5. Wolff's Potentiometer

Range of High-resistance Null Type. — This potentiometer has a range up to 15 volts in steps of 0.0001 volt and up to 1.5 volts in steps of 0.00001 volt.

Brooks Potentiometer (Fig. 6). — In this instrument no attempt is made to obtain an exact balance; the dial switches are set so near to the null point that

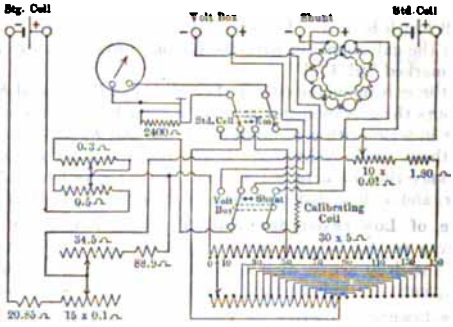


Fig. 6. Connections of Brooks Potentiometer

the galvanometer deflection is small. The galvanometer is so graduated that it gives the amount that must be added to the reading of the dial in order to give the unknown p.d. The potentiometer proper, regulating rheostat, galvanometer and necessary keys and switches are mounted in one box, making the instrument semiportable. The only accessories required to make measurements within the range of the instruments are a standard cell and storage battery.

For complete description of these instruments see *Bulletin of the Bureau of Standards, Vol. 8, No. 2.*

White Potentiometer (Fig. 7). — This is a four-dial low-resistance potenti-

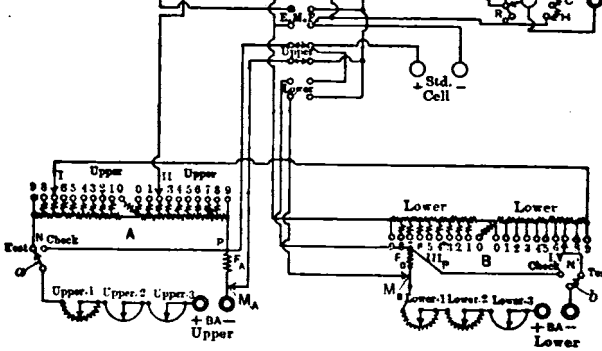


Fig. 7. White Potentiometer.

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ometer used for measuring small potential differences to high precision. It is well adapted for making high precision temperature measurements using thermocouples. The potentiometer is so constructed that parasitic thermoelectric forces are entirely eliminated. The resistance in the galvanometer circuit is kept constant by means of compensating coils which enable the instrument to be used as a deflection potentiometer.

A description of this potentiometer is given by Walter P. White in Zeitschrift für Instrumentenkunde 27, 210, 1907.

Queen-Gray Potentiometer (Fig. 8).—This potentiometer is of the "split circuit" type and is a compromise between high- and low-resistance instruments,

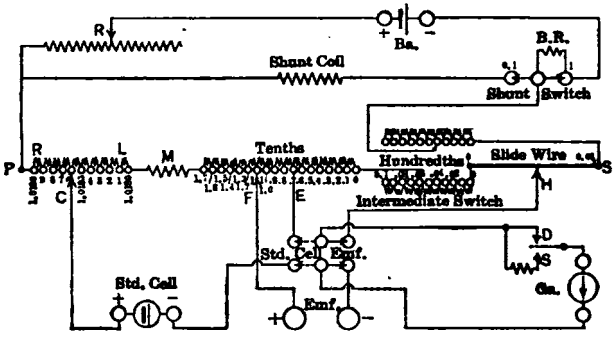


Fig. 8. Queen-Gray Potentiometer.

thereby possessing the advantages of each form without their disadvantages. The current to operate is 0.002 ampere, thus permitting the use of a dry battery. The drop over each resistance in the first group of coils is 0.1 volt, over the second is 0.01 volt and over the slide wire which consists of but one turn is also 0.01 volt. The slide wire is divided into 200 parts or 0.00005 volt. Each scale division can easily be estimated to its 0.2 part, thus making the final reading 0.00001 volt, which can be reduced 0.1 by a shunt coil, thereby making the lowest reading 0.000001 volt. The maximum direct range is 1.8 volts, which can be extended by means of multipliers. It is direct reading with any cadmium cell and has a contained rheostat for accurately controlling the 0.002 ampere regardless of the type of battery used.

ALTERNATING-CURRENT POTENTIOMETER.—The principles involved in the use of the potentiometer for alternating-current measurements are the following: Referring to Fig. 1, a balance is obtained with a battery at *B*, a standard cell at *P* and the contact *S* at the point on the scale corresponding to the e.m.f. of the standard cell, and the current flowing in the potentiometer circuit noted by means of an electrodynamometer or a.c.-d.c. ammeter connected between *B* and *A*. The battery *B* is then replaced by a source of alternating current and the rheostat *R* adjusted until an alternating current of the same effective value, as read on the electrodynamometer or ammeter, flows through the potentiometer. The standard cell at *P* is replaced by the unknown alternating p.d. to be measured and the galvanometer by an alternating-current galvanometer (*see Galvanometers*). To obtain a balance, however, it is now not only necessary that the contact *S* be moved along until the drop between *A* and *S* has the same effective value as the unknown p.d., *but also that this drop and the unknown p.d. have the same frequency and are in the same phase.* Con-

sequently the p.d. at B must be supplied from the same source as the p.d. to be measured, and means must be provided for shifting the phase of one with respect to the other.

The coils of an a-c. potentiometer are wound non-inductively, and consequently the p.d. due to the potentiometer current is in phase with this current. Hence the phase adjustment consists in bringing the potentiometer current into phase with the unknown p.d.

Phase-shifting Device. — One means of shifting the phase of the potentiometer current with respect to the unknown p.d. is to use two small alternators mounted on the same shaft, with the field frame of one adjustable with respect to the other. This, however, can be more conveniently accomplished by using a device similar in construction to a polyphase-induction motor, the primary of which is supplied either from a two- or three-phase circuit, or from a two-phase circuit derived from a single-phase circuit by connecting a resistance and condenser in series, and tapping off the p.d. across the resistance for one phase and the p.d. across the condenser for the other phase. By setting the secondary of this phase shifter at a fixed angle with respect to the primary, a p.d. can be obtained from the secondary at any desired phase with respect to the source of supply. A phase-shifting device based on this principle, and so designed that the change of phase resulting from shifting the position of the secondary does not alter the effective value of the secondary e.m.f., has been recently devised by C. V. Drysdale (*Phil. Mag., 1909, Vol. 17, p. 402*). With this instrument the phase of the potentiometer current and p.d. to be measured may be adjusted to 0.1°.

Drysdale-Tinsley Alternating-current Potentiometer (Fig. 9).— A diagram of connections is shown in the figure. A vibration galvanometer is used

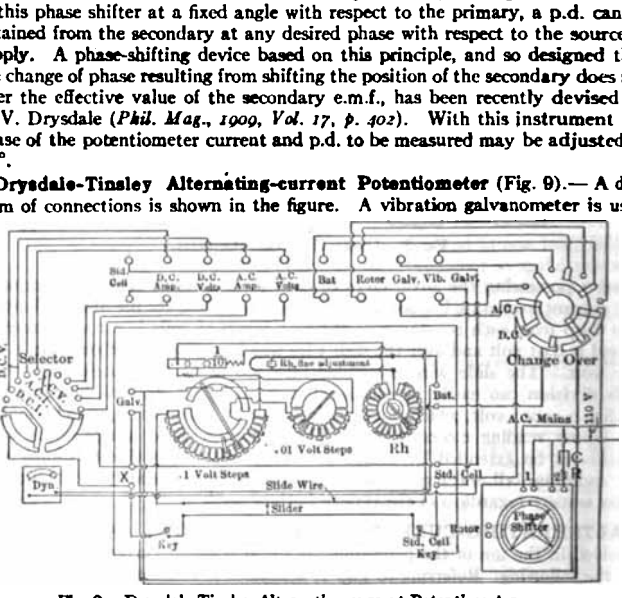


Fig. 9. Drysdale-Tinsley Alternating-current Potentiometer

as an a-c. detector and is tuned to the impressed frequency. The potentiometer is first balanced with an ordinary battery and standard cell and the reading of the electrodynamometer noted. By means of the change-over switch, alternating is substituted for direct current and the reading brought to the same point and held there. The phase of the potentiometer current is then roughly adjusted and the unknown p.d. is balanced as nearly as possible by shifting the potentiometer slides. The balance is then improved by shifting the phase of the potentiometer current and by resetting the slides; thus, by a process of double adjustment, the vibration galvanometer is brought to rest.

As the vibration galvanometer is a tuned instrument, *the frequency of the a-c. supply must be kept constant*. Also, the wave shape of the potentiometer current

and that of the unknown p.d. must be the same, as the vibration galvanometer shows a *balance for the fundamental frequency only*.

Current and Power-Factor Measurements. — By the use of suitable non-inductive shunts alternating currents may also be measured with this potentiometer. Also, by noting the reading of the phase-shifting device corresponding to a balance first of the given p.d. and then for the given current, the phase angle between the p.d. and current can be obtained by taking the difference of the two readings.

Range of Drysdale-Tinsley Potentiometer. — This potentiometer has a range of from 0 to 1.5 volts in steps of 0.001 volt. With suitable non-inductive volt boxes its range may be extended to 750 volts. It may also be used, in conjunction with suitable shunts, for measuring alternating currents of any value.

PRECISION OF POTENTIOMETER MEASUREMENTS. — The precision obtainable with a potentiometer depends upon the accuracy to which the e.m.f. of the standard cell is known, the accuracy to which the various resistance coils in the potentiometer circuit and shunts are adjusted, and the relative magnitude of the various contact resistances, and the proportion of the total resistance in the potentiometer circuit. For a-c. measurements the accuracy is also dependent upon the inductance and capacity of the coils. The Bureau of Standards calibrate the Weston cell to 1/50 per cent. The various coils of a potentiometer are adjusted to different degrees of accuracy, little attention being paid to the absolute accuracy of coils as long as they bear definite relations to each other. Instruments are calibrated as potentiometers to give the following accuracies.

PRECISION OF POTENTIOMETER MEASUREMENTS

Kind of potentiometer	Degree of precision, per cent	
	Voltage measurements	Current measurements
Low-resistance null type	1/50	1/20
High-resistance null type	1/50	1/20
Brooks	1/25	1/10

COST OF POTENTIOMETERS. — The following are approximate costs of the potentiometers proper, exclusive of the standard cell, galvanometer, volt box and shunts for current measurements.

Low-resistance null type (pre-war price)	$240
High-resistance null type, rheostat not included (pre-war price)	250
Brooks deflection type, including galvanometers (pre-war price)	350
White, including rheostats (1920 price)	500

BIBLIOGRAPHY. — A complete bibliography on potentiometers is given in *Circular No. 21, Bur. Stand.*, 1910; H. B. Brooks, *Bull. Bur. Stand.*, Vol. 8, 1911, p. 395. See also Laws, F. A., *Electrical Measuring Instruments;* Pedersen, P. O., *A. C. Potentiometer for Telephone Frequencies*, Electrician, 83, p. 523, 1919; Kennelly and Velander, *A. C. Potentiometer giving Rectangular Components*, J. Frank. Inst., 188, p. 1, 1919; Ryan, H. J., *High Voltage Potentiometer*, Proc. A.I.E.E., 35, p. 1187, 1916.

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POWER-FACTOR INDICATORS AND REACTIVE VOLT-AMPERE INDICATORS. — (*See also Alternating Currents; Generators, Alternating-Current; Wattmeters.*) A power-factor indicator is an instrument designed to give a direct reading, at any instant, of the power factor in a circuit or system of circuits as well as to indicate whether the current is leading or lagging; see *Alternating Currents*. The power factor of a single-phase circuit may be calculated from the readings of an ammeter, voltmeter and wattmeter. The power factor of a balanced three-phase circuit can also be calculated directly from the readings of the two wattmeters used to measure the power (*see Wattmeters*). A direct-reading power-factor indicator, however, is usually to be preferred for station purposes, since it gives the power factor directly and also indicates directly whether the current is leading or lagging.

Under certain conditions it is more convenient to obtain a direct measure of the reactive (wattless) power supplied to a circuit; ordinary wattmeters may be thus used as explained below.

Closely allied to power factor meters are the "reactive factor meters" which, however, should not be confused with "reactive volt-ampere meters." Reactive volt-ampere meters are also often called "reactive component indicators," or "reactive component watthour meters." In order to clearly indicate the various instruments involved in phase angle measurements of a-c. power circuits the following table is appended:

Instrument	Measurement	Symbol
Wattmeter	True power	V. A. cos ϕ
Volt-ammeter K V. A. meter	Apparent power	V A
Reactive volt-ammeter	Reactive component of apparent power or of volt amperes	V. A. sin ϕ
Power factor meter	Angle of lag between C and V, indicating according to cosine	cos ϕ
Reactive factor meter	Angle of lag between C and V, indicating according to sine	sin ϕ

SINGLE-PHASE POWER-FACTOR METERS. — Instruments for measuring the power factor of single-phase circuits are provided with one current coil circuit and one potential coil, the latter, however, being generally a double-circuit coil, the two portions being located with axes at right-angles to each other. The one is supplied with current from the potential binding posts through a non-inductive resistance and the other through a highly inductive resistance or "choke coil" so as to receive currents in the divided circuits corresponding in electrical phase angle to the mechanical angle between the coils.

POLYPHASE POWER-FACTOR METERS. — These can be classified as follows:

For Balanced Polyphase Circuits. — Such instruments are provided with a single-current coil connected to one phase of a polyphase circuit, and two or more voltage coils star-connected to each polyphase line. They are calibrated to indicate the cosine of the angle of lag between the line supplying the current coil and the voltage from this line to the artificial neutral point formed by the voltage coils within the instrument. It is assumed that the angle of lag is equal

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in all phases within an accuracy sufficient for the purpose for which the instrument is used.

From the above it will be understood that "balanced polyphase" instruments differ from single-phase instruments only as regards the voltage coil connections and the calibration.

For Unbalanced Polyphase Circuits. — The development of such instruments in the United States can be said to date from the adoption of a standard definition by the A.I.E.E. for power factor of unbalanced polyphase circuits (see A.I.E.E. Standards.)

Let the active (power) and reactive (stored) components of the volt-amperes of each phase be represented in Fig. 1 by the small triangles *a*, *b*, *c*, in which the watts are plotted horizontally and the reactive components vertically. Then the total power in the polyphase circuit is *OX*, the total volt-amperes *OA*, and the power factor is the cosine of the angle *AOX*.

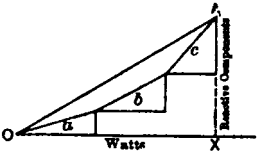


Fig. 1

Power-factor meters for correctly measuring unbalanced polyphase circuits are inherently quite complicated, comprising three voltage circuits and three current circuits or their equivalents. However, by measuring the power factor of each phase separately with instruments having single-phase current coils, the unbalanced-circuit polyphase power factor can be determined.

An instrument intermediate between the balanced and the unbalanced circuit types consists of three star-connected current coils one connected to each line and one voltage coil connected to one phase. Although more accurate on moderate unbalances than the single current-coil instrument, and simpler than the instruments for unbalanced circuits, it is more difficult to connect and calibrate than the single-current coil type. An unbalance of 20 per cent produces an angular error of indication of 7° maximum in such instruments.

MOVING-COIL TYPE. — Power-factor indicators of this type operate on the same principle as wattmeters of the electrodynamometer type, except that the coils are so arranged and so connected to the circuit that a differential action is produced which depends only on the power factor of the load.

In order that the differential action may be correct under all balanced-load conditions, mechanical control forces such as springs must be avoided or made negligibly weak.

Three-phase, Moving-coil Type. — Fig. 2 is a diagram of a three-phase power-factor indicator having three voltage coils and one current coil. *C* and *C'* are current-coil sections in series with one leg of circuit and P_1 and P_2 are potential coils connected as shown through the non-inductive resistances r_1 and r_2. Connections into and out of the moving coils are made by light spirals having very small torque, or through the bearings, so that the final position of the moving system depends solely upon the relative forces between the fixed and moving coils.

If the instrument is connected properly, the current coil acts with the two potential coils like the two elements of polyphase wattmeter (see *Wattmeters*). The torques of the two moving elements are developed in opposite directions. The torque of each element depends on the position of its potential coil. The potential coils are fixed with relation to one another at such an angle that the torque of one element always increases when that of the other decreases, due to the movement. Hence the needle will come to rest where the two torques

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are equal, and will give a scale reading dependent upon the ratio of the watts supplied to the two elements, i.e., in the case of a balanced load dependent on the ratio $\cos(30 - \theta) + \cos(30 + \theta)$, where θ is the power-factor angle. Hence, for unity power factor, ($\theta = 0$), the moving element will take up a position which is symmetrical with respect to the two potential coils, i.e., the pointer will take up a vertical position. For 50 per cent power factor, lagging, ($\theta = 60°$), the moving element will swing to the right until the axis of the potential coil P_1 coincides with the axis of the current coil. Similarly, for 50 per cent power factor, leading, ($\theta = -60°$), the moving element will swing to the left until the axis of P_2 coincides with the axis of the current coil. The character and range of the scale can be modified by varying the angle between the two potential coils.

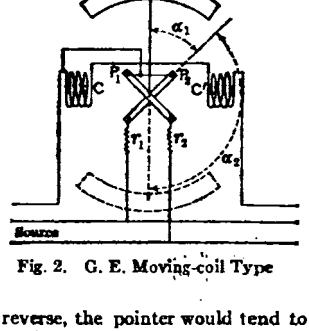


Fig. 2. G. E. Moving-coil Type

Should the direction of flow of power reverse, the pointer would tend to take up the dotted position in Fig. 1. Some instruments are provided with scales to take advantage of this effect.

MOVING-VANE TYPE. — In place of the movable coils this type of power-factor meter contains a movable soft iron vane, which, in the case of polyphase instruments, is magnetized through a stationary coil carrying a current in phase with the current of one phase of the circuit. There is one stationary voltage coil for each phase, the arrangement being such as to produce a rotating field. The iron vane then takes up a position in which the direction of the flux produced in it by the current coil when at a maximum, is coincident with the direction of resultant flux due to the voltage coils. In the three-phase instrument three voltage coils, placed 120° apart, are used; in the two-phase meter two voltage coils at 90° are used. In the single-phase type the Iron vane is magnetized by a stationary coil placed in series with the line, while the rotating field is produced by two potential coils 90° apart, one of which is connected to the line through an inductance, the other being connected to the same line through a non-inductive resistance. For the purpose of damping the deflections, an aluminum disk moving in the field of two permanent magnets is attached to the movable system.

REACTIVE WATTLESS VOLT-AMPERE INDICATORS. — Operating conditions on polyphase circuits are sometimes such that the reactive component of the volt-amperes in the circuit does not vary through wide limits of load between light load and full load, whereas the power factor may vary greatly. Under such circumstances it is frequently more convenient to have a direct measure of the reactive volt-amperes rather than the power factor.

Ordinary wattmeters may be used for indicating the reactive component of the volt-amperes, by changing the voltage connections so as in effect to rotate them through 90 electrical degrees, thereby causing the instrument to read $VA \sin\theta$ instead of the usual $VA \cos\theta$ or "active" component usually known as watts or kw. If this rotation is affected without varying the ratio of transformation the calibration of the wattmeter is the same as for ordinary watt measurements. If such connection alters the ratio of transformation, the calibration constant is altered accordingly.

When applied to circuits which may either have lagging or loading current the

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zero may be placed in the center of the scale, like zero-center wattmeters which are applied to circuits which are liable to reverse in direction of power flow. Fig. 3 (*a*) shows connections when the phases are rotated without change in calibration being necessary, but requiring voltage transformers having taps. This is the preferable method. Fig. 3 (*b*) shows connections when the phases are rotated requiring special calibration, but not requiring special transformer taps. Fig. 3 (*c* and *d*) shows connections combined with a double-throw switch

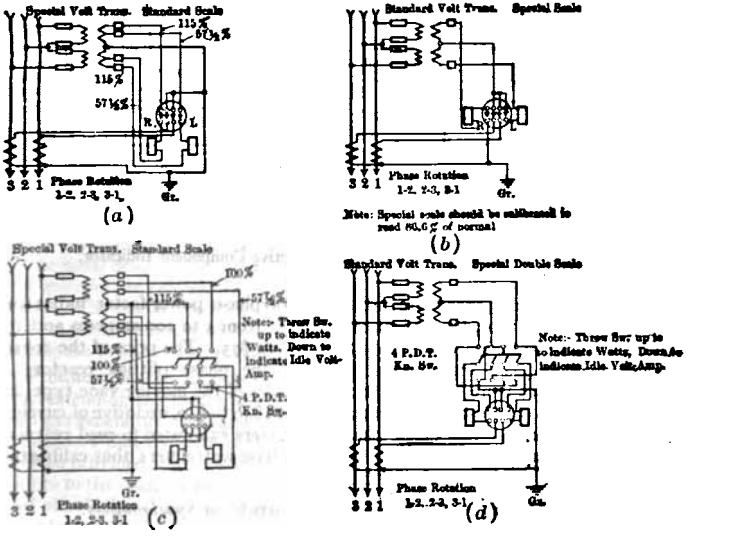


Fig. 3. Diagram of Connections for Reactive Component Indicator.

to read either reactive or active component (*KW*). Fig. 4 shows corresponding connections for 3-phase, 4-wire circuits.

RANGES OF THE VARIOUS TYPES. — The largest capacity of instrument of the moving-coil type for direct connection to the circuit is 100 amperes and 300 volts for the single-phase and 200 amperes and 600 volts for the two-phase and three-phase types. The range of power factor on standard instruments is from 0.60 leading to 0.60 lagging, although instruments with ranges as low as 0.00 leading to 0.00 lagging have been made.

Instruments of the moving-vane type have a current capacity of 5 amperes. They are made for direct connection to circuits of 110, 220 and 440 volts. For all other capacities and voltages the 5-ampere, 110-volt instrument with suitable current and potential transformers is used. The instruments are made for frequencies of either 25 or 60 cycles per second. The range of power factor on the moving-vane type of meter is unlimited.

Power-factor indicators of either type may be connected to instrument transformers which are used in connection with other meters.

Five amperes and 115 volts are standard for wattmeters used as reactive volt-ampere indicators, with transformers for higher ranges. However, single-

phase instruments for direct connection are furnished up to 200 amperes and 600 volts, and polyphase instruments for direct connection, up to 60 amperes and 600 volts.

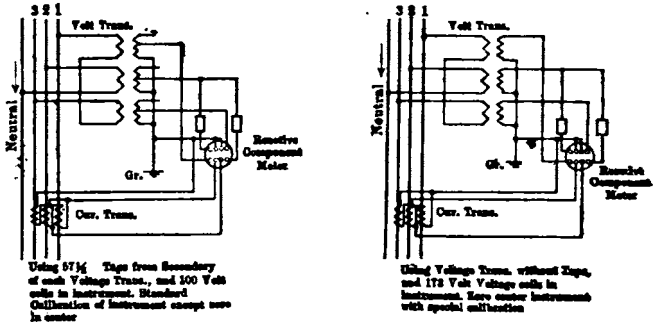


Fig. 4. Diagram of Connections for Reactive Component Indicator.

COSTS. — The approximate prices of polyphase power-factor indicators of the moving-coil type, for current capacities of from 5 to 100 amperes and for voltages from 100 to 600 volts, range from $45 to $75. The price of the corresponding single-phase instruments, including the phase-splitting reactor, is approximately $10 more. Power-factor indicators of the moving-vane type for voltages from 110 to 440 cost approximately from $30 to $40, exclusive of current or potential transformers. Single-phase wattmeters calibrated to read reactive volt-amperes cost about $45 each and polyphase wattmeters thus calibrated cost about $65. (Prices as of 1921.)

BIBLIOGRAPHY. — See *Bibliography* in article on *Synchronizers*.

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POWER STATIONS, GAS-ELECTRIC. — *(See also Gas; Gas Engines; Gas Producers; Generators; Power Stations, Steam-Electric; Power Stations, Hydroelectric.)*

Number and Capacity of Units. — As gas engines have little overload capacity a total rating of engines should be installed sufficient to carry the extreme peak load and afford ample emergency reserve. In many cases the kilowatt rating of generators is made but 60 to 65 per cent of the horse-power rating of the engines, in order to provide overload generating capacity. This is not always wise, as the most efficient load of a gas engine is quite near its maximum capacity. The units in very large plants are usually of the horizontal, twin, tandem type and range from 4000 to 6000 h.p. in rating, the latter size being the largest available. Producers are quite flexible in capacity, but heavy forcing is apt to produce clinker and impair the quality of the gas. The total producer capacity usually corresponds with the total engine capacity, unless the load fluctuates greatly and considerable tank capacity for gas storage is available. In most cases not less than three engine and producer units should be provided.

Buildings. — The practice in this field follows quite closely that described in the article on *Power Plants, Steam-Electric* (q.v.). In a few cases producers are set in the open air. Producers and engines are sometimes in separate buildings. In the usual design the engine and producer rooms are parallel and electrical control galleries are provided on the side of the engine room opposite the producer room. The engine room should be spanned by an electrically operated crane with capacity sufficient to handle the heaviest engine part. In some important plants the producer room is also provided with a crane.

Producer Room Lay-out. — The gas producers are usually set in a single row extending the length of the producer room. Each unit comprises one or two gas generators, an evaporator, a scrubbing tower, a gas pump and tar filters grouped so that the path of the gas is toward the engine room. A coal bunker is often provided above the producers, preferably along the outside wall. Down-spouts to the charging bells of the several producers should be somewhat inclined and should have cut-off valves. When desired, automatic weighing hoppers may be attached between the bunker and each down-spout to record the coal consumption of each producer. In some producer rooms a shallow pit is provided along the front of the gas generators so that ashes may be raked into this pit. In other cases ashes are raked out onto the main floor to be carted away. A skeleton gallery of steel connecting the producers at their charging levels is often a convenience.

Engine Room Lay-out. — Horizontal engines are usually set in a single row with piston rods across the engine room. The power end of each unit is on the side of the gas supply and the electrical end on the side nearer the control gallery. In a-c. plants a group of independently driven exciters is placed near the middle of the room. The spaces between units and the clearances at their ends are determined by the room needed for erection, dismantling, making repairs and access during operation.

Piping. — The piping scheme is usually a simple parallel plan. A main gas header is provided and runs the length of the wall between the engine and producer rooms. Branches from this header run to each producer unit, to each engine and to the storage tank. Piping may be of relatively light weight and needs no special provision for expansion, but all joints should be secure, as producer gas is of a poisonous nature. The storage tank may properly be at one end of the building. Each producer is usually set beneath a vent pipe or short steel chimney run a few feet above the roof to discharge the smoke and raw gases produced when starting up.

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Space Required. — The following table shows the floor space provided per kw. of plant capacity in modern stations.

Plant capacity, kilowatts	Number of engine units	Number of producer units	Square feet per kilowatt	
			Engine room	Producer room
360	3	2	6.0	2.2
700	2	2	4.5	2.9
1,620	3	2	5.5	1.56
3,000	3	2	3.7	0.93
34,000 (*a*)	17	0	3.0	....

(*a*) Blast-furnace gas plant.

Fuel, Labor and Water. — *Fuel.* — Assuming the coal to have 12,000 B.t.u. per lb., about 1½ lb. coal are required per kw-hr. generated at full load; 1¼ lb. per kw-hr. at ¾ load; and 1⅝ lb. per kw-hr. at ½ load. For coal of any other heating value the weight required is approximately inversely proportional to the B.t.u. per lb.

Labor. — 1 fireman required for each producer in operation and 1 oiler for each engine in operation. Supervision, switchboard attendance, coal handling, etc., as for a steam-electric station. The total cost of labor for operation is usually about 50 per cent of the fuel cost.

Water. — About 9 gallons of water per kw-hr. are required when the supply water is at 50° F., and about 13 gallons per kw-hr. when at 70° F.

COST OF GAS POWER PLANTS. (Pre-war figures.) — The cost per kilowatt of gas power plants varies with the capacity of the plant, the number of units installed and the source of gas supply. The construction cost of engine plants using natural gas ranges from $65.00 to $100.00 per kw., depending on the size of plant. The construction cost of blast-furnace gas plants, including the necessary gas-cleaning equipment, ranges from $85.00 to $120.00 per kw. and of producer plants from $90.00 to $125.00 per kw. according to capacity. The cost per kw. diminishes very slowly above a plant capacity of 12,000 kw.

The reported cost of five blast furnace gas-electric installations is as shown in the following table :

Power plant No.	1	2	3	4	5
No. of units	17	2	3	4	5
Cap. kw., max. con. rating	40,000	4,500	9,000	9,000	11,400
Cap. b.h.p. max. con. rating	56,400	6,400	12,800	12,800	16,300
Cost of installation per kw. max. con. rating:	$	$	$	$	$
(*a*) Buildings	9.87	.....	10.17	10.90	10.52
(*b*) Eng. equipment	71.78	75.50	72.75	77.78	80.32
(*c*) Gas cleaning plant	5.85	16.80	14.40	13.00	12.76
Grand total, power plant, complete, per kw	87.50	92.30	97.32	101.86	103.60

Operating Costs of Producer-gas Plants. — The following division of the items making up the cost of operation of producer-gas plants is taken from a typical plant in commercial operation:

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	Minimum	Normal	Maximum
put, kw-hrs. per day	5000	8000	10,000
l, cents per kw-hr	0.25	0.22	0.20
or, cents per kw-hr	0.28	0.17	0.14
plies and repairs, cents per kw-hr	0.17	0.13	0.11
rating cost, cents per kw-hr	0.70	0.52	0.45
d charges, cents per kw-hr	0.45	0.28	0.22
al cost, per kw-hr	1.15	0.80	0.67

st of Blast Furnace Gas-Electric Power. — The cost of producing ic power by means of blast-furnace gas engines in one of the large steel s is reported to be as follows:

r	1910	1911	1912
acity in kw	40,000	40,000	50,000
-hr. produced	116,535,000	157,742,510	286,575,000
factor, per cent	33.3	45.0	64.5
t of installation, per kw	$88.00	$88.00	$88.00
ual cost, cents per kw-hr.:			
abor	0.0678	0.0421	0.0302
epairs and maintenance	0.0366	0.0305	0.0273
ubricants	0.0116	0.0100	0.0085
Vater	0.0074	0.0057	0.0036
liscellaneous	0.0064	0.0153	0.0128
t of purified gas, cents per kw-hr	0.1951	0.1727	0.1608
d charges, 15 per cent, do	0.4520	0.3360	0.2310
rand total at switchboard	0.7769	0.6123	0.4742

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POWER STATIONS, HYDROELECTRIC. — (*See also Power Stations, Gas-Electric; Power Stations, Steam-Electric; Dams; Generators; Hydraulics, Principles of; Hydrology; Pipes and Piping; Switchgear Equipment for Power Stations; Transformers; Water Wheels; etc.*) This article deals primarily with those features in which a hydroelectric plant differs from a steam electric plant; these features arise chiefly from the nature of the prime movers and from the use of the very high voltages (up to 150,000) at which power from hydroelectric stations is transmitted. The individual constituent items, such as generators, water wheels, transformers, switchgear, etc., are treated in the separate articles, dealing with these subjects. The following is a brief table of contents of this article:

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LOCATION OF POWER HOUSE. — The location of the power station of a hydroelectric plant is determined primarily by the head utilized and by the location of the dam (*see Dams*). In the case of low head developments the substructure of the power station is usually a portion of the dam itself or a "wing" offset from it. In choosing the location of both the dam and the position of the power station relative thereto, particular attention should be paid to the liability of ice and débris clogging the intakes. For high head developments, using penstocks, the power station is so located as to give the maximum head consistent with economy of construction and availability of a suitable natural channel for carrying off the discharge. Available sites for storage reservoirs should also be considered.

The location of the development generally has to be such that high-tension transmission is necessary, so that provision must also be made for housing the transforming and high-tension switching apparatus. If it is desired to place them indoors, or if it is decided to place the high tension equipment out of doors, an ample area of preferably flat ground should be selected to accommodate, without congestion, this apparatus along with the necessary structures for supporting the buses, etc.

DESIGN OF BUILDING. — (*See also Water Wheels and Their Setting.*) The design of power houses differs greatly, depending on the conditions which are to be met. It is affected to a very great extent by natural conditions, such as the location with respect to the stream, the condition of the soil, etc. Low and high head developments require different types of turbines and these may furthermore be of horizontal or vertical construction, necessitating entirely different lay-outs.

A hydroelectric power-house building is generally divided into two longitudinal bays, a front or main bay, containing the turbines and generators, and a rear bay containing the transformers, switching apparatus, etc.; see Figs. 1 and 1a.

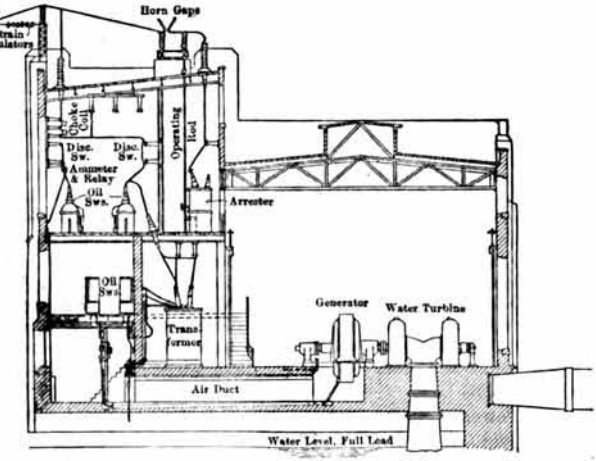


Fig. 1. Cross Section of Power House

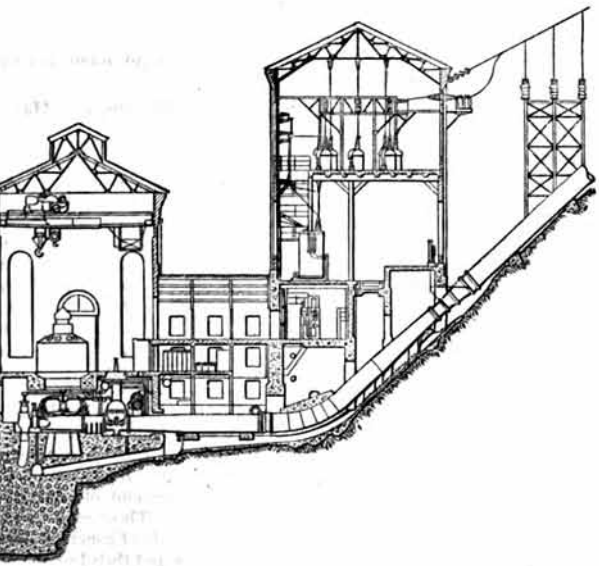


Fig. 1a. Cross Section of Power House; Roof Trusses with Raised Chord

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The two bays are separated either by a wall or by a row of supporting columns. The rear bay is divided into two or more floors and these, in turn, into various rooms or compartments to accommodate the step-up transformers, switches, bus-bars, lightning arresters, etc.

Outdoor Step-up Substations. — During recent years, as a result of the cost of buildings necessary to house high-tension transformation and switching apparatus, outdoor substations have come into general use. This is particularly true in those cases where the operating potential exceeds 100,000 volts. Experience confirms the wisdom of this type of construction, for when compared with the indoor type, it is found that although it is a little more difficult to make repairs in the case of the outdoor station, this is largely offset by lower cost of the installation and reduction of the fire hazard. The difference in cost of apparatus designed for the two classes of service is insignificant. The net difference in cost is that between the cost of the large buildings necessary for housing the high-tension equipment and the cost of the light concrete bases and steel structures required in the case of the outdoor installation. The operation of these stations does not seem to be in any way impaired by the low temperatures and snow of our Northern winters nor the heat of our Southern summers.

Bearing Power of Soils. — The most important part of the building is the foundation, and careful soundings must be made to ascertain the underlying strata. If bedrock is found within moderate depth, the foundation should be carried down to the same. The safe bearing loads usually allowed for soils in this country are given in the following table:

SAFE BEARING POWER OF SOILS
(*From Baker "Treatise on Masonry Construction"*)

Material	Load in tons per sq. ft.	
	Minimum	Maximum
Rock, hardest kind	200	..
Rock, equal to Ashler masonry	25	30
Brick, equal to Ashler masonry	15	20
Brick of poor quality	4	7
Clay in thick beds always dry	4	6
Clay in thick beds moderately dry	2	4
Clay, soft	1	2
Gravel and coarse sand	8	10
Sand, fine and compact	4	6
Sand, clean and dry	2	4
Alluvial soils and uncertain sand	0.5	1

For foundations it is considered good practice to use somewhat lower values. About one-half is a good working basis for such work, thus allowing a maximum load of about 1000 lb. per sq. ft. for ordinary alluvial soils. Clean sharp sand is considered to be a good bearing soil, and it may only be necessary to cover it with a concrete mat, which requires a minimum amount of concrete. For soft or alluvial soils piling is almost always required. These may be of wood, although in the last few years much use has been made of concrete piles, both plain and reinforced. Such piles are less apt to decay and their bearing power is higher, due to their greater friction. They may also be made of larger diameters than can be obtained with wood piles and a less number is therefore required to support a given load.

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Design of Foundations. — The weight on a foundation includes the machines, fittings, the weight of the foundation itself, and, in the case of the turbines, the weight due to the water thrust unless this is balanced. Separate foundations should be provided for the different units so as to isolate any failure as far as possible. Concrete is always used for the foundations.

Machinery foundations should be solid, but buildings may be supported on columns or arches so as to economize the concrete (*see Concrete*). Where there is danger of high water in the tail race, the outside foundation walls should necessarily be made water-tight so as to prevent water from entering the basement. For such cases a sump is generally provided into which the seepage may collect and from which it can be pumped out.

Basements. — A basement should be provided below the generator room when vertical turbines are to be used. That part of the floor on which the turbine discharge casings rest should be reinforced by heavy I-beams, and provision should be made for supporting the penstocks and draft tubes. There must be provided an intermediate basement floor which is generally made of concrete and should be carried on I-beams supported by the concrete piers which also support the generators and the main floor. With horizontal turbines no basement is needed. Ventilating and cable ducts for the generators, and tunnels for piping, etc., are, however, often installed below the main floor.

Floors. — No combustible material of any kind should, if possible, be used in the construction of a power house. As the sub-structure of the building is generally built of concrete, it is but natural that the floors should also be of concrete. A dark color is preferable so as to render drops of oil inconspicuous. A tile or mosaic floor is smooth, easy to keep clean and has a very handsome appearance if made to conform with the general interior finish of the station.

Walls. — The walls may be either of reinforced concrete construction or of brick with a steel skeleton frame work. Where future extensions are contemplated a false wall is provided on one end of the building. The interior should be kept as light as possible and it is therefore advisable to apply a smooth surface of cement plaster and whitewash or paint the same. For more important stations the walls may be faced with pressed brick and up from the floor to about ten feet with enameled brick so that they may be readily washed and cleaned. Where the extra expense is warranted, the walls may be entirely lined with enameled brick and a wainscoting of contrasting color, preferably olive-green.

Roof. — The roof of the building should always be supported on the steel trusses, carried on the side walls or on steel columns. The slope should not be excessive, two inches per foot being sufficient with gravel covering. This construction requires less material, and is advantageous when the transmission wires are to enter the station through roof entrance bushings, or where the lightning arrester horns are to be installed on the roof.

The roof covering may simply consist of boards covered with roofing paper, tar and gravel. Reinforced concrete is sometimes used in place of boards so as to make an absolutely fireproof construction. Roofs covered with red tile are often used and present a very pleasing appearance. Corrugated iron roofs are objectionable due to the liability of moisture condensing on the inner surface and dripping into the station. They may also cause the station to be extremely hot in the summer unless an insulating lining is provided below the roof trusses to keep out the heat. With tile or metal roofs it is necessary to provide steeper inclines than with gravel roofs so that the water may run off rapidly. Monitors are sometimes provided so as to give additional ventilating facilities.

Roof trusses with a raised chord, shown in Fig. 1a, are in many instances of great advantage in that they provide an increased headroom without unneces-

sarily raising the walls of the building. This is of special importance in the high-tension part of the station, where ample headroom must be provided for the busses.

Windows. — Good lighting is imperative, and large windows are therefore essential. They should be symmetrically located with regard to the generating units and their design should be such as to harmonize with the building, arched windows being very generally used. Skylights of glass tile placed in the roof will also add considerably to the lighting. The window sashes should preferably be metallic and the glass reinforced with wire netting so as to prevent shattering when broken. Ribbed or non-transparent glass is also desirable, because it keeps out the intense rays of the sun. In order to provide for ventilation, provision should be made so that the windows can be opened, but precaution should be taken so that rain, snow or dust will not blow in on the machinery or apparatus. This is especially important on the switchboard side where the wiring is exposed and it is therefore better practice not to provide any means for opening the windows on that side. For tropical climates the windows which are liable to be opened should be equipped with mosquito screens.

Doors. — The location of the doors is naturally governed by local conditions. One of the openings should be of sufficient size to admit a railroad car, for which tracks should be provided. Very often these doors are of the rolling type, this design being most economical as regards space.

Traveling Crane. — Provision should always be made for supporting the track for a traveling crane, which should span the generator room and run the full length of the station. The track is generally supported on pilasters in the outside wall and on the steel columns separating the generator and switch rooms. There should be ample headroom allowed so that the various machine parts can be readily removed when repairs are to be made. This is especially important with vertical units where the water-wheel rotor is mounted on the same shaft as the generator field, and in which case it should be possible to lift out the whole revolving element by simply removing the top bracket and bearing of the generator.

Miscellaneous Rooms. — Repair rooms, store rooms, offices, toilets, etc., should be provided. Ample stairway provision is essential so as to permit a ready access to important points, such as between the generator room and the switchboard gallery.

LOCATION OF APPARATUS. — The arrangement of the apparatus should be very carefully considered from the standpoint of simplicity and reliability of operation. The purpose of the station being to give reliable service consideration must also be given to the causes of disturbances and means for minimizing their effects. In anticipating these abnormal or so-called emergency conditions, the failure of every piece of apparatus must be considered as a possibility, and a definite plan worked out for limiting the magnitude and area of such disturbances.

Location of Generators. — The turbo-generator units are located on the main floor and are almost always arranged in a line along the long axis of the station. They should be spaced far enough apart so that ample space for passage is provided between them. Horizontal sets may be installed either at right angles or parallel to the long axis, the latter method being necessary for high heads where impulse wheels are used. The arrangement of the rest of the equipment, such as the transformers, may also be a determining factor in regard to which direction the sets should be installed. If one transformer bank, consisting of single-phase units, is to be installed for each generator, the space occupied by them may be of such a length that it would be more economical to install the

turbo-generator sets parallel to the long axis, thus reducing the width of the building.

Location of Turbines. — (*See Water Wheels.*) With horizontal sets the turbines may be located together with the generators in the generator room or in separate wheel chambers built in the dam. The latter practice is only used for very low head developments, where one of the power-house walls forms part of the dam structure. With vertical units the turbines are always located in a basement, the thrust bearing being supported on an intermediate floor below the main floor, unless suspension bearings are used, these being mounted on top of the upper generator-bearing bracket.

Location of Exciters. — The exciters are as a rule installed on the same floor as the main generators and in the center of the station. The advantage of such an arrangement is that the exciters will be located close to the operating switchboard and the amount of copper required for the exciter leads is thus a minimum. The system may readily be sectionalized, one exciter serving the generators located in one-half of the station, and the other the generators on the opposite side. This does not, of course, refer to direct-connected exciters.

Location of Transformers. — Due to their weight, the step-up transformers should preferably be located on the main floor. They are generally installed in isolated compartments in the rear bay, separated from the generating room by fireproof steel curtains. These compartments should be sufficiently large to allow a good ventilation. A car track is provided on the generator-room floor in front of the transformer compartments whose floors are raised so that the transformers can be run out on the car and moved to some convenient place in the station where repairs can readily be made. For large units it may be necessary to provide a hole in the floor above the repair room so as to enable the transformer core to be lifted out of the tank, or a pit may be provided into which the transformer may be lowered so that sufficient headroom is obtained for lifting out the core. Sometimes the repair room is so situated that the main crane cannot be utilized for dismantling the units. In such a case a chainfall supported from a heavy I-beam in the floor above may be provided.

Transformers Installed Out-of-Doors. — Considerable activity has recently taken place in installing transformers and associated high-tension apparatus outdoors. With the exception of the bushings the transformers for such installations differ comparatively little from the indoor type; the only feature out of the ordinary being the necessity of keeping the moisture from entering the transformer cases under the covers and leads. To prevent this the joints have been made with waterproof gaskets and breathing chambers have been provided.

Special precautions must naturally be taken to protect transformers of the outdoor type both from the extreme heat and from the cold in the winter. The former can readily be obtained by providing sunshades, and in certain instances very good results have been obtained by simply painting the cases white. It is more difficult, however, to provide for the cold winter temperatures, especially with water-cooled transformers. With the transformers in service there seems to be no danger of freezing and if such should be the case some sort of heating grids could readily be provided in the bottom of the tanks. The main difficulty lies in the formation of moisture which takes place when the temperature of the transformer is allowed to fall below that of the surrounding air; this applies also to indoor transformers. Precautions must therefore be taken that this does not happen, and may be accomplished by either reducing the water rate at times of cold weather, or by using the cooling water over and over again. Non-freezing oil may be used in such transformers, but its cost is so high that it is almost prohibitive from a commercial standpoint.

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Location of Switchboards and Switchgear. — (*See also Switchboards; Switchgear Equipment for Power Stations.*) The different pieces of apparatus comprising the switching equipment are distributed on the various floors in the switch-section of the station, each story being partitioned to suit the various purposes. The operating room with the control switchboard is generally located on the second floor and in such a position that the operator may have an unobstructed view of the station, and be able to readily communicate with the turbine operators: A balcony, somewhat overhanging the generator room in front of the switchboard, is often provided or the operating room is built with a curved front wall extending out over the generator room.

Location of Oil Switches. — The low-tension oil switches are generally of the enclosed type and, together with the low-tension bus-bars (*see Bus-Bars and Bus-bar Structures*), are located generally in compartments on the main floor back of the transformer compartments. The switches themselves should preferably be set opposite the generator and transformer bank which they control, so as to call for as short a connection as possible and in order that these connections may be of equal length. The high-tension oil switches and bus-bars, and also as a rule the lightning arrester tanks, are installed on the floor above, or outdoors as the case may be.

Disconnecting Switches. — It is customary to install disconnecting switches on both sides of an oil switch so that they may be entirely disconnected from the circuit when repairs are to be made on them, when the oil tanks are to be refilled, etc. Disconnecting switches may also be used in a number of cases for changing connections, when this is not to be made under load. Such switches should be provided with locking devices, as experience has shown that the magnetic fields caused by short-circuits may cause disconnecting switches to open, which in turn may cause serious disturbances by the arcs set up.

Spacing of Bus-Bars. — (*See also Bus-Bars and Bus-bar Structures.*) The following spacings are suggested in laying out bus-bar structures:

Voltage	Dimensions in inches			
	Outdoors		Indoors	
	To ground	Between live parts	To ground	Between live parts
2,000 - 3,500	3½	4	3	3½
3,501 - 7,500	5½	6	4½	5½
7,501 - 15,000	9	10	7	9
15,001 - 25,000	14	15½	10½	14
25,001 - 37,000	19½	22	14½	19½
37,001 - 50,000	25½	29	19	25½
50,001 - 73,000	36	41	27	36
73,001 - 95,000	47	53	34½	47
95,001 - 115,000	56	64	41	56
115,001 - 135,000	66	75	48	66
135,001 - 155,000	75	86	55	75

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Location of Lightning Arresters. — (*See also Lightning Protectors; Switchgear Equipment for Power Stations.*) The aluminum arrester is now generally used in all high-voltage stations. Both the arrester tanks and the associated horn gaps may be located within the building, or the horn gaps may be placed outside and the tanks inside, or both may be placed outside, provided there is no danger of the electrolyte freezing. Standard equipments of 27,000 volts and below are usually designed as complete units to be installed inside the station, whereas for those above 27,000 volts the horn gaps should preferably be installed outside the station and the tanks inside. Exception to this rule can be made where there is sufficient space in the station over the gaps.

The arrester tanks should naturally be located close to the line entrances. The horn gaps, when installed out-of-doors, may be placed on the roof of the building if roof-entrance bushings are used, or on a separate structure at the side of the building if wall-entrance bushings are used. The location of the arresters should also be such that the path for the discharge from the line conductors to the arresters and ground will be as straight as possible.

Clearance over Horn Gaps. — Wherever horn gaps are mounted inside the building sufficient clearance should be allowed over them. There is no appreciable arc at the gaps, but in abnormal cases where the film has been allowed to get out of order, the arc may be of considerable size. Where there are no fusses or inflammable apparatus, the following are the minimum clearances from the tops of horns to be allowed:

Volts	Clearance, feet
Up to 16,100.....	3
16,101 to 37,900.....	4
37,901 to 70,000.....	6

These clearances should be materially increased when there are wires, cables, fusses or any inflammable material over the horn gaps.

Above 70,000 volts, the horn gaps should never be placed indoors.

Effect of Climatic Conditions on Arresters Installed Out-of-Doors. When aluminum arresters are installed out-of-doors, there is always present the possibility of freezing the electrolyte in cold weather and that of abnormal rm dissolution during extremely hot days. The electrolyte is not permanently injured by freezing, but when frozen, the internal resistance of the arrester is considerably increased and hence its discharge rate is materially lowered. This is not of any practical consequence, for during the winter months there is usually a total absence of lightning. The rapid dissolution of the films on the cores of the arrester during warm summer days may be counteracted by more frequent charging. In some locations it may be found advisable to charge two or more times a day. When operating under conditions of high temperature, failure to regularly charge the arrester increases the liability of damage from a heavy electrical discharge through it.

There has recently been introduced a new form of arrester designed to overcome the necessity of periodic charging as in the case of the aluminum arrester. This new arrester is known as the oxide-film type. It requires no charging, is about the same discharge capacity, may be built for either indoor or outdoor operation, and due to the small arc formed across the gaps during discharge, may be covered in the case of out-door arresters thereby obtaining prac-

tically the same arc-over potential for these outdoor arresters during dry or wet weather.

WATER WHEELS AND GOVERNORS. — The available types of water wheels and governors and the conditions under which they should be used are treated in detail in the articles on *Water Wheels and Their Settings*, and *Water Wheels, Speed Regulation of*.

GENERATORS AND THEIR CONNECTIONS. — (*See also Generators, Alternating-Current.*) Water-wheel-driven alternators are always of the revolving field type. Machines of this type are generally direct-connected to the water wheel. The horizontal construction has been used mostly, but recently the vertical construction has been used to a great extent, especially in low-head developments. The choice is usually determined by hydraulic conditions; see *Water Wheels and Their Settings*.

Use of Power-limiting Reactances. — See article on *Reactance Coils*.

Operation of Generators in Parallel, Synchronizing, etc. — (*See Generators, Alternating-Current; Synchronizers.*)

EXCITATION AND EXCITER SYSTEMS. — It is a good practice to have the combined normal capacity of all the exciters correspond to the excitation required for all the generators, when these are operating at their maximum overload, and at the actual operating power factor. A spare unit to be kept in reserve in case of the break-down of any exciter should generally be provided. This is especially desirable where an uninterrupted service must be secured at any cost and where the exciter units are few in number, as in such a case the shutdown of one exciter would seriously cripple the system.

Amount of Excitation. — The curves in Fig. 2 give approximately the average excitation required for water-wheel-driven alternators of high and slow speeds. It is seen that, as compared to the rating of the generator, the exciter capacity ranges from 0.75 per cent for large high-speed machines to 3 per cent for small slow-speed machines.

"Time Element" of Exciters. — The "time element" of the exciters should be such that the insertion into its field circuit of an external resistance equal to about three times the resistance of its field circuit, will cause the voltage to drop from 125 to 25 volts in from 4 to 6 seconds. This is particularly important when automatic voltage regulators are used (*see below*), for the exciter voltage must respond quickly to the short-circuiting of the field rheostat by the regulator.

Exciter Voltage. — For large installations a 250-volt system of excitation will generally be found more economical than a 125-volt system. This higher voltage will permit the use of smaller exciter and field switches, leads of reduced size may be used between the exciters and the generator field, and the cross-section of the exciter bus-bars will be

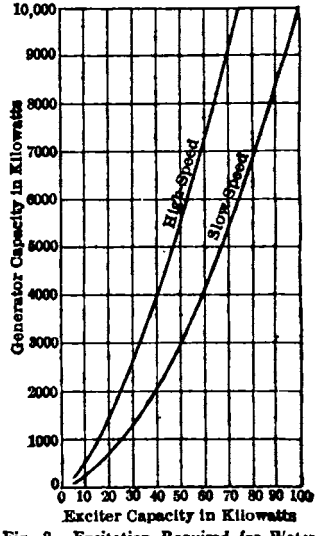


Fig. 2. Excitation Required for Water wheel-driven Alternators

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reduced. A considerable saving can also generally be accomplished in the exciter itself.

Methods of Driving Exciters. — Although the exciters can be either belt-driven or direct-connected to the machines driving them, the latter practice is almost exclusively used except in the very smallest plants. The direct connection may be either to the main generators, to separate water wheels, or to motors. Sometimes (although rarely) an exciter is connected to both a motor and a turbine, the latter running idle when the motor is carrying the load, and the motor running idle when the turbine is doing the work.

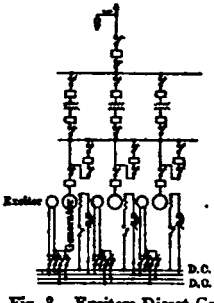


Fig. 3. Exciters Direct Connected to Main Units

Exciters Direct-connected to Main Units. — The practice of installing an exciter direct connected to each generator is very common and desirable. As a rule each exciter is only of sufficient capacity to excite its corresponding generator and is operated as a unit with it. In those stations where it is felt advisable to install spare exciter capacity, this spare capacity usually takes the form of a motor-generator set. The generator of the set is connected to a bus and the switching so arranged that it can be used to excite the field of any one generator in the case of failure of the corresponding direct connected exciter. Fig. 3 shows another arrangement of connection commonly used in which all exciters are paralleled on a common exciter bus and the fields of all machines in operation excited from this bus.

This method of employing direct-connected exciters is mostly applicable in the case of medium- and high-speed generators. In the case of low-speed generators the high cost of the slow-speed exciters usually makes the arrangement prohibitive.

Three-exciter System. — A system which is commonly used and which offers a sufficient degree of reliability, is that in which the excitation is obtained from a common source, consisting of as few exciters as possible, Fig. 4. Three units are then generally provided, of which two are all that are needed for supplying the required excitation, the third unit being held in reserve. Sometimes the two exciters normally in service are driven by water wheels, the reserve unit being motor-driven. From the point of view of economy, however, it is evident that two motor-driven units with a water-wheel driven set as the spare will cost less. In the latter case, however, the exciter trouble with the exciter driven by the prime mover would prevent starting up the system, unless a storage battery were provided.

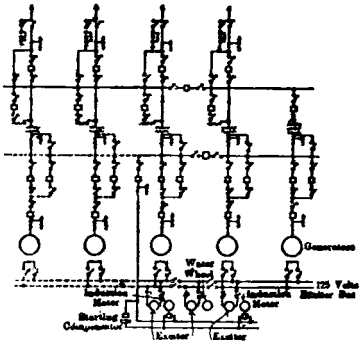


Fig. 4. Three-exciter System

Individual Motor-driven Exciters. — Fig. 5 represents the practice when an individual motor-driven exciter is used for each main unit. Each ex-

citer is connected directly to the field of its respective generator. The exciters are not arranged for parallel operation, but are each provided with its own automatic regulator, so that it is possible to compensate for "wattless" or reactive cross-currents between the generators. In the system shown, the induction motors are fed either from two low-voltage alternating-current generators driven by separate water wheels, or alternatively from the main alternating-current bus-bars through step-down transformers. The auxiliary low-voltage generators are the normal source; the exciter system is thus entirely free from voltage fluctuations or disturbances on the alternating-current system. In another installation of this kind the auxiliary generators are provided for combination drive, one end being connected to a water wheel and the other to an induction motor, which in turn can be connected to the main alternating-current buses through step-down transformers, unless the voltage will permit of a safe operation of the motors without the transformers. In such an arrangement the exciter sets are not provided with independent group connections to the main bus, as shown in the illustration, as it is considered that a breakdown would most commonly be caused by a clogging up of the turbines, in which case the alternating-current units could be driven by the motors. It would seem, however, that the scheme shown in the diagram is more flexible and reliable.

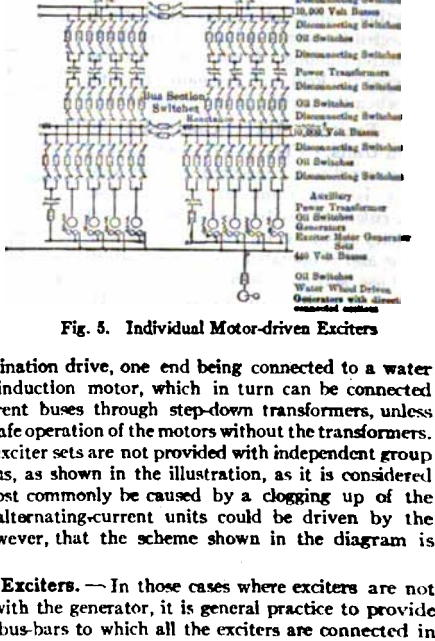


Fig. 5. Individual Motor-driven Exciters

Electric Connections of Exciters. — In those cases where exciters are not chosen to operate as a unit with the generator, it is general practice to provide one or two sets of common bus-bars to which all the exciters are connected in parallel and from which the fields of the different generators are excited, a rheostat being inserted in each generator field circuit. Where exciters are chosen of just sufficient capacity to excite the field of one generator, they are usually operated independently of each other, each with its armature connected to its corresponding generator field. If no spare exciter set is provided in the station, no exciter bus is necessary. Where a spare exciter is installed a single bus is used to permit of transferring it to any one generator field, in which case the corresponding direct connected exciter is taken out of the field circuit. In these latter two cases, no generator field rheostats are necessary.

Hand-operated field rheostats mounted on the back of the switchboard, or operated by chain drive from a handwheel on the switchboard, are generally used. For large plants the alternator field and the exciter field rheostats are nearly always electrically operated. This method of operation should be used in plants where the main control board is on another floor or distant from the machines.

No automatic overload circuit breakers or fuses should be installed in the exciter circuits. The field current may rise to several times its normal value when the alternator is subject to a short circuit, and an automatic circuit breaker would then naturally open the exciter circuit, which must not be allowed. A

such troubles are rather infrequent, it is considered better practice to risk injury to the exciter rather than to install overload devices which may operate at the wrong time. With exciters operating in parallel on a common bus it may be desirable to have reverse current circuit breakers in the connections between the exciters and the bus.

The alternator field switches should be provided with discharge resistances, and these field switches as well as the exciter switches should be electrically operated in all large plants. The field switches should never open on overload, but may be made to open automatically when the main alternating current circuit breaker opens by the action of reverse power or differential relays in the main alternator leads.

Shunt versus Compound-wound Exciters. — Compound-wound exciters are generally considered preferable for parallel operation with automatic voltage regulators. Non-regulating exciters should be more or less highly saturated to insure a stable parallel operation. However, if such exciters are used with automatic regulators, they will be rather slow to correspond to the changes in field excitation. If a shunt-wound exciter is designed for a low saturation, so as to make it a good regulating exciter, there is a tendency to unstable operation when operating in parallel with other machines and without a regulator. For regulating exciters, which are not to be operated in parallel, the shunt-wound type is entirely satisfactory, provided it has been designed with this point in view, that is, for low saturation.

Storage Battery on Exciter Bus. — The use of storage batteries in connection with exciters is sometimes employed. The storage battery is generally floating on the exciter busses, the pressure of which is kept constant. A separate exciting bus is provided and between this bus and one of the exciter bus-bars a booster is installed which can be operated to either raise or lower the voltage, its field being controlled by an automatic voltage regulator. In case of failure of the exciters the excitation would be furnished by the storage battery, and the booster in connection with the regulator would take care of the voltage regulation.

AUTOMATIC VOLTAGE REGULATION. — Without some form of automatic voltage regulator it is impossible to take care of the heavy swings in the voltage caused by fluctuating power and railway loads. Even in the case of a purely lighting load it is exceedingly difficult to properly take care of the voltage by hand regulation, especially at peak loads. The present tendency of designing generators for a high internal reactance, in order to reduce destructive short-circuit currents, results furthermore in a rather poor inherent regulation of the generators.

Many different forms of automatic regulators have been devised. Some of them have been designed to operate directly on the alternating-current generator field rheostat by varying the resistance. Such a system has, however, proved to be entirely too sluggish in operation. The most successful type of automatic regulator is the T. A. Regulator in which the regulation is effected entirely in the field circuit of the exciter, by rapidly opening and closing a shunt circuit across the exciter field rheostat. See the article on *Regulators*.

TRANSFORMERS AND THEIR CONNECTIONS. — (*See also article on Transformers.*) The number and size of the transformers depends entirely on the nature of the development and on the conditions to be met. With a moderate voltage development it has in the past been the general practice to install one transformer bank for each generator and having a capacity equal to that of the generator, even if this size was not the most economical.

In some instances transformer capacities are selected so that a bank of transformers corresponds in capacity with the rated carrying capacity of a trans-

mission line. In such cases a bank of transformers is usually operated as a unit with one of the lines. During the early stages of high-tension transmission development this method was almost invariably employed as it permitted the employment of low-tension switching to clear trouble on the high-tension system. In such cases as this the transformers might be considered as a part of the transmission line. With the advancement of the art of building high-potential apparatus and as a result of the experience gained in operating high-tension systems, this manner of operation is gradually giving way to the use of high-tension switching, in which case it is no longer necessary to select transformer banks of the same capacity as that of the transmission lines. The tendency is rather to select them on the basis of the generator capacity.

In order to facilitate moving the transformers in or out of their compartments. wheels should be provided in the base or trucks may be installed on which the transformer will rest. The design should also preferably be such that the complete core and coils, with the cover and leads can be lifted from the tank as a unit. Eyebolts are provided for this purpose and also for lifting the entire transformer filled with oil.

Single- versus Three-phase Transformers. — No specific rule can be given regarding the selection of single-phase or three-phase transformers since both designs are equally reliable; local conditions will generally determine which type is preferable. See the article on *Transformers*.

Use of Auto-Transformers. — (*See also Auto-Transformers.*) Auto-transformers are sometimes used in connection with Y-connected generators for obtaining a moderate rise in the voltage. Where such is the case a path must be provided for the flow of the triple-frequency exciting current, which is required for the normal magnetizing of the transformer. With a grounded generator neutral (*see Generators, Alternating-Current, and Grounding of Electric Circuits*), this can be obtained by also grounding the neutral point of the auto-transformers, although it is also highly desirable to connect the two neutrals together as any ground offers more or less of a resistance. If a sure path for the triple-frequency exciting current is not provided, a third harmonic will appear in the no-load e.m.f. from line to neutral and cause an excessive strain in the windings, which under such conditions should in all cases be insulated for a higher voltage than the normal.

Cooling of Transformers. — Transformers for hydroelectric generating stations should obviously be of the water-cooled type. Ordinarily the water rate to keep a transformer of this type cool is approximately one-half gallon per minute per kw. loss, the temperature of the incoming water being 15° C.

Cooling coils are generally made of extra heavy lap-welded wrought iron pipe with electrically-welded joints. These coils will withstand a hydraulic test of 1000 pounds per square inch. In some cases the quality of water available for cooling purposes may make it necessary to use either brass or copper pipe, in order to avoid corrosion which would prohibit the use of iron pipe.

Drying of Transformers. — It was formerly customary in shipping transformers to pack the cores separately from the tanks. Where the railroad clearances will permit, transformers are now shipped assembled with the oil in the tanks, the cores being securely braced in the tank. In this manner the transformers should arrive at the destination with the insulation and oil practically dry and free from moisture. Where transformers are shipped without the oil in the tanks it is almost invariably necessary to dry them out first. This may be accomplished in several ways, as explained in the article on Transformers (q.v.).

Transformer Oil. — The oil, whether shipped in the transformer case or

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separately, should always be tested before it is used in service (*see the article on Oil, Transformer*), and should be dried if it punctures at too low a voltage. Oil for transformers of 40,000 volts and over should be dried before using, if it punctures below 35,000 volts. For transformers having voltages less than 40,000 volts, the oil must be dried if it punctures below 25,000 volts. Where oil is dried it may easily be brought to a puncture of 40,000 volts. If a sample contains sediment, it will puncture at a lower voltage than it would without the sediment.

Transformer Connections. — With the three-phase system the transformers are usually connected in delta or Y, and when the Y-connection is used the neutral may be grounded or not. It is a much-disputed question which connection is to be preferred. In general it may, however, be said that in transmission systems where continuity of service is the most important factor, delta-connected transformers (both primary and secondary) are preferable on account of the increased reliability which such a system affords. See articles on *Transformers* and *Grounding of Electric Circuits*.

For high-voltage systems it is, however, now being generally conceded that the Y-connected system with the neutral grounded is preferable, if not almost essential. The fact that any ground will then constitute a short-circuit followed by a shut-down, is outweighed by the limitations of the rise in voltage caused by such grounds. Modern transmission line apparatus must furthermore be designed to withstand the mechanical strains imposed by short-circuits. With a ground on a delta-connected system it is evident that the neutral is shifted from the center of the delta to one corner, and the charging current, which is a function of the voltage from wire to neutral, is therefore increased in proportion, or about 73 per cent. This increased charging current will in turn cause a corresponding increase in the voltage rise which may take place when the lines are cut in circuit at no load. Actual experience has shown that this voltage may reach prohibitive values which, of course, would not be the case with the Y-connected, grounded system.

SWITCHING EQUIPMENT AND ELECTRICAL CONNECTIONS. — Continuity of service is the most essential part in the protection and operation of a large high-tension power system. A maximum degree of reliability can naturally be obtained by providing reserve and duplicate apparatus, the maximum reliability thus being governed by the permissible investment in the apparatus, by the price paid for the power and by the competitive situation.

In small and medium-size power plants the switching equipment may be of the hand-operated type, mounted directly on the back of the switchboard panels or on a separate framework and operated by hand by means of levers located on the front of the panels. For large modern power houses the switches should, however, always be of the remote-control type. The control board is then located so that the operator may obtain the best view of the station, while the switches and bus-bar structure are installed with regard to convenience of wiring and safety.

The switch and bus-bar structure for large stations may be either of the enclosed or open type, but is mostly a combination of the two.

The entire subject of switchgear equipment is discussed in detail in the separate article on *Switchgear Equipment for Power Stations*, which see.

Sectionalized Low-tension Bus. — (*See also Bus-Bars and Bus-bar Structures.*) The generators should preferably be paralleled on a low-tension bus, and where the total capacity is large the bus should be sectionalized, it being the general practice to limit the normal capacity of each section to from 30,000 to 50,000 kv-a. The sections may be connected by means of automatic switches provided with instantaneous overload relays which in case of trouble in one section will immediately disconnect the same from the other sections and thus

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limit the power which the oil switches will have to rupture to the capacity of one section. In some of the recent systems reactance coils have been inserted between the bus sections, and the sectionalizing switches have been made non-automatic. The reactances are selected of such a value as to limit the short-circuit current to an amount that can be safely ruptured by the installed circuit breakers.

In sectionalizing the bus it is desirable to make such provision that sufficient generator capacity to supply the charging current of one transmission line can be entirely separated from the rest and used for testing out the lines. A ring bus will generally insure sufficient flexibility to accomplish this, although for large systems a double bus may be desirable if the extra expense is warranted.

Generator Switches. — The generator switches are usually made non-automatic, as it is of the utmost importance to keep the generators in service, and the possibility of trouble between the generators and buses is rather remote. If, however, automatic protection is desired for the generator switches, the relays (*see Relays*) should be of the definite-time limit type, set very high so as to trip the switches as a last resort, after the automatic switches more remote from the generators have failed to isolate the trouble.

Sometimes the generator switches are provided with reverse energy relays which will cut out from service a damaged generator on the reversal of the power. In the case of large important generator installations the most highly recommended practice, perhaps, is to equip each with differential relay protection. This type of protection is so designed that in case of an internal electrical failure within the generator armature, the generator will be instantly cut out of service. The protection is also usually so arranged that, when the generator main switch opens, the field circuit is simultaneously opened, thereby reducing burning within the machine to a minimum.

Transmission-line Connections. — (*See also Transmission Lines.*) Double transmission lines are nearly always provided to important load centers, and it is then also desirable to so proportion the line conductors that in case of trouble, one line alone or together with a section of the other can take care of the greater part of the load without causing too poor a regulation.

Up until recent years it was customary to recommend that high-tension lines be normally operated electrically apart from one another, each connected at each end to a bank of transformers, the paralleling and switching being done on the low-tension side of the transformers in both generating and substations. This method of operation was early adopted to reduce to a minimum the electrical stresses resulting from high-tension switching. With the growth of high-tension transmission systems with their multiplicity of interconnected transmission lines and as a result of the cost of equipment to adopt a large high-tension net-work for operation in this manner, the method has to a large extent been superseded by the simpler one based upon high-tension switching. Due to the rapid advancement in the art of designing high-tension apparatus and the practical experience gained in its operation, it is now possible to construct high-tension systems with perfect assurance that high-tension switching will give entirely satisfactory results.

All switches should be provided with carefully selected relays, so arranged as to select and cut out of service in the minimum time any circuit in which a fault has occurred so that uninterrupted service may be maintained over the remaining circuits.

LIGHTNING ARRESTERS, EQUIPMENT AND CONNECTIONS. — Aluminum and oxide film lightning arresters are now generally used for lightning protection of high-voltage transmission systems, see article on *Light-*

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ning Protectors, for description of the various available types of arresters. The arrester, however, is not a universal protector against all kinds of interruptions. For example, while it meets the usual, and most of the unusual, needs in protection against disruptive potentials from lightning, an arrester located in the station cannot, and is not expected to, protect an insulator out on the line from a lightning flash. Neither is it designed to protect against surges of comparatively low voltage.

Arresters for Grounded and Ungrounded Circuits. — It is important to avoid the mistake of choosing an arrester for a thoroughly grounded neutral when the neutral is only partly grounded; that is to say, grounded through an appreciable resistance. In an arrester for a grounded neutral circuit, each stack of cones normally receives the neutral potential when the arrester discharges; but if a phase becomes accidentally grounded the line voltage is thrown across each of the other stacks of cones until the circuit breaker opens the circuit. Line voltage is 173 per cent of the neutral or normal operating voltage of the cells and therefore about 150 per cent of the permanent critical voltage of each cell. This means that when a grounded phase occurs this 50 per cent excess dynamic potential is short-circuited through the cells until the circuit breaker opens. The amount of energy to be dissipated in the arrester depends upon the kilowatt capacity of the generator, the internal resistance of the cells and the time required to operate the circuit breakers. It is evident that the greater the amount of resistance in the neutral, the longer will be the time required for the circuit breakers to operate. Therefore, in cases when the earthing resistance in the neutral is great enough to prevent the automatic circuit breakers from opening practically instantaneously, an arrester for a non-grounded neutral system should be installed. It is difficult to determine these factors of ground resistance and time elements in the operation of switches and therefore no mistake can be made by adopting the 4-tank arrester even on grounded Y circuits.

Wiring Connections for Lightning Arresters. — The wiring connections of lightning arresters are an important consideration. The discharge circuit should contain minimum impedance and hence must furnish the shortest and most direct path from line to ground. The most severe disturbances which an arrester is called upon to handle are of high frequencies and it is, therefore, imperative to eliminate all unnecessary inductance. The features favorable for low inductance are short length of conductor, large radius bends and large surface of conductor. For wiring high-voltage arresters the use of copper tubing is therefore recommended. Such copper tubing has the advantage over either copper-strip or solid conductors in that it is easily supported, requires fewer insulators and is, therefore, cheaper to install. From arrester to ground it is sometimes more convenient to use copper strip than tubing. Copper strip, say 1.5 in. by 0.03 in., can be fastened to the station wall leading directly down to ground.

Ground Connections for Lightning Arresters. — In all lightning-arrester installations it is of the utmost importance to make proper ground connections since many lightning-arrester troubles can be traced to bad grounds; see article on *Ground Connections*. As noted in the article referred to, a very satisfactory method of making a ground is to drive a number of one-inch iron pipes six or eight feet into the earth about the station, connecting all these pipes together by means of a copper wire, or preferably, by a thin copper strip. A quantity of salt should be placed around each pipe under the surface of the earth and the ground thoroughly moistened with water. It is advisable to connect these earth pipes to the iron framework of the station, and also to any water mains, metal flumes or trolley rails that are available. For the usual size station the following recommendation is made: place three earth pipes equally spaced near each outside wall, making twelve altogether, and place three extra

pipes spaced about six feet apart at a point nearest the arrester. When plates are placed in streams of running water, they should be buried in the mud along the bank in preference to laying them in the stream. Streams with rocky bottoms are to be avoided.

From time to time the resistance of these ground connections should be measured to determine their condition; see article on *Ground Connections*. The resistance of a single pipe ground in good condition has an average value of about 15 ohms. A simple and satisfactory method of keeping account of the condition of the earth connections is to divide the earth pipes into two groups and connect each group to the 110-volt lighting circuit with an ammeter in series. If there is a flow of about 20 amperes the conditions are satisfactory, provided the earth pipes are properly distributed around the station.

Charging of Aluminum Cell Arresters. — This is accomplished as follows:

First. — Operate the charging mechanism so as to bring the charging contact securely against the horn gap and charge for five seconds. The contacts should be so adjusted as to eliminate arcing when gaps are closed. The closing and opening of the charging contact should be performed quickly so as to avoid unnecessary arcing. Note should be made of the size and color of the arc which forms when the contact is broken at the close of the charging period.

Second. — With the horn gaps in normal position reverse the transfer device, thereby interchanging the connections to the ground stack of cones and one of the line stacks.

Third. — The first operation should again be repeated, thus charging the fourth stack of cones, which was originally the ground stack.

When an arrester is first installed and also when one has been off the circuit for several days the initial charging current is sometimes above normal. It is recommended that the cells be charged six or eight times the first day and three times a day during the remainder of the first week. This charging should be performed as just described. After the first week the regular daily charging will usually be found sufficient. It is important that the charging should be done at a time of the day when the line voltage is at a maximum value. The charging period should always be five seconds.

In cases where aluminum lightning arresters are installed in places where the temperature is excessive, it is sometimes advisable to charge the arresters twice a day. This condition will be indicated by an increase in the charging arc and charging current from day to day.

Charging-current Indicator. — The charging-current indicator is a device for measuring the current taken by an alternating-current aluminum arrester during charging; it also indicates the condition of the arrester cells. An arrester in good condition has a charging current of approximately 0.25 ampere on 25-cycle circuits, 0.30 ampere on 40-cycle, and 0.40 ampere on 60-cycle circuits. Should these values be doubled, the arrester must be charged more frequently and the current carefully measured until it comes down to normal. It is only when this additional charging fails to reduce the charging current that an inspection of the cells is necessary.

The essential parts of the charging-current indicator are an ammeter mounted on a specially-constructed switch stick and a set of jacks. These jacks are so connected in the arrester circuit that when the ammeter switch stick is inserted in them and the horn gaps short-circuited, the charging current flows through the meter.

Choke Coils. — Choke coils should always be installed in the power circuit between the lightning arrester and the apparatus to be protected. All choke coils should be very rigidly supported as they are subject to severe mechanical strains when short-circuits occur on the system. See article on *Lightning Protectors*.

Use of Arcing Ground Suppressor. — This apparatus is described in the article on *Ground Detectors and Arcing Ground Suppressors*. One arcing ground suppressor is sufficient for controlling the entire system. When several power stations feed into one transmission system special attention should be given to the best location of the suppressor.

STATION WIRING. — The design and construction of the cabling and wiring system of the station is of equal importance to the rest of the equipment. Experience has shown that in a great number of instances the shut-down of power plants was caused by defective installation of the station wiring. Every cable and wire should have a definite place provided for it in advance, just as much as any other piece of machinery, and wires carrying currents of different voltages should, as far as possible, be kept apart from each other.

Braided vs. Lead-covered Cables. — For generator and low-tension transformer leads, braided or lead-covered cables are used, and may be run in ducts or exposed upon racks in cable-ways or tunnels. Lead-covered cables are necessarily more expensive than braided cables, and their use seems to be justified only in places where protection against water and moisture is required. As the lead sheath is necessarily grounded along its entire length, such cables are more apt to be punctured. As a protection against fire the lead covering is obviously useless and due to its softness it is not very efficient in withstanding mechanical injuries.

Installation of Cables. — (*See also article on Wires and Cables, Insulated.*) In many plants the cables are installed in ducts in the floor, and in such instances the cables should preferably be lead-covered to protect the cables from abrasion when drawn into the ducts. There are, however, several other objections to installing the cables in ducts. With high-voltage single-conductor lead-covered cables, static discharges may take place through the insulation to the lead, which rapidly injures the insulation and a breakdown soon follows. If the cable is not lead-covered a static discharge may take place to the tile duct, this also having a tendency to break down the insulation in time. In multiple-conductor cables this action does not occur, the static activity probably being neutralized. With cables carrying large low-voltage currents the lack of ventilation in the ducts may furthermore cause overheating of the cables.

In a large number of stations the open method of cabling is used. Tunnels or cable subways are then provided in which braided cables are supported in free air upon insulators mounted on racks, these insulators themselves having sufficient insulation to withstand the operating voltage of the cable. Where single-conductor, high-voltage cables are used, they should be separated far enough to prevent static discharges between the cables, and also in order to obtain the best possible ventilation and to minimize trouble in case of short-circuits. The cables should also be rendered fireproof by wrapping them with asbestos tape.

Size of Cables. — Due to the skin effect it is generally considered good practice to limit the size of single-conductor cables to 1,250,000 cir. mils for 25-cycle service and 700,000 cir. mils for 60 cycles. Where the value of current is such that it can be carried safely by one three-conductor cable, this is preferable in every respect to three single-conductor cables. If more than one cable has to be used to carry the current the difficulty of making connections will generally offset the advantages of three-conductor cables, and under such conditions it is usually found to be more advantageous to use single-conductor cables.

High-tension Wiring. — Bare wire or tubing supported on post insulators or hung from suspension insulators is generally used for all high-tension wiring. High-tension station wiring is described in detail in the article on *Switch-gear Equipment for Power Stations*.

OPERATION AND OPERATING RECORDS. — The selection and

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maintenance of an efficient and reliable operating force is essential. Most modern systems of any size have a method of operation which corresponds to that of a train dispatcher on steam railroads, and where many different plants are attached to the same network, this becomes practically necessary. The directions for operating the different stations and apparatus come from a central source, where the dispatcher has before him a diagram of the whole system and information regarding the capacities of the generators in use and the magnitudes of the loads at the different places of distribution.

Organization of Operating Force. — The organization of the operating force of a hydroelectric generating station is necessarily less complicated than in a steam station. It is determined largely by the location and the arrangement, and there are so many different conditions in such systems that it is impossible to recommend any exact form of organization, as really no two can be quite alike. If the station is not too large, it is desired to have the hydraulic superintendent report to the station superintendent, but if the development is of such a magnitude as to require the entire time of a superintendent for each of the departments under consideration, a position is warranted for a man to whom both electric and hydraulic superintendents will report, thus still bringing the responsibility of operation of the two departments under one head.

As a general rule, for the same capacity installed, a plant having horizontal units can get along with a smaller force than one using vertical units. It is a general practice to maintain one man at all times on each of the different levels or floors of the power house, such as the switchboard gallery, the main floor and the basement, where with vertical units the turbines proper as well as the oil pumps and other auxiliaries are located. The man in the basement could in all probability be dispensed with in plants using horizontal units. In addition to these men a chief operator should be provided for each shift, whose duties should carry him to all parts of the building. For a very large station the above force may be entirely inadequate, and for small plants the force may be reduced.

Switching Operations. — The switching operations are determined by the general method of operation. It is desirable to eliminate all high-tension switching under load, due to the fact that such switching may set up surges which may be dangerous to the transformers and other apparatus.

When a line is to be cut into service, the high-tension switches in both the main and substations should be closed first, then the low-tension transformer switch in the generating station should be closed, energizing the transformers and the line, after which the low-tension transformer switch in the substation is closed and the load picked up. In case it becomes necessary to open a high-tension switch in a loaded line, the circuit should if possible first be parallel with another before opening the switch. If, on the other hand, transformers are to be paralleled on both high- and low-tension sides, the low-tension switch should be closed first, assuming that the low-tension bus is energized. Similarly, in cutting out the transformer the low-tension switch should be opened last.

Operating Records. — One of the essential things in connection with the operation of hydroelectric generating stations is the keeping of accurate records. Record sheets should contain only the most important readings, as with complicated forms the attendant generally realizes that a large number of the readings are of no importance and for this reason he becomes very lax in his attention to the readings in general and as a consequence the important ones may suffer

The following description applies to an actual record sheet which has been found to give satisfactory results. The sheet is of the size of ordinary letter paper and is ruled for hourly records of "Water," "Main Units," "Cycles," "Power Factor," "Exciters," "Transformers" and "Floodgates." These items are listed vertically and the sheet is divided into 24 vertical columns, one for

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each hour. At the top are given the "Forebay" readings and "Tail Race" readings, the difference between which gives the "Effective Head." Immediately below are listed the indicated kilowatts and per cent gate opening of each generator in service, following which are given the "Total Indicated Kilowatts" and "Total % Gate." The total kilowatt-hours during each hour, as read from the watthour meters, is plotted as a block-curve extending across the face of the sheet.

This serves as a better record for the actual station output than the indicated kilowatts. It has been found necessary, however, to follow the indicated kilowatts to serve as a check on the efficiency and condition of the units in general, from time to time, as well as to determine what capacity would be required for short interval peaks. The station voltage is also plotted as a block curve across the face of the sheet.

The exciters form an individual group, and for each exciter the voltage, current and per cent gate opening are recorded.

Transformer records are limited to the temperatures. These are taken hourly, at which time the oil elevation is noted but not recorded. If the transformer is not in service the column in which the temperature is listed is left blank; if in service the temperature is taken and recorded.

Under the item, "Floodgates" the total opening of the floodgates in feet is recorded, rather than each one separately. This record is maintained daily, the flow of the river at each of the stations being followed very closely.

At the bottom of the sheet appear the daily readings of the various generator and feeder watthour meters taken at midnight of each 24 hours. The following items are also recorded at the bottom of the sheet: "Total Generated," or the total output of the station for 24 hours; the "Maximum Hour Time," or the maximum kw-hr. of any particular hour during the day; the "Maximum Kw. Time," or the maximum indicated kilowatts at any particular instant; the "Average Load," obtained by dividing the total kilowatt hours generated by 24; the "Load Factor," obtained by dividing the "Average Load" by the "Max. Kw. Time"; the "Average Flow of the River in Cubic Feet per Second," calculated each day and converted into "Available Capacity of River," which is shown in kw-hr.; the "Available Capacity of Power House," shown in kw-hr., and determined by calculating the capacity of the machines under the average head for 24 hours; the "Kw-hr. Lost," or the difference between what was actually generated by the machines and what could have been secured from the river during the same number of hours.

Any important notes of operation are entered on the back of each day's log sheet. These notes, together with certain records for log sheets, are also entered each day in a log book kept on the operator's desk at all times, for reference purposes. Weather conditions and temperatures are recorded four times daily, at midnight, 6 A.M., noon and 6 P.M. A rain gauge is provided on the roof of the station, from which records of precipitation covering each 24 hours are obtained

CAPITAL COSTS AND APPROXIMATE DIMENSIONS. — (*See also section below on Capital and Annual Costs of Some Typical Plants.*) The cost of a large water-power development is generally very great. The estimates of the amount of power available are always subject to error and many times are greatly exaggerated. On account of unforeseen obstacles in dam construction, it is always possible that the actual cost will exceed the engineering estimates, and such elements of uncertainty must always be taken into consideration. Moreover, as the large water powers of the country are generally more or less remote from power markets, there is necessitated the construction of expensive high-tension transformer equipments and transmission lines to transmit the power to the point of consumption. This additional cost is often greater than that of the

dam and power-house construction. The provision of large storage reservoirs is often necessary in order to meet the irregularities in the flow of streams, while, on the other hand, the most economical utilization of water power often requires the erection of auxiliary steam plants.

The main items entering into the cost of construction of a hydroelectric power plant are: (1) Dam, (2) Water Conductors, (3) Reservoirs, (4) Power house, (5) Land and Water Rights, (6) Transmission Lines. In addition to the cost of the above physical equipment certain overhead and organization expenses must also be included. These may be classified as follows: (7) Engineering and Contingencies, (8) Administration, (9) Organization, (10) Taxes and Insurance, (11) Interest during Construction, (12) Working Capital.

Range of Total Capital Cost per Horse-Power. — Extensive investigations by the Bureau of Corporations show that the cost of a hydroelectric power development, including the construction of dams, the erection of transmission lines and other equipment, ranged from $50 to $375 per horse-power delivered at the substations. These figures represent extremes, as the usual cost will fall between $100, and $200 per horse-power, depending upon physical conditions and the length of the transmission lines.

Approximate Dimensions and Construction Costs. — It is obvious that there are certain minimum costs that can readily be approximated when the rough dimensions of dams, pipe lines, etc., are available, so that rough minimum figures can readily be made. Such rough figures cannot be expected to take into account expensive contingencies that must be anticipated.

Dams. — Given the length and height of dam, the dam structure itself will have a cost of material that can be estimated roughly, and the ordinary cost of placing such material — including tools and forms — can be added, but the extraordinary labor costs due to the construction of expensive foundations and coffer dams and the cost of placing dam material under difficult conditions can, of course, only be estimated by experienced engineers thoroughly familiar with the local conditions.

Expressing the height of dam in yards as h, the approximate sections of dams and approximate costs of dams not used as weirs or spillways are:

SECTIONS AND COST* OF DAMS NOT USED AS SPILLWAYS

Type of dam	Batter or slope		Approx. section in sq. yards	Approx. cost per cubic yard	Approx. cost per lineal yard
	Common upstream batter horizontal to vert.	Common down stream batter			
1. Earth	2 to 1	3 to 1	$2.5\,h^2$	$0.50	$1.25\,h^2$
2. Crib	1½ to 1½	1½ to 1	$1.5\,h^2$	1.50	$2.25\,h^2$
3. Rock fill	2 to 1	2 to 1	$2.0\,h^2$	2.00	$4.00\,h^2$
4. Masonry, straight	Vertical	4/10 to 1	$\frac{4}{10}\,h^2$	12.00	$4.80\,h^2$
5. Masonry, arched	0.15 to 1	0.30 to 0	$\frac{1}{4}\,h^2$	15.00	$3.50\,h^2$

It should be borne in mind that maintenance and depreciation on Types 1, 2 and 3 are far heavier than on Types 4 and 5.

* Pre-war conditions

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These figures are intended to cover all costs under ordinary conditions, for the cost per cubic yard is taken sufficiently high; but they cannot be used for extraordinary conditions, producing costs possibly four or five times greater.

Low crib or masonry dams used practically throughout their length as weirs or spillways may easily cost many times these figures.

No figures are given for intakes, owing to the great variety of conditions to be met.

Flumes. — The use of flumes of wood becomes less and less as hydroelectric work becomes more permanent in character. For estimate purposes it is then suggested that the cost of wood-stave or riveted-steel pipe be used instead of using the presumably lower cost of the flume. It is obvious that repairs and depreciation on flumes are heavy, and hence they would seem to have little use in permanent construction.

Low-pressure Pipes. — (*See also Pipes and Piping.*) In hydroelectric work cast-iron pipes are seldom used. Wooden-stave and riveted-steel pipes have been widely used for low pressures. The approximate costs of these, as compiled by A. L. Adams for Chicago, are given in the following tables.

COST* PER FOOT OF WOODEN-STAVE PIPE
Including laying but omitting hauling

Diameter in inches	25-foot head	50-foot head	100-foot head	200-foot head
12	$0.42	$0.49	$0.63	$0.85
18	0.69	0.80	1.02	1.46
24	0.79	0.91	1.14	1.61
30	0.96	1.12	1.44	2.06
36	1.19	1.40	1.82	2.65
42	1.40	1.68	2.23	3.33
48	1.55	1.85	2.46	3.67
54	2.23	2.62	3.43	5.02
60	2.85	3.35	4.37	6.40
66	3.21	3.81	5.00	7.38
72	3.65	4.38	5.83	8.73

COST* PER FOOT OF RIVETED-STEEL PIPE
Including laying but omitting hauling

Diam. in in.	No. 14	No. 12	No 10	No. 8	No. 6	¼ in.	5/16 in.	⅜ in.
12	$0.32	$0.38	$0.44	....	....	....	....	....
18	....	0.57	0.65	$0.78	$0.98	....	....	....
24	....	....	0.85	1.04	1.28	$1.55	$1.99	....
30	....	....	....	1.27	1.59	1.93	2.46	$3.04
36	....	....	....	1.55	1.93	2.30	2.92	3.58
42	....	....	....	1.61	2.18	2.66	3.37	4.12
48	....	....	....	....	2.48	3.03	3.83	4.66
54	....	....	....	....	2.80	3.41	4.29	5.21
60	....	....	....	....	....	3.79	4.75	5.74
66	....	....	....	....	....	4.35	5.21	6.29
72	....	....	....	....	....	4.52	5.66	6.83

* Pre-war conditions.

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High-pressure Piping. — In high heads the high-pressure piping may be either riveted-steel pipe or lap-welded pipe with bolted flanged joints. It is suggested that a percentage amount be allowed for this, as the cost must vary widely for different conditions.

Tunnels. — Tunnels for hydroelectric work are usually lined. Naturally the cost per cubic yard varies, but for ordinary conditions an average unit cost of $15 per cubic yard will cover all expense including timbering and lining. Allowing a velocity of 10 ft. per second (except in the smallest tunnels), approximate dimensions and costs are as follows:

COST* AND DIMENSIONS OF TUNNELS

Carrying capacity in cubic feet per second	Velocity in feet per second	Net sectional area, square feet	Dimensions in feet, width by height	Approximate slope, feet per 1000 feet	Approximate cost per linear foot
100	3.6	28	4 by 7	0.46	$16.00
500	10.0	50	7 by 7¼	2.0	28.00
1,000	10.0	100	10 by 10	1.5	56.00
1,500	10.0	150	12 by 12½	1.1	85.00
2,000	10.0	200	14 by 14¼	0.9	115.00
5,000	10.0	500	20 by 25	0.6	280.00
10,000	10.0	1000	30 by 33	0.3	500.00

Canals. — In ordinary earth a velocity too small to produce erosion and yet sufficiently great to prevent undue deposit of silt and other matter, and sufficiently great to prevent growth of weeds, should be used. For preliminary calculations a velocity of 2 ft. per second will give approximate results. For this velocity the following approximate figures will serve:

DATA ON AND COST* OF CANALS IN ORDINARY EARTH

Cubic feet per second	Velocity in feet per second, V	Area of wet section, sq. ft.	Water depth, feet	Approximate slope in feet per mile	Approximate cost per running foot	
					Low	High
50	2	25	2.5	4	$0.375	$0.75
100	2	50	3.5	2	0.75	1.50
200	2	100	5	1½	1.50	3.00
300	2	150	6	1	2.25	4.50
400	2	200	7	¾	3.00	6.00
500	2	250	7	¾	3.75	7.50
1000	2	500	10	½	7.50	15.00
1500	2	750	12	½	11.25	22.50
2000	2	1000	12	⅛	15.00	30.00
3000	2	1500	15	¼	22.50	45.00

In rock the velocity in a canal may be much higher, and if the canal be lined 8 ft. per second may be used. For preliminary calculations this velocity will give approximate results. The following approximate figures are on this basis:

* Pre-war conditions.

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DATA ON AND COST* OF CANALS IN ROCKS

Cubic feet per second	Velocity in feet per second, V	Area of wet section, sq. ft.	Water depth, feet	Approximate slope in feet per mile	Approximate cost per running foot	
					Low	High
50	8	6.25	2.5	40	$0.32	$1.28
100	8	12.5	3.5	25	0.63	2.50
200	8	25.0	5.0	16	1.25	5.00
300	8	37.5	6.0	12	1.87	7.50
400	8	50.0	7.0	10	2.50	10.00
500	8	62.5	7.0	9	3.25	13.00
1000	8	125.0	10.0	6	6.00	24.00
1500	8	175.0	12.0	4½	8.75	35.00
2000	8	250.0	12.0	3½	12.50	50.00
3000	8	375.0	15.0	3	18.75	75.00

Values are given for lined canals only, since a higher velocity will be allowable without producing too great a lost head and the cost will probably be more favorable.

It must be considered that these figures are wholly approximate since even for a desired useful section the amount of excavation per lineal foot of canal must vary with the character of the route — whether this be flat, rolling or side-hill.

In this connection the following approximate costs based on the annual reports of the United States Reclamation Service are of interest.

APPROXIMATE COST* OF EXCAVATION PER CUBIC YARD

Class	Cost per cubic yard		
	Low	High	Fair value
1. Plowable with 4 horses	$0.098	$1.00	$0.18
1a. Plowable with 6 horses	0.1225	2.00	0.30
2. Indurated material	0.29	2.00	0.60
3. Loose Rock	0.35	3.00	0.75
4. Solid Rock	0.60	5.00	2.00
4a. Excavation below plane of saturation	0.20	3.00	1.80
4b. Solid rock under water	....	....	4.50

Tail Race. — Frequently the cost of the tail race is negligible, but for some developments the cost is an appreciable percentage of the total. No data are given for estimating tail race since those given for canals, pipes and tunnels can be used.

Receivers. — No data are given for approximation of the costs of reservoirs, vent-pipes and surge tanks on account of the varied character of these. Generally speaking the percentage of the total hydro-electric cost to be allowed for these is small and a lump sum or a percentage can be allowed for the same.

Hydroelectric Power Houses. — The following figures upon the approximate space and cost of hydroelectric power houses are wholly approximate, and will give only a rough idea of what may be expected under ordinary conditions, without any allowances for high freight, long haulage, unusually expensive labor charges, etc.; and a wide departure from these figures is to be expected. See also the articles on *Water Wheels*, *Generators*, *Transformers*, *Switchgear*, *etc.*

* Pre-war conditions.

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DIMENSIONS AND COST OF POWER HOUSES (Pre-war Conditions)

Item	Low head*			Medium head*			High head*		
	Small†	Medium†	Large†	Small†	Medium†	Large†	Small†	Medium†	Large†
Cu. ft. per kw. for hydraulic apparatus	30	20	10	7	6	5	6	5	4
Cu. ft. per kw. for generators, exciters and switchboards (no transformers)	20	18	15	18	13	10	16	12	10
Cu. ft. per kw. for generators, exciters, transformers and switchboards	30	25	20	28	20	15	26	19	15
Total cu. ft. per kw. for hydro-electric power house (without transformers)	50	38	25	25	19	15	22	17	14
Total cu. ft. per kw. for hydro-electric power house (with transformers)	60	45	30	35	26	20	32	24	19
Approx. cost of power-house building not including foundations (without transformers) per kw:									
Low	$5.00	$3.80	$2.50	$2.50	$1.90	$1.50	$2.20	$1.70	$1.40
High	15.00	11.40	7.50	7.50	5.70	4.50	6.60	5.10	4.20
Approx. cost of power-house building, not including foundations (with transformers) per kw.:									
Low	$6.00	$4.50	$3.00	$3.50	$2.60	$2.00	$3.20	$2.40	$1.90
High	18.00	13.50	9.00	10.50	7.80	6.00	9.60	7.20	5.70
Approx. cost per kw. for hydraulic machinery	15.00	12.00	7.00	12.00	10.00	7.00	10.00	8.00	5.00
Approx. cost per kw. for exciters, generators, switchboards and cables (without transformers)	24.00	15.00	10.00	20.00	12.00	9.50	15.00	9.50	7.50
Approx. cost per kw. for exciters, generators, switchboards, transformers and cables	32.00	22.00	16.00	27.00	17.00	14.00	22.00	14.00	12.00
Approx. cost per kw. for complete power-house and foundations (without transformers)	54.00	38.40	24.50	39.50	27.70	21.00	31.60	22.60	16.70
Approx. cost per kw. for complete power-house and foundations (with transformers)	65.00	47.50	32.00	49.50	34.80	27.00	41.60	29.20	22.70

* Low head = 50 to 200 ft.
Medium head = 200 to 600 ft.
High head = 600 and above.

† Small capacity = 200 to 1000 kw.
Medium capacity = 1000 to 5000 kw.
Large capacity = 5000 kw. and above

It is assumed that the large capacity stations with transformers will be for a line oltage of from 60,000 to 110,000, the medium from 40,000 to 60,000 and the small om 10,000 to 40,000.

Overhead and Organization Expenses. — In addition to the expenditures for the actual construction of the physical plant allowance must be made for the following items to cover overhead and organization expenses.

Engineering and Contingencies. — This item should cover all the cost of engineering, drafting and supervision of construction and of all the items properly chargeable to construction engineering; 5 per cent of the construction cost is a conservative estimate for this item. An equal amount (5%) is also generally allowed to cover contingencies, errors, etc.

Administration. — All items which go to make up the cost of administration for construction, general office expense, etc., come under this head. An additional charge of 5 per cent of the construction cost should also be ample to cover these expenses.

Organization. — This item covers the cost of organization and promotion, such as legal expenses, allowance for brokerage connected with the disposal of the securities, discount on the same, etc., 5 to 10 per cent of the construction cost is usually allowed for this item.

Taxes and Insurance. — Taxes must be provided for until the operation is begun, and usually for some time thereafter, until the income is available for such expenses. Similarly with insurance, including fire, casualty, etc. One per cent of the construction cost is generally allowed to cover these items.

Interest During Construction. — Allowance must also be made for the accrued interest on the idle capital during the construction period.

Working Capital. — A certain amount of money should be provided for working capital, the amount depending on the nature of the business transactions. About 1 per cent of the construction may be allowed to cover this item.

OPERATING COST AND FIXED CHARGES (Pre-war figures). — (*See also section below on Capital and Annual Costs of Some Typical Plants.*) The cost of hydroelectric power can be considered as made up of two parts: the operating expenses and the fixed charges. The former consist of: (1) Labor; (2) Administration; (3) Oil, Waste, etc.; (4) Maintenance and Repairs; and the fixed charges of; (5) Interest; (6) Depreciation; (7) Taxes and Insurance.

It is difficult to give any general figures as to the cost of generating hydroelectric power, on account of the widely varying cost of such developments. The load factor also has a very great bearing on the cost, much more so than with steam plants because the items making up the power cost are affected very little by a change in the load.

The annual operating cost per kilowatt of generator capacity in general (excluding transmission costs) ranges between the following values:

Labor	$1.00 to $2.00
Administration	0.25 to 0.50
Oil, Waste, etc.	0.25 to 0.50
Maintenance & Repairs	1.00 to 2.00
Total operation	$2.50 to $5.00

Or, considering the annual cost items as percentage of the capital cost, the following figures are representative for a large station for which the capital cost is $125 per kilowatt, transmission costs excluded:

	Per cent
Labor	1.00
Administration	0.25
Oil, Waste, etc.	0.25
Maintenance & Repairs	1.00
Taxes & Insurance	1.00
Depreciation	3.50
Total	7.00

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The cost of power per kilowatt-year is thus 7 per cent of $125 or $8.75. Power at the bus bars of such a station could then be sold for $16, say, per kilowatt-year, leaving $7.25, or approximately 6 per cent for interest on the investment.

Primary and Secondary Power. — Hydroelectric power is generally sold as primary and secondary power. The former must be supplied continuously and is usually marketed by the horse-power-year or kilowatt-year. The secondary power is only available during certain months of the year, and the price obtained for it is necessarily considerably less than for the primary power. To maintain the primary power at the most economical value a steam auxiliary station is usually required; this is frequently obtained by operating the hydroelectric plant in conjunction with an existing steam plant.

CAPITAL AND ANNUAL COSTS OF SOME TYPICAL PLANTS (Pre-war figures). — Below are given data on some typical plants, ranging in size from 750 to 16,000 horse-power.

Minidoka Project. — The following data illustrate the development and power cost of the Minidoka project of the U. S. Reclamation Service:

COST* OF GENERATING STATION

Capacity of station, 9000 kw.
Transmission voltage, 33,000
Hydraulic head, 46 feet

Item	Total cost	Cost per kw.
Building	$82,000	$11.70
Hydraulic machinery	73,000	10.40
Electric machinery	83,000	11.80
Freight and hauling	26,200	3.75
Erection	55,500	7.90
Tailrace	60,000	8.50
Roads and telephone lines	7,300	1.10
Camp and permanent quarters	23,200	3.30
Engineering and incidentals	11,100	1.55
Administration charges, etc.	15,000	2.10
Total	$436,300	$62.30

ANNUAL COST* OF OPERATION

Item	Expense per year
Operation:	
Labor	$5,700
Supplies	950
Repairs:	
Labor	900
Supplies and material	800
Superintendence, clerical, camp, etc.	1,700
General expense and administration	450
Operating expense	$10,000

*Pre-war conditions.

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A depreciation of 5 per cent ($21,800) has also been charged to this development. No taxes or interest is charged, the undertaking being done by the Government. Assuming 7 per cent for interest and taxes the total operating expenses would amount to $62,000. A total of about 15 million kw-hr. were delivered during the year, thus corresponding to a cost of $0.0041 per kw-hr.

Costs* Reported by Ontario Commission. — The following table gives the estimated cost of development and yearly operating expenses of various plants from reports of the Ontario Hydro-Electric Power Commission.†

Location of development	Available head in feet	Developed power in horse-power	Estimated capital cost	Cost per horse-power	Annual operating expenses, including administration	Annual maintenance and repairs	Depreciation	Interest at 4 per cent	Total annual charges
			$	$	$	$	$	$	$
Healey's Falls, Lower Trent River	60	8,000	675,000	84.33	16,875	13,500	13,500	27,000	70,875
Middle Falls, Lower Trent River	30	5,200	475,000	91.37	11,875	9,500	9,500	19,000	49,875
Maitland River (*a*)	80	1,600	325,000	203.12	5,665	2,754	2,755	13,000	24,174
Saugeen River	40	1,333	250,000	187.53	4,840	3,247	3,247	9,984	21,318
Severn River (Big chute) (*b*)	52	4,000	350,000	87.50	17,433	8,571	8,571	14,000	48,575
South River	85	750	115,000	153.33	4,100	2,620	2,620	4,534	13,874
St. Lawrence River, Iroquois, Ont.	12	1,200	179,000	149.16	6,864	5,119	5,118	7,151	24,252
Mississippi River, High Falls "A" (*c*)	78	2,400	195,000	81.25	9,391	3,840	3,841	7,777	24,849
Mississippi River, High Falls "B"	78	1,100	123,000	111.82	6,390	2,491	2,491	4,908	16,280
Dog Lake, Kaministiqula River	310	13,675	832,000	61.00	13,760	16,427	15,927	32,278	79,392
	310	6,840	619,700	91.00	11,296	10,632	10,132	24,787	56,847
Cameron Rapids	39	16,350	815,000	50.00	16,375	17,327	16,727	32,561	82,990
	39	8,250	600,000	73.00	14,390	11,478	10,978	24,003	60,854
Slate Falls	40	3,686	357,600	97.00	6,000	6,634	6,334	14,303	33,271
	40	1,843	260,000	141.00	6,000	3,868	3,669	10,400	23,937

(*a*) Expensive dam.
(*b*) Inexpensive construction of canal and headworks.
(*c*) Includes storage development.

* Pre-war conditions.

† Capital costs cover hydraulic development (such as dams, headworks, pipe lines), power house, hydraulic and electrical equipment, with one spare unit, and step-up transformer station with electrical equipment. It does not include cost of vested rights and land damages or transmission lines.

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Company	State	Voltage	Journal	Year
Alabama Pr. Co.	Alabama	110,000	Eng. Record	1914
		44,000	Mins. Record	1914
			Elec. Engrg.	1914, '15
			G. E. Review	1916, '19
Aluminum Company of America	Tennessee	150,000	Proc. A.I.E.E.	1920
Appalachian Pr. Co.	Virginia	88,000	Elec. World	1912, '13, '19
			Power	1913, '19
Arizona Pr. Co.	Arizona		Elec. World	1910, '20
			Journ. of El.	1920
California-Oregon Power Co.	California	60,000	Elec. World	1918
			Jour. of Elec.	1918
			Eng. Record	1913
Canadian Light and Power Co.	Canada	44,000	Elec. World	1912
Carolina Power and Light Co.	North Carolina	100,000	Water Power	1913
		60,000	Chronicle	
Colorado Pr. Co.	Col.	100,000	Elec. World	1911, '12
Columbus Pr. Co.	Georgia	66,000	Elec. Engr.	1913
Connecticut Lt. and Power Co.		66,000	Elec. World	1917
Consumers Pr. Co.	Michigan	140,000	Elec. World	1918, '20
		110,000	Power	1918
		72,000	Elec. Review	1919
Ga. Rwy. & Pr. Co.	Georgia	110,000	Elec. World	1913
		60,000	Elec. Engrg.	1914
			G. E. Rev.	1914
Great Western Power Co.	California	100,000	Jour. of El.	1920
		160,000	El. World	1909, '14
Hydro-El. Power Commission of Ontario	Ontario	110,000	Engr. News Rec.	1919
			Engr. World	1919
			El. World	1912
			Elec. News	1915
Idaho Power Co.	Idaho	44,000		
		66,000	Elec. World	1916
Mexican Lt. and Power Co.	Mexico	85,000		1914
Mexican Northern Power Co.	Mexico	110,000	Elec. World	1914
Mississippi River Power Co.	Iowa	110,000	G. E. Review	1914
			El. World	1913 '14
			El. Engr.	1914
			Eng. Record	1912, '13

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Company	State	Voltage	Journal	Year
Montana Pr. Co.	Montana	100,000	G. E. Review	1911, '16
			El. World	1915
			El. Rev.	1917
			Elec. World	1915, '20
Montreal Lt. and Power Consolidated	Canada	66,000	Elec. Rwy. Jl.	1917
			Can. Engr.	1917
			G. E. Rev.	1916
			Engr. Rec.	1913, '17
New England Pr. Co.	Mass.	66,000	Eng. Record	1913
			G. E. Rev.	1911, 14, '19
			El. World	1913
			Water Chronicle	1914
Northern State Power Co.	Minnesota	50,000	El. World	1907
		60,000	Eng. Record	1914
		110,000	Power	1914
Pacific Gas and El. Co.	California	110,000	Jour. of El.	1916, '13
		104,000	El. World	1912, '16, '19
		60,000	El. Journ.	1915
Pacific Pr. Lt. Co.	Oregon	66,000	G. E. Rev.	1914
			El. World	1917
Penninsular Pr. Co.	Michigan	66,000	Bul. A.I.E.E.	1915
			El. Rev.	1918
			El. World	1914
			Power	1919
Pa. Water and Power Co.	Pennsylvania	70,000	Power	1913, '19
			Proc. A.I.E.E.	1915
			El. World	1912, '15
			Eng. Record	1915
Portland Rwy. Lt. Pr. Co.	Oregon	57,000	El. Rev.	1920
			Jour. of El.	1913
			El. World	1913, '15
Puget Sound Pr. and Lt. Co.	Washington	110,000	El. Rev.	1920
		55,000	El. World	1912, '20
			Jour. of El.	1918
Shawinigan Water and Power Co.	Canada	100,000	El. Rev.	1917
			El. World	1912
			El. Times	1920
			El. News	1918

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Company	State	Voltage	Journal	Year
Southern Cali-				
Edison Co.....	California	150,000	Jour. of El.	1920
			El. Rev.	1911, '20
		60,000	El. World	'07, '16, '19, '20
			Power	1911
Southern Pow.Co	N. Carolina	100,000	Eng. News	1917
		44,000	G. E. Rev.	1909, '10
			El. Jour.	1911
			El. World	'15, '10, '11, '20,
			Eng. News Rec.	1920, '17
			Eng. Record	1917
Southern Sierras				
Power Co.....	Tennessee	120,000	Power	1914
			Elec. Engrg.	1913, '14
Turners Falls Pr.				
and El. Co.....	Mass.	66,000	Elec. Rev.	1917, '19
			El. World	1915, '18
			G. E. Review	1917
Utah Power and				
Light Co.....	Utah	130,000	Jour. of El.	1914
			El. World	1915
			Engr. Record	1913
Washington				
Water Pr. Co...	Washington	60,000	El. Rev. & West.	
			Elec.	1917
		110,000	El. World	1908, '12, '20
			Eng. Record	1912
			Jour. of El.	1914
			El. Rev.	1920
Western Pr. Co.				
of Canada.....	Canada	60,000	El. Rev.	1917
			El. World	1912
Wisconsin-Minn.				
Lt. & Pr. Co...	Wisconsin	120,000	El. World	1916
		66,000		

BIBLIOGRAPHY. — In the preceding table are given references to some of the more important hydroelectric stations. A great amount of valuable data on the control and transmission of energy from hydroelectric stations is also given in the report of the Engineering Data Committee of the A.I.E.E., entitled *Engineering Data Relating to High-Tension Transmission Systems* presented at the annual convention of the A.I.E.E., June 25, 1914.

In addition to the above the following articles on the subjects listed contain valuable data: **Exciters and Excitation:** *Elec. World*, 1907, Vol. 49, p. 880; 1912, Vol. 59, p. 1247; *Trans. A.I.E.E.*, 1912, Vol. 31, p. 1841; *G. E. Rev.*, 1912, Vol. 15, p. 626; 1914, Vol. 17, p. 567; *Power Plant Eng.*, 1920, p. 888. **Voltage Regulation:** *G. E. Rev.*, 1912, Vol. 15, p. 468, p. 530; 1912, Vol. 15, p. 44, p. 626; *Trans. A.I.E.E.*, 1912, Vol. 31, p. 1841; *Elec. Jour.*, 1911, Vol. 8, p. 943; 1912, Vol. 9, p. 609; *Elec. World*, 1912, Vol. 60, p. 996. **Station Wiring:** *Elec. Jour.*, 1904, Vol. 1, p. 123; 1906, Vol. 3, p. 412; 1907, Vol. 4, p. 43; *G. E. Rev.*, 1913, Vol. 16, p. 361, **Operation;** *G. E. Rev.*, 1913, Vol. 16, p. 355. **Ventilation of Station;** *G. E. Rev.*, 1914, Vol. 17, p. 572. See also *Bibliography* in articles on the component apparatus.

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POWER STATIONS, STEAM-ELECTRIC. — (*See also Power Stations, Gas-electric; Power Stations, Hydroelectric; Boilers; Condensers; Generators; Steam Engines; Steam Turbines; etc.*) The following is a brief table of contents of this article:

Location ..... p. 1205
Foundations 1205
Superstructure 1206
Boiler-room Layout 1206
Generating Room Layout 1211
Piping Systems 1213
Generator and Control Equipment 1215
Costs, Capital and Operating 1217

LOCATION. — The selection of a site for a power plant depends on the following factors:

(1) The cost and availability of land, adequate in area and suitable in form for present and future needs.

(2) Provision for the economical handling of fuel and ashes. The site should afford navigable water frontage if possible and railroad connection in every case unless the delivery of coal by water is assured at all seasons. In comparing sites the cost of dredging channels and of track construction, including right of way, should be carefully considered.

(3) The nature of the water supply. Ample water supply from natural sources suited to all the needs of the plant is highly desirable. The life, efficiency and cost of maintenance of boilers and condensers depend greatly on the quality of the water supply. Water analyses should be made in connection with preliminary surveys.

(4) The bearing power of the sub-soil for foundations, the probability of costly difficulties in construction, the elevation of ground water, the normal, maximum and minimum stages of adjacent bodies of water.

(5) The general character of the surroundings and the existence of restrictive ordinances relating to smoke, noise, vibration and the movement of coal cars.

(6) Proximity to the load center of gravity, if power is to be distributed at low voltages.

FOUNDATIONS. — (*See also Concrete; Concrete, Reinforced.*) The design of foundations depends on the bearing power of the soil, the concentration of loads and the necessity of suppressing vibration. For table of the bearing power of various soils see the article on *Power Stations, Hydroelectric.*

The taking of borings is usually essential to the proper design of foundations, especially where the site is on alluvial soil near a water frontage. Concentrated loads may reach a maximum of 15 tons per square foot. Foundation footings should rest on rock whenever practicable. Soils of inadequate bearing power are reinforced by driving piles of wood or concrete at points of concentrated load or under the entire foundation, as the soil may require. Rafts of reinforced concrete resting on a soil stratum or on piling are often used to distribute loads, to prevent the flowage of alluvial soil and to reduce the transmission of vibration. The foundation structures proper are usually of reinforced concrete. The following table of safe loads on foundations is given in Snell's *Power House Design.*

Foundations for machinery are usually made separate from those of the walls to reduce the transmission of vibration. Boiler-room equipment is usually carried on the steel framing of the superstructure, but main generating units have separate foundation piers of concrete. Foundations for reciprocating engines have extended bases, and in extreme cases cushions of felt, sand or rubber composition are provided to suppress vibration. Anchor bolts for machinery are

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TABLE I. — SAFE LOADS ON FOUNDATIONS

Loads in tons per square foot

Good concrete	4
Steel rails in concrete	8
Concrete piles	12
Ordinary bricks in cement mortar	5
Hard bricks in cement mortar	8
Blue bricks in cement mortar	12

accurately located in concrete work by means of templates. Bolts may be cast in the foundations, or holes may be provided, together with side holes to permit the adjustment of the bolts. When the concrete has set, the machine is lifted into place, aligned and leveled and the interstices run in with cement grout.

The datum line of a power plant should be fixed by consideration of water levels. Tidal limits and flood water stages fix the levels of condenser intake and outlet tunnels, of engine room floors and of furnace grates.

SUPERSTRUCTURE. — A power house should be fireproof in every respect, clean, well-lighted, well-ventilated and well-drained. The skeleton structure is usually of steel with wall panels of brick or of reinforced concrete. All structural members should be computed with a factor of safety of not less than 3 (*see Structures, Simple*). The most heavily-loaded members are the pillars carrying overhead bunkers and those supporting an engine-room crane. The roof should be of fire-proof material, truss-supported and with sufficient pitch to insure good drainage. The roof may properly have glazed monitors to assist in lighting and ventilation. Windows in the generating room and switch houses should be designed to exclude rain when partly open.

Interior walls are usually finished in brick set with close joints and neatly pointed. Glazed brick or tile are appropriately used for walls in generating rooms. The upper portion of such walls should be of light color. The basement floors are usually of smooth cement. Generating room floors should be of tile, brick or other material not tending to form dust. The boiler room floors are usually hard-burned brick or special concrete. The battery rooms should have floors of brick or acid-resisting asphalt. Stairways are preferably of iron and should be provided with non-slip treads.

Recent practice has evolved a standard type of building division, providing a boiler room and a generating room side by side and separated by a solid wall. All electrical control apparatus is placed at the side of the generating room opposite the boiler room on galleries outside the crane span or in a separate section of building. This general ground plan has a number of important advantages. The framing may be proportioned to the loads in the different sections, the boiler plant and generating plant may be extended with equal facility, all wiring is isolated from steam piping, dirt and smoke are excluded from the generating room and accidents may be isolated in the section in which they arise.

BOILER-ROOM LAYOUT. — (*See also Boilers; Chimneys; Draft, Mechanical; Fuel; Smoke Prevention; Steam; Stokers, Mechanical; Feed-water Heaters and Purifiers.*)

Capacity and Number of Boilers. — The rating of boilers is purely nominal and their evaporative capacity is limited largely by the rate at which fuel can be economically burned in their furnaces. A well-designed unit is capable of giving from 75 to 100 pounds of equivalent evaporation per hour per rated horsepower. Considerably higher rates have been maintained in some of the large

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central stations. This high capacity demand may result in some sacrifice of efficiency. The boiler plant should have sufficient steaming capacity to operate all steam machinery at its maximum output during the period of peak load, plus reserve capacity to insure against boiler shut-downs. The most economical boiler capacity depends largely on the form of the load curve. It is economical to force boilers to very high outputs during short and severe peaks, due to the reduction of investment and of fuel required for banking fires. With a very even load curve lacking extended banking periods it is most economical to install capacity sufficient to carry the average load at the highest efficiency. In modern public service stations it is customary to draw on boilers up to 200 or 250 per cent of their nominal ratings during peak loads. In a large number of modern stations ranging in capacity from 400 to 10,000 kw. the average boiler installation was found to be 0.4 boiler horse-power per kilowatt of generating capacity. In very large stations of recent design this ratio is from 0.25 to 0.3 boiler horse-power per kilowatt.

The simplest arrangement possible is to group with each generating unit one or two boilers, but this scheme lacks operating flexibility. In large steam plants the boilers are all operated in parallel on a common steam header, though provision is often made to isolate groups of boilers in emergencies. With this arrangement the boiler plant may properly be subdivided into the number of units affording the greatest economy and convenience. Large boilers are usually more efficient than small. The unit costs of boilers, stokers, piping, flues, air ducts and building are apt to be less for large boilers than for small. The crippling of a large boiler withdraws from service a larger portion of the total capacity and correspondingly larger reserve equipment may be needed. There is no evidence to show that small boilers afford greater safety than large. In general a boiler plant should comprise not less than 4 units if continuous operation is anticipated.

Grouping of Boilers. — Two common boiler room plans exist. In one the boilers are ranged in a single or double row facing a firing aisle which runs the length of the plant. In the other there are several lateral firing aisles, each serving a double row of boilers. The former plan is appropriate when the aggregate length of firing aisle does not exceed the length of the generating room. The latter plan lends itself well to the unit or group scheme of connection to generators. When the greatest economy of ground space is necessary, the boiler plant is double-decked, but this plan complicates the handling of fuel and ashes, reduces the natural light and ventilation and requires a building of very heavy framing. A basement space is provided below the boiler room. This space contains the ash hoppers, air ducts for forced draft and ash disposal equipment. Boiler feed pumps, blowers, hotwells, feed water heaters and flues are often placed in this space. The head room of the basement should be not less than 10 feet.

Boiler Spacing and Clearances. — With few exceptions boilers are set in batteries of two, with a space of 5 feet or more between batteries. A space not less than 5 feet wide should be left behind the settings for repair work, access to blow-off valves and minor piping. If the main piping or flues occupy this space it should be at least 8 feet wide. Each firing aisle should afford ample space to withdraw boiler tubes, drums and furnace structures for replacement or repairs. The width is usually between 18 and 25 feet and varies with the type of boiler and furnace. Clear head room above the boilers should be ample to install and repair the main piping and valves and to remove and replace boiler drums. An allowance of from 10 to 12 feet is usually ample. The following table gives minimum allowances of floor space for water-tube boilers of the most widely-used types, set in batteries of two:

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TABLE II. — MINIMUM BOILER ROOM SPACE ALLOWANCES FOR WATER-TUBE BOILERS

400-hp. units in batteries of two.....	1.25 sq. ft. per hp.
500-hp. units in batteries of two.....	1.20 sq. ft. per hp.
600-hp. units in batteries of two.....	1.05 sq. ft. per hp.

In power plants of modern design the actual boiler room area per boiler horse power ranges from 0.9 to 2.00 square feet, the average being very nearly 1.4 square feet.

Location of Flues. — Boiler flues may be placed on the floor at the rear of the settings, in the basement space beneath the rear of the boilers, or may be carried overhead. Flues may be of brickwork or of steel plates reinforced with angle-iron stiffeners. In the most compact designs steel flues are used over the rear of the settings. Brick flues should be lined with firebrick. Steel flues are built up from ⅛-inch plates when indoors and of 5/16-inch plates outdoors. Flues should be as short, air-tight and straight as possible and should preferably have an upward gradient toward the chimney. It is good practice to allow from 4.5 to 5.5 square feet of flue section for each 1000 pounds of coal burned per hour in the boilers served. Branch flues should be equipped with swivel dampers to permit boilers to be shut down independently.

Location of Economizers. — Economizers are most frequently set on a steel gallery above the rear of the boiler setting. Less frequently they are set on the boiler room floor behind the boiler settings or on a floor above the boiler room. Each economizer unit is provided with a by-pass flue below or behind the economizer setting. A soot chamber is provided beneath the tubes and should be from 2 to 2.5 feet in depth. Access must be allowed along the front of the economizer to permit the opening of the cleaning holes in the bottom branch pipes. Clear space of 10 feet or more is required above the setting to permit the withdrawal and replacement of the tubes. Economizers are usually set in brickwork and subdivided into sections, each associated with a battery of boilers. A large central economizer can often be installed at lower cost, but affords less flexibility in operation.

Chimneys and Mechanical Draft Appliances. — (*See also Chimneys; Brick and Brick Masonry; Draft, Mechanical.*) Brick chimneys are usually carried down to foundations independent of the building and outside of its walls. In exceptional cases where greatest space economy is necessary, brick chimneys are carried by steel columns integral with the framing of the boiler house. Steel stacks are usually supported on cast-iron base plates carried by the structural frame work of the boiler house. Fans for forced draft are commonly set at centrally located points on the boiler room floor and distribute air to the various furnaces through ducts of sheet steel beneath the main floor. Induced draft fans are usually installed in duplicate and are located at the bases of the chimneys. Short steel chimneys are generally employed with induced draft systems.

Coal and Ash Handling Equipment. — (*See also Conveyors; Cranes; Fuel; Hoists, Electric; and Unloaders.*)

Coal Storage, External. — Continuity of fuel supply is a vital necessity to power stations. Insurance against interruptions of delivery is commonly made by use of internal bunkers and external coal storage yards. The amount of fuel to be kept in reserve is a local problem and depends on the certainty of delivery, the fluctuation of the market, the rate of deterioration of coal in storage and the danger of spontaneous combustion. Coal exposed to the weather loses heat value at a rate which depends on its content of volatile fuel and which may

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exceed 1 per cent per month. Coal stored in deep piles is liable to spontaneous ignition, especially if it contains much sulphur. Both difficulties may be obviated by storing coal in basins under water. Bituminous coal should not be piled deeper than 35 feet unless submerged. As a precautionary measure iron pipes may be sunk into coal piles at intervals and the temperature read periodically by a suspended thermometer. A coal yard is commonly spanned by a gantry crane carrying an automatic grab bucket for distributing and reclaiming.

For the latest information regarding storage of fuel, see *Bituminous Coal Storage*, Univ. of Illinois Bulletin 116, 1920.

Coal Storage, Internal. — Internal storage is provided in overhead bunkers supported by the boiler house framing above the firing aisles. Bunkers are of two general types, suspended steel tanks hung from the framing, and hopper-shaped structures of reinforced concrete incorporated into the building proper. Suspended bunkers are usually concrete-lined and have a limited storage capacity, the practicable limit being about 10 tons per linear foot. Built-in bunkers are best adapted to large storage capacities up to 40 tons per linear foot. Bunkers should be divided by transverse bulkheads to increase their strength and assist in isolating trouble from spontaneous combustion. Hopper bottoms should have a slope of 45° or more to make them self-clearing. Cut-off gates should be provided at point of attachment to down-spouts. Automatic weighing and recording hoppers may be installed between bunkers and down-spouts to good advantage as their records assist in keeping check on boiler performances. Down-spouts should be not less than 12 inches in diameter and should be slightly inclined to lessen the tendency of the coal to pack. The firing aisle is sometimes equipped with an electrically-operated traveling hopper which may draw coal from any desired bunker section and distribute it to the several stokers.

The bunker capacity desirable in a boiler plant depends on the extent of the external storage and the facilities for fuel handling. Bunker capacity sufficient for from 4 days' to 7 days' supply is generally adequate. Very large bunkers are costly and are apt to lead to trouble from spontantous ignition. In computing bunker capacity it is customary to allow 40 cubic feet per ton of coal.

Coal Handling. — The handling of coal which is delivered by rail and is to be delivered directly to overhead bunkers is most readily accomplished by the following plan. The loaded car is run over a track hopper into which it dumps from beneath. The hopper delivers to a crusher which reduces the coal to a uniform size suitable for the use of the stokers. The coal is delivered by the crusher to an elevator which may consist of some type of skip hoist, inclined belt or endless chain of buckets. If a skip hoist or belt is used the coal is dumped into a receiving hopper after its ascent and is finally distributed to the bunker by a horizontal belt, flight or bucket conveyor. A chain of pivoted buckets may be used as both elevator and distributor.

When the boiler room is arranged on the unit plan, i.e., boilers in rows facing transverse firing aisles, each aisle should have its bunker system, track hopper, crusher, elevator and conveyor. Such a conveyor may properly be of the pivoted-bucket type and may serve to elevate and distribute coal or to collect ashes from the ash hoppers beneath the boilers and deliver them to an ash bunker built out over the railroad track.

Reliability is a most important factor in all coal-handling systems and is promoted by making the system mechanically simple and rugged, by installing duplicate sets of equipment and by the sectionalizing of bunkers and conveyor outfits into independent units.

Coal delivered by water is usually handled by a clam-shell or grab-bucket unloader which dumps it into a receiving hopper. After being crushed the coal is conveyed to the storage yard or bunkers by equipment similar to that just described.

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Ash Handling. — If ashes are handled by a conveyor when wet or hot the corrosive action on the buckets may make maintenance costly. When the ashes are not handled by a conveyor system it is customary to provide a track running beneath the ash hoppers on which small cars may be run to haul ashes to the dump.

Feed-water Systems. — (*See also Pipes and Piping; Feed-water Heaters and Purifiers; Pumps and Pumping Engines; and Valves.*) Condensing plants usually draw feed water from the hot-wells of the condenser system. When surface condensers are used a small amount of make-up water must be added from outside sources. The water discharged from jet condensers may be used for boiler feeding if of suitable quality. Non-condensing plants operating in connection with steam heating systems usually draw feed water from the return system, with added make-up water as required. Open heaters of all types are placed on the suction side of feed pumps. Closed heaters are placed on the delivery side. Meters are usually placed in the delivery pipe and should be in duplicate if continuous indication is important. Otherwise they should be by-passed, as are all heaters and economizers, to provide for cleaning and repairs during operation.

Water is supplied to boilers through a feed main which is run along the front or rear of the boilers, often in the basement space below. Double and ring mains are occasionally used though the gain in reliability is doubtful. An auxiliary injector main running direct to boilers from the source of cold water is sometimes installed as a reserve. Iron pipe is generally employed with cold water and brass pipe for water above 200° F., or water which has a pitting tendency. Screwed joints are generally used with pipe diameters less than 2 inches. Larger pipes are fitted with screwed flanges.

Feed pumps should be installed in duplicate on each feed main or cross-overs provided between pumps. There is wide divergence in the location of feed pumps. In most plants of the unit type each feed pump is associated with the auxiliaries of a generating unit and is cared for by the turbine operator or oiler. In other cases feed pumps are grouped in a central position on the main floor of the boiler room and are cared for by a water tender. In other cases the feed pumps are placed in a separate basement pump room.

A relief valve should be placed in the pump delivery to prevent strains from excess pressure. The size of feed pipe is usually such as to allow a maximum velocity of from 300 feet to 400 feet per minute. At least two valves, a regulating valve and a check valve, should be placed in each boiler branch.

Condenser Water System. — (*See also Condensers, Steam; Cooling Systems for Power Stations.*) Cooling water for condensers is obtained from an adjacent body of water whenever possible and in other cases from a cooling pond or the basin beneath a cooling tower. In the former case large concrete intake and discharge tunnels are usually provided. These run beneath the generating room in alignment with the intake and discharge pipes of the condensers. The cross-section of these tunnels should be ample to keep the flow of water down to 5 or 6 feet per second. Intakes should have generous openings fitted with trash racks and should if possible be placed at a considerable distance upstream from the discharge outlet. In some cases it is necessary to build a baffle wall in the stream between the two tunnels. A shut-off gate is usually provided in each tunnel to facilitate cleaning and repairs. The tunnels should be of sufficient depth to insure an adequate supply of water at the lowest stage of tide or stream flow. The circulating system of surface condensers is fully enclosed and the work done by the circulating pump is merely that necessary to overcome the fluid friction in the system.

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GENERATING ROOM LAY-OUT. — (*See also Condensers, Steam; Cranes; Feed-water Heaters and Purifiers; Generators, Alternating Current; Generators, Direct Current; Lubricants and Lubrication; Pipes and Piping; Pumps and Pumping Engines; Steam Engines; Steam Turbines; and Valves.*)

Capacity and Number of Units. — A generating plant should have sufficient capacity to serve its peak load with any one generating unit shut down. The reserve capacity needed above normal requirements may be provided most economically by selecting types of equipment capable of giving large overloads in emergencies, by maintaining in service condition obsolete machinery which is physically sound but uneconomical, by installing a large reserve storage battery, or by tying in parallel several power plants so that a moderate reserve may be shared in common. More reserve capacity is needed when a plant contains few large units than with many of small size. A smaller number of units than four is disadvantageous, due to the relatively large reduction of capacity by the disabling of one. A larger number than eight units has no inherent advantages. Large units are generally more economical than small units if kept well loaded. If the plant has a normal daily period of very light load it may be economical to employ one small unit well suited to this load.

Types of Equipment.—Steam-turbine generators are used almost exclusively for alternating-current generation in units exceeding 500 kw. The turbine has little or no advantage over the engine in smaller sizes and in non-condensing plants the engine is often superior. On account of its high speed the turbine is poorly adapted to the direct driving of d-c. generators. Large d-c. generators are becoming obsolete in steam plants, for it is usually more economical to generate alternating current in turbine units and convert it to direct current either locally or in distant substations. A self-contained unit comprising boiler, engine and condenser, known as the *locomobile*, has been largely used in very small European plants and to some extent in this country.

Arrangement of Generating Rooms. — The modern standard power house has a long and narrow generating room placed between a boiler house and a switch house or series of electrical control galleries. The generating room is spanned by an electrically-operated crane. The generating units are usually ranged along this room in a single or double row. Each unit comprises a prime mover, electric generator, condenser and the associated pumps and their motive power. In most instances a basement space or series of open pits is provided below the main floor in which the condensers, pumps and most of the piping are located.

Arrangement of Turbines. — In many plants using vertical-shaft turbines the basement has been omitted and the auxiliaries grouped about the base of the turbine on the main floor. In such cases the condenser is either incorporated into the base of the turbine or is placed on the floor immediately beside it. This grouping of equipment on a single floor has several operating advantages. All apparatus has good light. A single operator can give efficient attention to a large group of equipment, and machinery so placed usually receives closer attention than it would in a pit or basement. All pieces can be readily handled by the crane without interference with other apparatus. The ample head room is advantageous in making repairs. The basement plan is especially economical of floor space, but makes the auxiliaries relatively less accessible. Placing condensing equipment in open pits beside the engine or turbine piers makes it accessible for inspection and for handling by the crane.

In determining the arrangement of a generating room it is essential to provide each element with ample space for all needed attention during operation or repairs. Sufficient clear floor space about a unit is usually provided to permit it to be dismantled without removing the parts to a distance. Clear trucking

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space is also desirable. The separate pieces of machinery should be so arranged that the crane can be conveniently used in assembling or dismantling any piece without interference with others. Clear overhead space below the crane hook should be sufficient to permit any heavy part to be lifted clear of its setting and carried away. The crane girder and trolley must clear all roof trusses and lighting fixtures. Clearance must be allowed at the generator ends of horizontal turbine units to withdraw the revolving field structures.

Arrangement of Condensers. — In setting surface condensers clear working space must be allowed at both ends to remove the heads and at one end clear space must be allowed to permit the withdrawal and replacement of tubes. Jet condensers should be set in such a manner that the head can be conveniently opened for repairs. Condensers in general should be set below the level of the associated prime mover and as close as possible to its exhaust port. The condenser connection should provide natural drainage for condensed steam. It should have as few joints as practicable to avoid occasion for air leaks. It is usually desirable to provide a copper expansion section in this connection as joints in a rigid pipe are difficult to keep air-tight with varying temperatures. The arrangement of a central condenser serving a group of prime movers is uncommon in electric power plants. Barometric jet condensers are often placed outside of the wall of the building on account of the long tail pipe required.

Floor Space in Generating Rooms. — The floor space provided per kilowatt varies greatly with the size, type and arrangement of equipment. The following data from modern steam-turbine stations are illustrative of the range of best practice.

TABLE III. — SPACE COVERED BY STEAM-TURBINE POWER STATIONS

Station No.	Capacity, kilowatts	Boiler room, square feet per kilowatt	Turbine room square feet per kilowatt	Total, square feet per kilowatt
1	3,000	0.71	0.70	1.41
2	8,000	0.74	0.69	1.43
3	11,000	1.11	0.70	1.81
4	13,500	1.13	0.50	1.63
5	16,000	0.90	0.37	1.27
6	24,000	0.92	0.40	1.32
7	30,000	0.44	0.40	0.84
8	32,000	0.60	0.30	0.90
9	100,000	0.48	0.17	0.65

Oiling Systems. — (*See also Lubricants and Lubrication.*) Steam power plants afford three classes of lubrication problems, viz., wearing surfaces exposed to high temperature steam, as in cylinders, valve chests and stuffing boxes; atmospheric surfaces of open guides and journals; and enclosed surfaces, chiefly journals. Steam surfaces are lubricated with cylinder oils of mineral origin supplied in atomized form by forcing the oil in small quantities into the steam supply pipe. Oil may be supplied by a local force-feed pump or hydrostatic lubricator or may be supplied from a central tank and pump supplying a group of cylinders. Bearings, guides and other exposed surfaces are lubricated by oil or grease supplied by hand or from adjustable feed cups. Enclosed surfaces are usually lubricated by splashing or by flooding with oil from a central source of supply. The flooding system is most efficient. Oil from a central tank is

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forced by pump or gravity to the various working parts whence it returns through a drip system to collecting pans and filters. After purification a small amount of make-up oil is added and the reclaimed supply restored to the oiling system.

PIPING SYSTEMS. — (*See also Pipes and Piping; and Valves.*) The various piping systems in a power plant are subdivisible into the following groups: (*a*) High-pressure steam piping between boilers, main units and auxiliary engines; (*b*) exhaust piping to condensers; (*c*) exhaust piping to feed-water heaters; (*d*) atmospheric-exhaust piping; (*e*) feed-water piping; (*f*) cooling-water piping; (*g*) pipe-drainage system and (*h*) oil piping. To facilitate the identification of pipes of various classes it is desirable to paint each a distinctive color.

High-pressure Steam Piping. — The chief considerations in laying out high-pressure piping are (*a*) to produce a reliable system without complexity; (*b*) to make all joints permanently steam tight; (*c*) to take up all expansion strains; (*d*) to maintain proper steam pressure at all points of delivery; (*e*) to reduce to an economic minimum the loss of heat by radiation and (*f*) to drain from the entire system all water of condensation. In many older systems of piping elaborate ring and multiple headers, with numerous by-passes, cross-overs and duplicate-connection branches were employed in the endeavor to promote reliability by making possible the isolation of any fault. Reliability is sought in modern systems by very simple connections with skillful design and the best possible construction.

Unit and Parallel Systems of High-pressure Piping. — The *unit system* and the *parallel system* of connection with their various modifications are now most extensively used. The unit system of piping connects a separate group of boilers to each prime mover and its auxiliaries. The parallel system provides a large steam header running the length of the plant into which all boiler branches deliver and from which all prime movers are supplied. Unit systems are usually provided with cross-overs between unit steam and water headers to permit the parallel operation of different sections in emergencies. Parallel systems are often provided with sectionalizing valves to permit the isolation of any section in case of accident. Diagrammatic sketches of unit and parallel grouping are shown in Figs. 1 and 2.

Size of Piping. — Pipe sizes for high-pressure work are generally determined by the maximum allowable steam velocity. It has been found satisfactory and economical to allow a maximum velocity of 6000 feet per minute with saturated steam and from 9000 to 12,000 feet per minute with superheated steam. The flow to piston engines is intermittent and the pipe size should be proportioned according to the velocity during admission unless a receiver is installed. The steam header of a parallel system serves as a reservoir to equalize pressures and prevent vibrations in the piping. Its cross section is properly proportioned according to the maximum cross flow of steam with any boiler section inoperative.

Joints. — Joints in high-pressure piping are usually of the screwed type for diameters under 3 inches and of the flanged type for larger sizes. Flanged joints may be made between ground faces or by aid of gaskets, the former type being preferable for high-pressure steam. An excellent joint is made by drawing up with loose collar flanges the turned-over ends of pipe sections with faces ground true, often called a Van Stone joint. Such joints are more expensive than rigid flanged joints but the possible swing of the pipe about its axis is a great advantage in the final aligning and connecting up of a system with many branches.

Provisions for Expansion. — Provision for the expansion of pipe without straining joints and fittings is imperative. Between two points which must be rigidly fastened expansion is taken up in expansion loops and bends. The

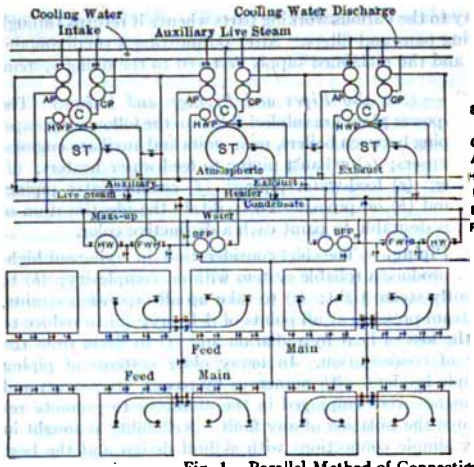


Fig. 1. Parallel Method of Connection

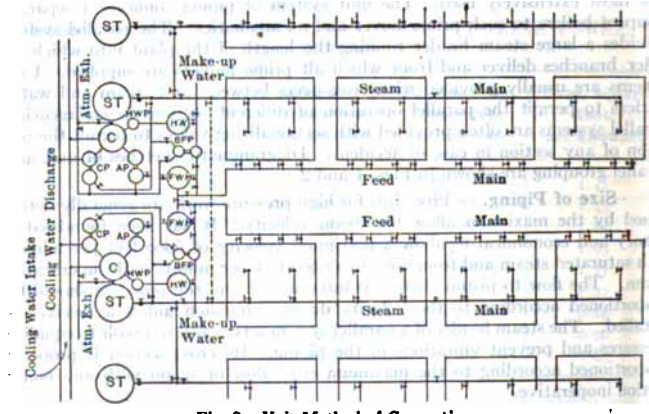


Fig. 2. Unit Method of Connection

radius of such bends should in all cases be not less than five times the pipe's diameter and at each end of the curve there should be a length of straight pipe not less than twice the diameter. Welded flanges are recommended for the attachment of bends. When bends cannot be used recourse must be had to swivel joints or slip joints, which should be avoided if possible. When screwed joints are employed expansion is commonly provided for by the use of sections having single, double or triple swing about a screwed connection. Pipes of considerable length must be anchored at more than one point to prevent vibration. Between each anchor expansion bends are required and the pipe must be support-

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ed by hangers, roller brackets or pedestals allowing longitudinal motion. Anchorage is usually made at points of attachment to branches, and fittings with anchor bases are employed for the purpose.

Lagging. — Live-steam pipes, boiler-feed pipes, steam drums, receivers and separators should be covered with heat-insulating material to reduce the radiation losses to a minimum. The loss from bare pipe is approximately 3 B.t.u. per square foot per hour for each degree difference of temperature. Good commercial coverings, such as magnesia, felt, asbestos, mineral wool, etc., will prevent from 75 to 90 per cent of this loss if properly applied.

Drainage. — Saturated steam in passing through pipes undergoes a small amount of condensation due to friction and heat radiation. The presence of water in steam piping is a source of danger, for a water slug, if picked up by the moving column of steam, may be driven with tremendous force against any opposing surface, such as a valve, sharp bend or cylinder, with destructive results. Pipes should be slightly inclined so that water drains away from the prime movers and every point where water may collect must be provided with a drip connection. These drip connections are run through traps to the hot-well so that the hot water may be returned to the boilers. In other systems the drip water is returned directly to the boiler. Separators are often installed at the inlets to reciprocating engines and exhaust steam turbines taking wet or saturated steam, to drain the moisture from the entering steam. Drip connections should always be made to these separators. Bleeder connections to live steam lines are provided in order that the water condensed in warming up the pipe when steam is turned on may be drawn off.

Valves. —Valves for steam pipes are of two general types, gate valves and globe valves. Either type may be outside screw or inside screw, according as the screw of the spindle is outside or inside of the casting. Outside screw types are preferred for high-pressure work as the position of the spindle is then an index showing whether this valve is open or closed.

Check valves are required in boiler connections to prevent steam flowing into the boiler when cold or when its pressure is below that of the header to which it is connected. Emergency valves are often provided to cut off the steam under abnormal conditions, such as the bursting of a pipe or the racing of an engine. These often take the form of a weighted valve which closes itself when a trip is released. Electric motors and hydraulic pistons are sometimes connected to ordinary valves to provide for remote control during emergencies.

Blow-off valves of boilers are subjected to very severe service and are made exceptionally rugged. Such valves must close without leaks, open readily and furnish a free path for the ejection of scale and sediment. The wearing parts of such valves should be readily renewable. Best practice requires the use of two blow-off valves or a valve and a cock. The steam, water and sediment are usually blown through a tank partially filled with water before being exhausted to the air.

A few rules relative to the installation of high-pressure valves and piping may be noted. All valves of a diameter above 6 inches should be by-passed to facilitate opening under pressure. Valve stems are often placed horizontally to lessen the tendency to form water pockets. Angle valves should be selected whenever convenient because of the greater room in them. Branches from mains to boilers should have at least two valves, an ordinary stop valve next to the main and an automatic check valve near the boiler. Valves are best placed at the highest points in the pipe to simplify the drip system. When the flow of steam is intermittent heavy valves should not be placed far to one side of a line joining the points where the pipe is supported as they may cause vibration.

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Branches from a main to a prime mover should have a stop valve at the highest point near the main. A receiver-separator from three to four times the volume of the high-pressure cylinder should be placed as close to the throttle of a piston engine as possible to equalize steam flow and drain moisture from the steam. When superheated steam is used cast-steel fittings and valves are preferred to cast iron. Branch pipes are almost invariably connected to the top of the main to prevent water from passing into the branches. When superheated steam is supplied to the main units and saturated steam to the auxiliaries a separate steam main for the latter is employed.

Exhaust Steam Piping. — The size of the exhaust pipe of a prime mover is determined by the permissible back pressure. High vacuum requires ports and exhaust piping of large diameter and the length of pipe to the condenser as short as possible. An atmospheric-relief valve which is normally closed by air pressure against a spring or weighted lever but which opens automatically when the vacuum fails should be installed in the condenser pipe. Atmospheric-exhaust pipe is usually spiral riveted as no precaution against leaks is required. This usually terminates in an enlarged exhaust head which contains baffles to drain from the steam condensed water and oil before it discharges to the air. A common exhaust main for a number of units is often employed. When exhaust steam is used for heating purposes the system is supplied through a back-pressure valve which automatically opens the atmospheric exhaust if the back pressure exceeds that required to operate the heating system and closes when normal back pressure is restored.

GENERATOR AND CONTROL EQUIPMENT. — (*See also Batteries, Storage, Applications of; Bus-Bars and Bus-bar Structures; Circuit Breakers; Generators, Alternating Current; Generators, Direct Current; Reactance Coils; Regulators; Relays; Switches; Switchboards; Switchgear Equipment for Power Stations; Transformers; Transformers, Instrument; Wires and Cables.*)

Direct-current Generators. — Three-wire lighting service may be provided (*a*) by the connection of generators in sets of two in series, (*b*) by the use of three-wire generators with external or internal compensator coils or (*c*) by the use of voltage balancer sets associated with standard two-wire generators. Railway generators are operated at or near 600 or 1200 volts and are grounded at one pole, usually the negative. Series fields and equalizer connections may be on either the positive or the negative side. Equalizer switches are often carried by pedestals near the generator terminals to save wiring to the switchboard. Satisfactory voltage regulation for railway systems is usually provided by the use of compound generators. The close voltage regulation required by lighting systems is best provided by the use of a regulator of the Tirrill type. (*See Regulators.*)

Alternating-current Generators. — Synchronous 3-phase generators are used most extensively. Induction generators are often advantageous in connection with exhaust-steam turbines Synchronous turbo-alternators are now designed with high internal reactance to prevent excessive transient currents immediately after the creation of a short-circuit. If the internal reactance is inadequate they may be connected to the bus-bars through reactance coils. (*See Reactance Coils.*) In some cases the generators are operated at half the bus-bar voltage and are connected through raising auto-transformers wound with large reactance.

Grounding the Neutral. — Three-phase alternators are usually Y-connected and provision is frequently made for the grounding of one generator at the neutral point to prevent dangerous potential rise should a wire become accidentally grounded. More than one grounded neutral in a group of genera-

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ors in parallel is undesirable, due to the possibility of a third-harmonic circulating current passing through the neutral connection.

Air Ducts for Forced Ventilation. — Modern turbo-alternators are designed for forced ventilation. A system of ducts should be provided, either overhead or beneath the floor of the generating room from which each generator may draw a supply of clean outside air. This air is forced through the ventilating spaces of the stator and rotor by the fan action of the rotor. Discharge ducts are also provided in case it is undesirable to discharge the heated air to the generating room. It is desirable to equip such ducts with dampers so that the air may be discharged indoors or outdoors as desired. In many cases where the air supply is dusty it is desirable to install air-conditioning equipment in the intake of the system. See *General Electric Review*, Vol. 16, p. 627 for a full discussion of turbo-generator ventilation.

Excitation. — Fig. 3 shows the exciter capacity required by modern alternators. In small plants each alternator is often provided with its individual exciter driven by the main shaft. Large stations are provided with central

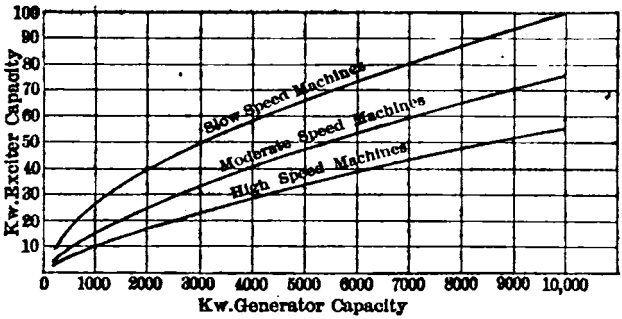


Fig. 3. Exciter Capacity Required by A-C. Generators

systems of excitation comprising not less than two, and generally more, direct-current generators, driven by independent motive power. At least one exciter in every plant should be steam-driven. Three-phase induction motors are quite generally used for the electric driving of exciters. The exciter system is frequently reinforced by a floating storage battery to insure the supply of exciting current in every emergency. (*See Batteries, Storage, Applications of.*) All alternator fields are supplied through adjustable rheostats from a set of excitation bus-bars, except that in a few very large plants the excitation system is sectionalized for the sake of reliability. Exciters are commonly rated at 125 or 250 volts, and are usually compound-wound, with magnetic circuits normally in a state of low saturation. The best position for exciters in large stations is generally near the center of the generating floor.

Voltage Control. — In both alternating- and direct-current stations very sensitive regulation of the bus-bar voltage may be obtained by the use of appropriate types of Tirrill regulators. (*See Regulators.*) When the load variations of different feeders are quite unlike it is often desirable to provide each feeder or group of parallel feeders with independent feeder regulators, which may be hand-operated or may be automatically controlled by voltage relays.

Transformers. — The arrangement of the transformers depends to some extent upon the type used. When it is not convenient or possible to allow above

each transformer clear head-room for crane handling, the transformer cells may be arranged to open at one side along a track and have raised floors at the level of a flat car, so that the assembled units may be slid into or out of place.

Air-blast Transformers. — These are largely used for step-up service in power stations in connection with feeders operating at 20,000 volts or less. Railway transmission lines and feeders operated at more than 20,000 volts are usually supplied through oil-insulated, water-cooled transformers. Air-blast transformers are usually placed above a common pressure pit whose air-supply is drawn from out-doors by electrically operated fans. Each transformer may be equipped with adjustable dampers to regulate the air supply.

Oil-insulated Transformers. — In some cases oil-insulated transformers are isolated in fire-proof cells built of concrete or masonry. The fire-risk is usually not sufficient to warrant isolation for each unit, but it is often desirable to enclose each 3-phase bank. Large oil-insulated transformers should be connected to an oil-drainage system to facilitate the withdrawal and replacement of oil.

Switching Equipment and Wiring. — For descriptions and standard arrangements see the following articles: *Bus-Bars and Bus-bar Structures; Circuit Breakers; Regulators; Relays; Switches; Switchboards; Switchgear for Power Stations; Synchroscopes; Transformers, Instrument*; and the articles on the various kinds of meters.

Wiring. — In direct-current stations the power conductors are usually rubber-insulated copper cables run from generators to switch-board and thence to outside circuits in ducts of tile or fiber. In some cases the duct system is dispensed with and the conductors are carried on open wallracks spaced by insulating knobs. In small alternating-current stations the wiring to and from the switchboard is usually in a duct system, but the switchboard and bus-bar wiring is open and is supported by porcelain insulators on walls and on a light frame work of pipes or angle-irons.

In plants of 12,000 kilowatts and up, operating at voltages of 20,000 or less, it is customary to isolate all conductors of unlike polarity as fully as possible in fireproof cells and barriers. The essential features of such a system of isolation are as follows: — (1) Each horizontal run of conductor is drawn into its individual duct of tile or fibre set in a concrete floor; (2) each bus-bar is mounted in a separate horizontal cell of concrete or masonry; (3) each instrument transformer and disconnecting switch is in a separate cell; (4) each pole of a bottom-connected oil switch or each complete top-connected switch is in its separate cell; and (5) vertical fire-proof barriers are placed between all vertical runs of conductor. Isolation of this nature is seldom practiced in systems above 30,000 volts, but open overhead wiring with generous spacing is employed.

In an enclosed system the power connections are appropriately formed by single-conductor copper cables, insulated with rubber or with cambric tape, and covered with a fire-resisting sheath. Lead sheathing is seldom employed unless the wiring is exposed to dampness. The cross section of such conductors is determined by the safe limits of temperature rise.

COST OF STEAM POWER STATIONS (Pre-war figures). — Power station costs are subject to wide variations with the type and elaborateness of equipment, construction difficulties and rated capacity.

Capital Costs. — Illustrative data showing the range of unit costs of the chief divisions of plant equipment are given by O. S. Lyford, Jr., and R. W. Stoval of the Westinghouse, Church, Kerr Co., in the Electric Journal, 1912, Vol. 9, p. 322, as follows:

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TABLE IV. — COSTS OF STEAM-ELECTRIC POWER STATIONS

Capacity, 2000 to 20,000 kw., based on maximum continuous capacity of generators at 50° C. rise

Item	Dollars per kw.	
	High	Low
Preparing Site: Dismantling and removing structures, making construction roads, tracks, etc	0.25	0.00
Yard Work: Intake and discharge flumes for condensing water, railway siding, grading, fencing, sidewalks	2.50	1.00
Foundations, including foundations for building, stacks and machinery, together with excavation, piling, waterproofing, etc	6.00	1.00
Boiler Room Equipment, including boilers, stokers, flues, stacks, feed pumps, feed-water heater, economizers, mechanical draft, and all piping and pipe covering except for condenser water	24.00	12.00
Turbine Room Equipment, including steam turbines and generators, condensers with condenser auxiliaries and water piping, oiling system, etc	22.00	12.00
Electrical Switching Equipment, including exciters, masonry switch structure with all switchboards, switches, instruments, etc., and all wiring except for building lighting	5.00	2.00
Service Equipment, such as cranes, lighting, heating, plumbing, fire protection, compressed air, furniture, permanent tools, coal and ash-handling machinery, etc	5.00	2.50
Building, including frame, walls, floors, roofs, windows and doors, coal bunkers, but exclusive of foundations, heating, plumbing and lighting	12.00	4.00
Starting Up. — Labor, fuel and supplies for getting plant ready to carry useful load	1.00	0.50
General Charges, such as engineering, purchasing, supervision, clerical work, construction plant and supplies, watchmen, cleaning up	6.00	3.00
Total Cost, except land and interest during construction	83.75	38.00

The same authorities give the costs of foundations at from $1.25 to $4.00 per square foot of building area, depending on the nature of the sub-soil. Table III shows that the ground area of buildings ranges from 0.8 to 2.0 square feet per kw. Building costs range from 8 to 12 cents per cubic foot of space, over-all. Power plant buildings range from 50 to 100 cubic feet per kw.

W. E. Wickenden has correlated miscellaneous data on power plant costs in the form of curves, see Fig. 4. The curves are shown in an additive sense, e.g., for a 2,000 kilowatt plant, boiler room equipment and piping cost $17.50 per kw., generating plant $37.00 − $17.50 = $19.50 per kw., etc., the total cost except land and interest during construction being $66.00 per kw.

Operating Cost and Fixed Charges. — The cost of producing electrical energy comprises two groups of items, viz., fixed charges on the investment in the power plant to cover interest, depreciation, taxes and insurance, and the

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TABLE V. — COSTS OF BOILER ROOM EQUIPMENT.

Item	Dollars per boiler horse-power	
	High	Low
Boilers, except settings	$11.00	$8.00
Superheaters	3.00	0.00
Stokers	5.50	3.00
Masonry settings of boilers	3.50	2.00
Flues	1.50	0.75
Stacks	4.00	2.00
Economizers	4.00	0.00
Mechanical draft	3.00	0.00
Feed pumps	1.50	0.50
Feed heaters	1.00	0.40
All piping and pipe covering	10.00	6.00
Coal chutes and ash hoppers	1.25	0.00
Miscellaneous items	1.00	0.50
Totals	$50.25	$23.15

cost of operating the plant. Fixed charges on the investment range from 10 to 14 per cent of the investment per annum and are practically independent of the load factor of the station. The amount assignable to each kilowatt-hour is therefore inversely proportional to the load factor and equals, in cents,

$$F = \frac{100\,RI}{8760\,K},$$

where I is the investment per kw. of capacity, in dollars, R is the rate of fixed charges expressed as a decimal fraction and K the annual station load factor expressed as a decimal fraction.

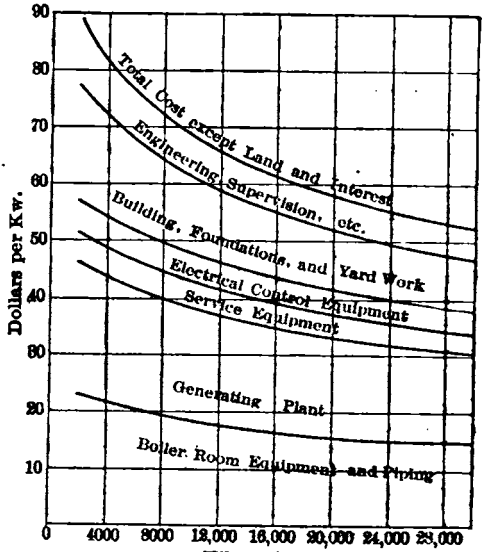


Fig. 4. Approximate Division of Construction Cost of Steam-electric Power Plants. (In additive sense, see text.)

Operating costs include supervision, labor, fuel, other materials consumed and current repairs. The cost of supervision per kw-hr. varies almost inversely

with the load factor. Labor cost per kw-hr. in boiler plants vary in almost direct proportion to the weight of coal burned per kw-hr. Labor cost per kw-hr. in generating rooms varies greatly with the size of the station and the number of units operated, since the number of men required depends more on the number of units of apparatus to be cared for than on the ratings of these units. Large plants are therefore at a large advantage in the item of labor cost. The cost of fuel per kw-hr. varies directly with the price of heat units in the coal burned and inversely with the over-all efficiency of the station. In modern steam turbine stations the cost of supplies other than fuel averages about 20 per cent of the total labor cost. The cost of current repairs in such stations is from $0.75 to $1.50 per annum per kw. of generating capacity. A high load factor is distinctly favorable to good physical efficiency, due to the reduction of stand-by and light-load losses, and to economy in the use of labor. H. G. Stott has pointed out that the production cost per kw-hr. varies inversely with the 4th root of the annual load factor. (*See Proc. A.I.E.E., Vol. 32, p. 1127.*)

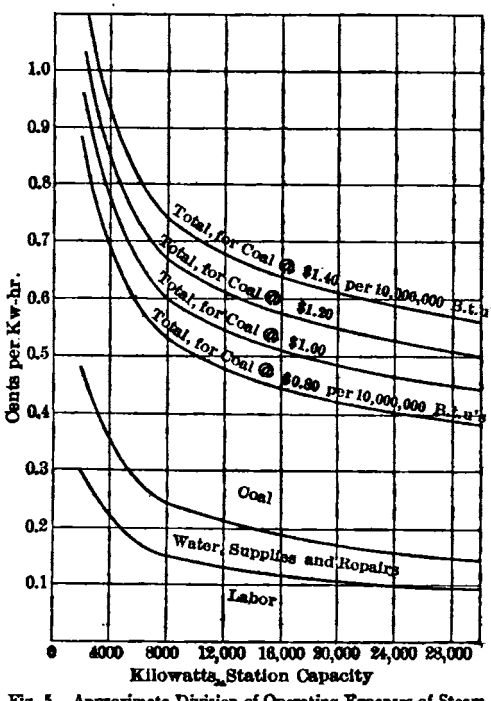


Fig. 5. Approximate Division of Operating Expenses of Steam-electric Power Plants. (In additive sense, see text.)

Wickenden has also correlated the records of the operating costs of a considerable number of railway and public service stations having load factors between 25 and 33 per cent, and from these data has prepared the curves in Fig. 5. (For the B.t.u. equivalent of a ton of coal see article on *Fuel*.) These curves are shown in an additive sense, in the same manner as the curves in Fig. 4.

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PRINTING PRESSES, ELECTRICAL OPERATION OF. — (*See also Motors, Industrial Applications of.*) Owing to the great variety of work performed, printing machinery as a rule requires a certain degree of speed variation in order that with a given equipment and operating force, the maximum of high-grade production may be turned out. All necessary speed variations are most readily, economically and satisfactorily obtained with electric drive and control. Each press can then at all times be under instant control, so that the entire time of the operator may be devoted to the work in hand.

Individual drive is particularly applicable to printing establishments, as in this class of service the ratio is small between the power required to drive the machines running idle and when performing actual productive work. With group drive the ratio between average and connected load is high, due to the large and constant character of the friction losses. The economy in power consumption is, therefore, in favor of separately-driven units, which may be shut down when not operating productively.

Printing presses may be divided into three principal classes, viz., job, flat-bed and web presses.

JOB PRESSES. — The job press is the smallest type and requires from ¼ to 1 horse-power, depending upon the size. The motor is generally mounted on or near the press and the drive may involve either a short belt with idler or occasionally some form of friction device. With these presses a speed variation of 60 per cent is often required, which, as a rule, is accomplished by armature control, shunt-wound motors being used with direct-current installations and single-phase repulsion motors with alternating-current.

FLAT-BED PRESSES are considerably larger than job presses and consist of a reciprocating bed containing the type form and a main cylinder on which the impressions are made. The presses require from 2 to 10 horse-power to drive them according to work and size. In the majority of plants a 50 to 60 per cent speed variation is desired, and as these presses require a considerable torque at starting it is usual to provide compound-wound direct-current motors or phase-wound polyphase induction motors. The series winding of the compound-wound motors is generally weaker than for standard motors, 10 per cent being an average value. The speed control is accomplished by field control for direct-current motors and secondary control for induction motors. Most presses of this type allow of mounting the motor under the bed toward the front of the machine and a belt drive with an idler is almost always used.

WEB PRESSES vary greatly in size and come under the head of rotary presses. Different makers have different classifications for the various sizes, such as the number of decks or webs, as 3-deck, 5-deck, 2-web, etc., or according to the number of groups of which they consist, as quadruple, sextuple, octuple, etc. A modern high-speed sextuple press, for example, has three paper rolls and six plate cylinders, each cylinder generally being four plates wide. The plate cylinders revolve at a maximum speed of 300 r.p.m. A wide range of operating speeds must therefore be provided on the controller as the press will often be called upon to operate at speeds as low as one-half of the above.

All of these presses require a slow threading speed, usually about 10 r.p.m. This speed must be steady as the operators have to thread the paper from roll to roll around the cylinder up over the carriers to the folder, and should the press turn by jerks it might mean the loss of a finger, hand or arm. The control must also provide for "jogging" or "inching along" when making the press ready for service, that is turning the cylinders through a small fraction of a revolution so as to bring them to the desired position for putting on the plates. Brakes must

also be provided so that in case of emergency the press may be brought immediately to rest.

Single-motor Equipment. — Motor equipments for web presses are of either the single or two-motor type. The former is used with small and medium-size direct-current units but is not practicable above 30 or 35 horse-power. The principal objection to single-motor equipments is the difficulty in maintaining a constant slow speed, due to the wide variation in torque during any given revolution of the press cylinders. The waste of power in the series and shunt resistances is also a disadvantage, particularly for the larger sizes. Compound-wound motors are generally used with the single-motor equipments so as to provide for the comparatively-heavy starting torque. Speed regulation down to 10 per cent is readily accomplished by connecting a resistance in parallel with the armature circuit which, in combination with the series resistance, gives a fixed slow speed.

Two-motor Equipment. — The two-motor equipment consists, as the name implies, of two motors, one of small size for driving the press at slowspeed through a worm-gear reduction, and a large motor to drive the press at the full-producing speed through ordinary direct gearing. The reduction gearing for the small motor is furthermore provided with an automatic ratchet and pawl clutch, which mechanically disconnects the small motor when the press is being accelerated by the large motor.

Either direct- or alternating-current motors may be used with two-motor equipments. When direct-current is used the small motor should be compound wound to insure sufficient starting torque. It is also a common practice to make the large motor compound wound, so as to accelerate the press more easily. With alternating-current the smaller motor may be of the squirrel-cage type but the larger must be of the phase-wound slip-ring type, as a smooth speed variation from the 10 per cent threading speed to the full running speed is most essential.

The capacity of the motors depends on the size and make of the press, and the accompanying table is only intended to give an approximate idea of the power required:

Type of press	Horse-power	
	Small motor	Large motor
Quadruple	5	35
Sextuple	7	50
Double quadruple	Two 5½	Two 35
Double sextuple	Two 7½	Two 50
Octuple	10	70

Control of Two-motor Drive. — Full automatic control in connection with two-motor drive has been almost universally adopted on larger presses. The essentials of this control are the complete automatic control of the press speed from any number of push-button stations located at different points about the press. From any of these stations it is possible to start the press, increase or decrease the speed or stop it. Five buttons are generally provided with each station marked "Fast," "Slow," "Stop," "Safe" and "Run."

Pressure on the "Fast" or "Slow" button causes the press to speed up or slow down until the button is released, when the press will continue to run at the

speed it has then attained. The manipulation of the "Stop" button will immediately stop the press, through the operation of a dynamic brake on direct-current equipments and a solenoid brake on alternating-current equipments. Pressure on the "Safe" button at any station opens the control circuit and renders the equipment inoperative until the "Run" button at that particular station is closed, releasing the "Fast" button. A "Jog" button is frequently also provided, particularly on a-c. equipments, by means of which the cylinders can be inched along to the desired position when plating is done.

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PROGRESSION. — (*See also Series, Mathematical.*) There are two kinds of progression, arithmetical and geometrical.

ARITHMETICAL PROGRESSION. — Quantities are said to be in arithmetical progression when they increase or decrease by a common difference.

Let a = first term of the progression,
d = the amount by which any term is greater than the next preceding, i.e., the common difference,
n = the number of terms in the progression.

Then the successive terms of the progression are

$$a,\ a + d,\ a + 2d,\ a + 3d, \text{ etc., to } n \text{ terms.}$$

The last term is

$$a + (n - 1)\,d.$$

The sum of the n terms is

$$\frac{n}{2}[2a + (n - 1)\,d].$$

GEOMETRICAL PROGRESSION. — Quantities are said to be in geometrical progression when they increase or decrease by a common ratio. Let

a = the first term of the progression,
r = the ratio of any term to the next preceding term,
n = the number of terms in the progression.

Then the successive terms of the progression are

$$a,\ ar,\ ar^2,\ ar^3, \text{ etc., to } n \text{ terms.}$$

The last term is

$$ar^{n-1}.$$

The sum of the n terms is

$$\frac{a(1 - r^n)}{1 - r}.$$

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PUMPS AND PUMPING ENGINES. — (*See also Boilers; Blowers and Compressors; Condensers; Fans; Power Stations; Steam Engines; Steam Turbines.*) Pumps may be classified according to (1) their mode of action as piston, plunger, centrifugal, rotary, jet and direct pressure; (2) their motive power, as engine-driven, turbine-driven, motor-driven, and power-driven (by belt or gearing); (3) the number of cylinders (or their equivalent), as simplex, duplex and triplex; (4) the number of stages or pump elements in series, as single-stage and multi-stage; (5) the mode of connection, as direct-acting, crank-driven and geared. Large steam-driven pumps are usually called pumping engines.

Piston and Plunger Pumps are the most common in use. In the single-acting type, water is taken in on one stroke and discharged on the return stroke. In the double-acting pump water is taken in and discharged on both strokes. In the direct-acting piston or plunger pump the steam piston and the water piston or plunger are both secured to the same piston rod and the steam is used non-expansively. Their steam consumption is consequently high, unless special compensating devices, substitutes for a flywheel, are used, as in the Worthington high-duty and the d'Auria pumping engines. Large piston pumps are usually provided with a crank and flywheel, so that the steam may be used expansively.

Centrifugal Pumps consist essentially of a rotating impeller which draws water in at its center and a stationary casing which guides the water to the discharge outlet. Centrifugal pumps having stationary guide-vanes inside of the casing are called "turbine" pumps. Centrifugal pumps are especially suited for low heads and large volumes, but are also built multi-stage for high heads. They are not as efficient as high-grade pumping engines, but are considerably cheaper.

Rotary Pumps. — Pumps with two parallel geared shafts carrying vanes or impellers which mesh with each other, and other forms of positive-driven apparatus, in which the water is pushed at a moderate velocity, instead of being rotated at a high velocity as in centrifugal pumps, are known as rotary pumps. They have an advantage over reciprocating pumps in being valveless, and over centrifugal pumps in working under widely-varying heads. They are usually not economical, but when carefully designed with the impellers of the correct cycloidal shape, like those used in positive rotary blowers, they give a moderately high efficiency.

Injectors. — The injector is a form of steam pump commonly used for feeding boilers. If a cylindrical tube 1 or 2 inches in diameter is reduced to one-half its diameter, or thereabouts, at one portion of its length, by gradual reduction and enlargement, and a smaller tube or nozzle inserted inside of it, so that the end of the smaller tube approaches the reduced section of the larger tube, then if the larger tube be connected to a supply of water and steam at considerable pressure be introduced through the smaller tube or nozzle, the water will be drawn into the larger tube and ejected from its outer end with such force as to cause it to overcome the pressure in the boiler supplying the steam, and thus to feed water into the boiler. The apparent paradox of the injector is explained by the fact that the violent rush of steam into the water gives the latter a high velocity and the momentum thereby induced cannot be overcome in a limited space without the exertion of a force greater than that of the steam in the boiler. As a boiler feeder the injector has a remarkably high efficiency, for so much of the heat energy of the steam as is not converted into mechanical work is carried into the boiler as heat in the water, but as a pump for ordinary purposes its efficiency is very low, since less than 1 per cent of the thermal

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energy of the steam is converted into work. The usefulness of the injector as a boiler feeder is limited by the fact that it will not handle hot water.

Direct-pressure Pumps. — These are of two types, the pulsometer and the air lift. In the pulsometer the water is raised by suction into the pump chamber by the condensation of steam within it, and is then forced into the delivery pipe by the pressure of a new quantity of steam on the surface of the water. Two chambers are used, which work alternately, one raising while the other is discharging. The air-lift pump consists of a vertical water pipe with its lower end submerged in a well and a smaller pipe delivering air into it at the bottom. The rising column in the pipe consists of air mingled with water, the air being in bubbles of various sizes, and therefore lighter than a column of water of the same height; consequently the water in the pipe is raised above the level of the surrounding water. The pulsometer is used for pumping out pumps, drains, etc., and the air lift for pumping from wells.

PERFORMANCE. — The performance of a pump is usually expressed in terms of steam consumption of the steam cylinder or engine driving it, the indicated horse power of the cylinder or engine driving it (or the brake horse power of the motor in case of a motor-driven pump), the mechanical efficiency of the pump, and the slip.

Useful or Water Horse Power. — Let p = difference in pressure in pounds per square inch between inlet and outlet of pump = pressure in pounds per square inch indicated by gauge on force main ± pressure in pounds per square inch indicated by gauge on suction main (+ if this reads below atmospheric pressure, − if above) + pressure in pounds per square inch corresponding to the distance between the two gauges; H = head in ft. corresponding to p; Q = actual discharge* in cubic feet per minute; W = pounds per minute discharged; w = weight of the fluid per cubic foot. For water at 62° F., w = 62.36 pounds and is about 0.1 per cent greater at 40° F., and 4 per cent less at 212° F. Then the useful or water horse power is

$$P_w = \frac{144\,pQ}{33{,}000} = \frac{pQ}{229} = \frac{pW}{229\,w} = \frac{HW}{33{,}000} = \frac{HwQ}{33{,}000}.$$

For water at 62° F., and approximately at any temperature between 32° and 212° F.,

$$P_w = \frac{pW}{14{,}300} = \frac{HQ}{529}.$$

Slip. — By the slip of a pump is meant the ratio of the difference between the piston displacement and the water delivered to the piston displacement.

Mechanical Efficiency. — By mechanical efficiency is usually meant the ratio of the useful or water horse power to the indicated horse power of the steam cylinder driving it, or to the brake horse power of the motor in the case of a motor-driven pump. Sometimes the useful or water horse power is figured on the basis of the amount of water corresponding to the piston displacement; the actual water delivered is then equal to the piston displacement multiplied by (1 − slip). The power required to deliver water at a given rate in the first case is equal to the useful or water horse power divided by the mechanical efficiency; in the second case the power required is equal to the useful or water

* Q is sometimes taken as equal to the piston displacement, which is greater than the actual water delivered, due to the slip of the water past the piston and valves.

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horse power (reckoned on the basis of piston displacement) divided by the product of the mechanical efficiency and (1 − slip). (*See table below.*)

Duty. — The performance of a steam-driven pump is also expressed as the number of foot-pounds of useful work done by the pump ($144\,pQ \times$ time in minutes) per million B.t.u. in the steam supplied to it above the temperature of the boiler feed water. (If the boiler takes water from several sources at different temperatures, the B.t.u. added by the boiler from each source must be reckoned separately.) This ratio is called the "duty" of the pump. Duty is also sometimes expressed as the useful work in foot-pounds done by the pump per 1000 pounds of dry steam supplied to it.

The efficiency of a pump falls off rapidly with use, due to wear of the moving parts, unless it is kept in first-class condition. The figures in the following table are for average full-load conditions at rated speed in ordinary practice:

EFFICIENCY AND DUTY OF PUMPS.

Type of Pump	Pounds steam per hour per h.p. of Useful Work	Mechanical efficiency	Per cent slip	Duty, million ft. lb. per million B.t.u.
Piston pumps:				
Small duplex, direct-acting	100 to 200	40 to 60	5 to 20	10 to 20
Compound, direct-acting, non-condensing	40 to 80	70 to 90	2 to 20	25 to 50
Ditto with "high duty" attachment	20 to 33	60 to 80	2 to 20	60 to 100
Single cylinder, flywheel, non-condensing	30 to 50	70 to 90	2 to 20	40 to 60
Multi-cylinder, fly wheel, non-condensing	25 to 40	70 to 90	2 to 20	50 to 80
Multi-cylinder, fly wheel, condensing	13 to 20	70 to 95	2 to 20	80 to 160
Direct-connected, motor-driven:	.....	50 to 80	2 to 20	60 to 80
Geared pumps	.....	50 to 90	2 to 20	30 to 90
Centrifugal pumps:				
Single-stage for low heads	22 to 66	40 to 70	.....	30 to 90
Multi-stage for high heads	25 to 50	40 to 60	.....	40 to 80
Rotary pumps	26 to 50	50 to 80	5 to 20	40 to 75
Pulsometer	100 to 400	.....	.....	5 to 20
Air lift	.....	10 to 40	.....	10 to 25

Steam Consumption of Feed Pumps. — With compound steam ends well lagged and covered 100 pounds of steam per indicated horse-power-hour should be safe consumption for feed pumps of large size, while in small pumps, 200 pounds appears to be nearer the mark. The pump efficiency should not be less than 80 per cent.

Performance of Injectors. — Kneass, *Theory of the Injector*, states that the pounds of water delivered (w) per pound of steam supplied is equal, very approximately, to the ratio of the B.t.u. per pound in the steam supplied, reckoned from the temperature (t) of the discharge water to the difference between the temperature (t) of the discharge water, and the temperature (t)

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of the suction water. That is, letting r = heat of evaporation, h = heat of liquid, and x = quality of the steam, then

$$w = (rx + h - t + 32) + (t - t_0).$$

ELECTRIC DRIVE. — (*See also Motors, Industrial Applications of.*) Since the reciprocating pump is essentially a low-speed machine, limited to about fifty revolutions per minute or thereabouts, it requires a speed reduction, as by gearing, for connection to the driving motor. The centrifugal pump, on the other hand, is suitable for direct connection to motors operating at speeds of up to 3500 r.p.m.

Motors for Reciprocating Pumps. — In starting large reciprocating pumps the water may be delivered through a by-pass until the motor is up to speed, when the by-pass is gradually closed and the water delivered into the system. The load at starting, therefore, only consists of the friction losses, and usually does not exceed 25 per cent of the full-load torque. Small- and medium-size pumps may, however, be required to start under full load.

When direct-current motors are used, the compound-wound type is generally selected for single-acting pumps on account of the rather pulsating load, but for double and triplex pumps having steadier load characteristics the shunt-wound type is used to advantage. Both squirrel-cage and phase-wound induction motors are suitable, the latter, as a rule, being selected where it is desirable to reduce the starting current to a minimum or where a somewhat variable speed is required. Synchronous motors may and are frequently used for driving large pumps. By-pass valves must then, however, be provided for reducing the torque at starting as previously mentioned.

Motors for Centrifugal Pumps. — On account of the peculiar characteristics of centrifugal pumps special care is required in the selection of the motor drive. With a reciprocating pump operating at constant speed an increase of the resistance increases the pressure and therefore the load on the motor; but with a centrifugal pump an increase of the resistance reduces the load. The volume of water delivered by a reciprocating pump is not affected by the reduction of the head, but the required power is reduced. A reduction of the head with a centrifugal pump, however, increases the volume of water, and as the efficiency at the same time goes down rapidly, the load increases. It is, therefore, of importance to know what this overload, caused by a reduction of the head, amounts to and the duration of this overload; and the capacity of the motor should as a rule be governed by the low and not the high head conditions.

The condition of starting must also be given careful consideration in selecting the motor. In starting a centrifugal pump the discharge valve may be entirely closed until the motor comes up to speed, so that the motor may start as nearly light as possible. At rest the torque required is small, usually from 15 to 25 per cent of full-load torque, and this drops from 5 to 6 per cent as soon as the machine starts turning over. The pump casing is full of water, however, and as the machine comes up to speed this water is churned around in the casing, causing the motor to load up as it approaches full speed, when with pumps of the usual design it takes from 40 to 50 per cent of full-load torque to drive it even though pumping no water.

Compound-wound direct-current motors, varying-speed brush-shifting motors, and either squirrel-cage or phase-wound induction motors, or synchronous motors are all well adapted for this type of pump and will readily meet the above conditions.

COST OF FEED PUMPS (Pre-war figures). — The cost of feed pumps is a small item in the cost of the station, varying from 20 to 50 cents per kilowatt of station capacity, or from 15 cents to $1 per boiler horsepower the lower prices

applying to the larger station. Duplex direct-acting pumps, of the Worthington type, and suitable for boiler feeding, vary in capacity from the 6 by 4 by 6 in. 100-gallon pump to the larger pot-valved pumps with compound steam ends, 14 and 20 by 10 by 15 in. delivering 500 gallons per minute. The price varies from about $300 for the small size to around $2000 for the large size, with the intermediate sizes at proportional prices. Centrifugal feed pumps, turbine-driven, run from 200 to 1000 gallons per minute, in about four sizes, and cost about $1500 in the 200 gallons size and about $3200 in the 1000 gallons size. Motor-driven centrifugal pumps are about 10 per cent higher in price, and triplex motor-driven pumps often run from 100 to 200 per cent higher.

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PYROMETERS. — (*See also Temperature and Thermometers.*) A pyrometer is any device for measuring high temperatures. By high temperature as here used is meant a temperature beyond the range of the ordinary mercury thermometer, say 350° C. and up. A great number of pyrometric methods have been proposed, the more important of which will be found treated in detail in Burgess and Le Chatelier's *Measurement of High Temperatures*, New York, 1912. The following brief treatment is adapted from this work.

CLASSIFICATION OF PYROMETERS. — The various types of pyrometers may be classified as follows. Some of these are more fully treated in the following sections.

Gas Pyrometer (Pouillet, Becquerel, Sainte-Claire-Deville, Barus, Chappuis, Holborn, Callendar, Day). — Utilizes the measurement of change in pressure of a gaseous mass kept at constant volume. Its great volume and its fragility render it unsuitable for ordinary measurements; it serves only to give the definition of temperature and should only be used to standardize other pyrometers.

Calorimetric Pyrometer (Regnault, Violle, Le Chatelier, Siemens). — Utilizes the total heat of metals, platinum in the laboratory and nickel in industrial works. It was formerly used for intermittent researches in industrial establishments because its employment demands almost no apprenticeship and because the cost of installation is not great. The cost of a metal ball to withstand over 1000° C. prohibits its use above this temperature in industrial works. Other and more convenient types of pyrometers have almost entirely superseded the calorimetric pyrometer.

Total Radiation Pyrometer (Rosetti, Langley, Boys, Féry, Thwing). — Utilizes the total heat radiated by warm bodies. Its indications are influenced by the variable emissive power of the different substances. Convenient for the evaluation of very high temperatures which no thermometric substance can withstand (electric arc, sun, very hot furnaces), or when it is not convenient to approach the body whose temperature is wanted. Can be made self-registering.

Optical Pyrometer (Becquerel, Le Chatelier, Wanner, Holborn-Kurlbaum, Morse). — Utilizes either the photometric measurement of radiation of a given wave length of a definite portion of the visible spectrum, or the disappearance of a bright filament against an incandescent background. Its indications, as in the preceding case, but to a much less degree, are influenced by variations in emissive power. The intervention of the eye aids greatly the observations, but diminishes notably their precision. This method is mainly employed in industrial works for the determination of the temperatures of bodies difficult of access — for example, of bodies in movement (casting of a metal, the hot metal passing to the rolling mill). Can be used to estimate the highest temperatures and is the best method for use above 1700° C. in laboratory and industrial works.

Electric Resistance Pyrometer (Siemens, Callendar, Waidner and Burgess). — Utilizes the variations of electric resistance of metals (platinum) with the temperature. This method permits of very precise measurements to 1000° C., but requires the employment of fragile apparatus. It merits the preference for very precise investigations in laboratories. As a secondary instrument for the reproduction of a uniform temperature scale throughout the range in which the platinum resistance thermometer can be used, to 1000° C. except in very heavy wire, it is unsurpassed in precision and sensibility. It is also now constructed in convenient form for industrial use.

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Thermoelectric Pyrometer (Becquerel, Barus, Le Chatelier). — Utilizes the measurement of electromotive forces developed by the difference in temperature of two similar thermoelectric junctions opposed one to the other. In employing for this measurement a Deprez-d'Arsonval galvanometer with movable coil or a millivoltmeter one has an apparatus easy to handle and of a precision amply sufficient for industrial and many scientific uses. With a potentiometer an instrument is obtained of the highest precision, available for use to 1600° C., or even to 1750° C. with proper precautions. This pyrometer was used for a good many years in scientific laboratories, before it spread into general industrial use, where it also renders most valuable service.

Contraction Pyrometer (Wedgwood). — Utilizes the permanent contraction which clayey materials undergo when submitted to temperatures more or less high. It is employed today only in a few pottery works.

Fusible Cones (Seger). — Utilize the unequal fusibility of earthenware blocks of varied composition. Give only discontinuous indications. Such blocks studied by Seger are spaced so as to have fusing points distant about 20° C. In general use in pottery works and in some similar industries.

Other Pyrometers (Hobson, Uhling-Steinbart, Job, Fournier). — There are a number of other pyrometers which have been found suitable in special cases or which for one reason or another have been found convenient in some particular line of work. Among these are the various industrial instruments based on the relative expansion of metals or of a metal and graphite used in air blasts and metal baths and pyrometers based on the flow or on the pressure of air or vapor.

TOTAL-RADIATION PYROMETERS. — These instruments utilize the radiant heat of *all* wave lengths given off by the body whose temperature is to be measured or by an auxiliary body at the same temperature. By means of a focusing device the radiant heat from a small portion of the hot surface is caused to fall upon a suitable detector. Various devices have been used as detectors, but in modern radiation pyrometers the thermocouple in conjunction with a galvanometer, millivoltmeter or potentiometer is almost universally employed. Instead of the thermocouple a spiral bi-metallic spring, with a pointer attached, is used in Féry's *spiral* pyrometer.

Total-radiation pyrometers can be made self-registering by simply substituting for the indicating galvanometer a suitable recording instrument.

Conditions of Use. — To obtain accurate results with a radiation pyrometer it should be sighted upon the bottom of a closed-end tube inserted into the furnace or bath. The radiating properties of the bottom of such a tube approach very closely those of a "black body" (*see Heat and Thermal Properties*); i.e., the total energy radiated upon the receiving device is proportional to the difference in the fourth powers of the absolute temperature of the hot body and that of the receiving device. Since the latter temperature is usually low compared with the temperature of the hot body, the radiation is practically proportional to the fourth power of the absolute temperature of the hot body. Hence, if the relation between the absolute temperature T_0 and the deflection D_0 of the galvanometer attached to the thermocouple is known at one temperature, and the deflection is known to be proportional to the amount of heat falling on the thermocouple, then the absolute temperature T corresponding to any other deflection D is

$$T = T_0 \sqrt[4]{\frac{D}{D_0}}.$$

It should be noted that this law does not apply unless the instrument is focused upon a "black body." If the instrument is focused upon objects in the

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open air its readings, if calibrated by the above law, will be too low, due to the selective radiating properties of all materials. However, the instrument may be calibrated by comparison with a standard pyrometer, e.g., a thermoelectric pyrometer, to give true surface temperatures when sighted upon any particular kind of surface, but this calibration will not hold for other surfaces.

Féry Radiation Pyrometer. — In this apparatus a concave mirror (gold on glass) is used to focus the rays upon the thermocouple. The gold mirror may be considerably tarnished without seriously influencing the readings; and if the aperture of the furnace sighted upon is of sufficient size and the telescope in focus, the temperature readings are practically independent of the distance. The instrument takes its final reading very promptly with only slight creep.

Foster has also transformed the Féry telescope into a "fixed-focus pyrometer" by putting the thermocouple and the aperture at the *conjugate foci* of the gold mirror. In a similar instrument recently issued by the Brown Pyrometer Company, the sighting of the instrument is facilitated by the use of a finder such as used with photographic cameras. The Féry pyrometer of constant-focus type has been coupled directly to a long closed-end tube by Whipple, so that the closed end may be plunged directly into the hot region or melted metal.

Thwing Radiation Pyrometer. — In Thwing's apparatus the reflecting mirror is replaced by a conical cone which by multiple reflection concentrates the radiation at its apex on one or more thermocouples in series with a portable galvanometer.

OPTICAL PYROMETERS. — These instruments utilize only the visible portion of the spectrum, and their indications depend on the comparison, by the eye, of the equality of brightness of two images, one of the object whose temperature is sought and the other a standard light source. Such instruments are therefore essentially the same as photometers (*see article on Photometers*). As a rule the comparison is made with approximately monochromatic light, the images being viewed through a colored glass, usually red.

Temperature and Intensity of Illumination. — Wien's Law. — Wien has shown that the intensity of the light given out by a "black body" (*see Heat and Thermal Properties*) may be expressed by the formula

$$I = A\epsilon^{-\frac{B}{T}},$$

where A and B are constants for a *given wave length*, ϵ is the base of the natural system of logarithms and T the *absolute temperature*. In general, however, the energy of a given wave length radiated by a body in the open air is less than that of a "black body," i.e., its emissive power is less than unity, and the emissive power varies with the temperature. The above law, however, is usually assumed to apply to such bodies, and although the temperature as thus obtained may differ from the true (gas thermometer) temperature by from 50 to 100° C., a *consistent* scale of temperature is obtained for any *particular* substance observed.

"Black Body" Temperature. — The temperatures indicated by a radiation pyrometer that has been calibrated against a black body, or on the assumption of the laws of "black body" radiation, are known as black-body temperatures. Thus, were a piece of iron and a piece of porcelain both at 1200°, the optical pyrometer, which used the red light emitted by these bodies, would give, as the temperature of these bodies, 1140° and 1100° C. respectively. This means that iron and porcelain at 1200° C. emit red light of the same intensity as is emitted by a black body at 1140° and 1100° C. respectively.

Féry Absorption Pyrometer (Fig. 1). — The optical system of this pyrometer is shown in the figure. pp' are a pair of absorbing-glass wedges, G is a

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mirror with only a narrow central strip silvered over, L is the standard light source, focused on the mirror G by the lens l. The resultant field, when observing a small crucible, is then as shown at ab. r is a red glass in the eye-piece. The instrument has a fixed angular aperture, so that no correction has to be made for focusing or for varying distance from furnace. The range of the instrument may be extended by the use of auxiliary absorbing glasses A, A'. The instrument is movable about a horizontal axis, which is a convenience in sighting.

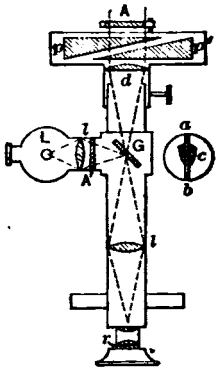


Fig. 1. Féry Absorption Pyrometer

A setting is made by adjusting the thickness of the absorbing glasses pp' by moving the wedges together by means of a micrometer screw. Let x = setting of micrometer screw, T = absolute temperature, then, assuming Wien's law to apply

$$T = \frac{a}{x+b},$$

where a and b are two constants, for a given set of wedges pp', and can be obtained by observing two known temperatures.

Le Chatelier's Optical Pyrometer. — The Féry pyrometer is a modification of an earlier form devised by Le Chatelier. The latter used an iris diaphragm instead of the wedges, the setting of the instrument being accomplished by changing the aperture. With this arrangement greater sensibility can be obtained, but with the decided disadvantage that the calibration will then hold only for a fixed distance of the instrument from the object viewed.

Wanner Pyrometer (Fig. 2). — In this instrument a Nicol prism is used to vary the relative intensities of the light received from the standard lamp and from the object viewed, the angle through which the prism must be turned to give equal illumination being a measure of the relative intensity of the light emitted from the two sources. The principle is the same as that of a Kŏnig spectrophotometer (*see Photometers*).

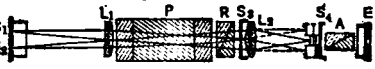


Fig. 2. Wanner Pyrometer

The slit S_1 is illuminated by light from the comparison source, a small 4-volt electric lamp not shown in the figure reaching S_1 after diffuse reflection from a right-angled prism placed before S_1. Light from the object whose temperature is sought enters the slit S_2. If the analyzer is at an angle of 45 degrees with the plane of polarization of each beam, and if the illumination of S_1 and S_2 is of the same brightness, the eye will see a single red circular field of uniform brightness. If one slit receives more light than the other, one-half of the field will brighten, and the two may be brought to equality again by turning the analyzer carrying a graduated scale, which may be calibrated in terms of temperature. Let ϕ = angle through which prism is turned to establish equal illumination, T = absolute temperature of furnace or bath; then, assuming Wien's law to apply,

$$T = \frac{a}{\log(\tan\phi) - b},$$

where a and b are constants determined by calibration. Only two known tem-

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peratures need be observed to obtain these constants, but it is safer to plot a calibration curve from several known temperatures.

In the latest form of this instrument the details of its mechanical construction have been improved, and it has been made direct-reading by providing a second scale on the instrument graduated in temperatures, corresponding, of course, to a definite normal point and for a source approximating a black body.

Incandescent Lamp Pyrometers. — In this type of instrument the current through the filament of an incandescent lamp is adjusted until a portion of the filament is of the same color and brightness as the object. When this occurs this part of the filament becomes invisible against the bright background, and the current then becomes a measure of the temperature as given either by a thermocouple or in terms of the intensity of illumination. This principle appears to have been first used by Morse and independently developed by Holborn and Kurlbaum. An absolute match of both color and brightness cannot be made unless monochromatic light is used or unless the lamp filament and viewed object radiate similarly. This instrument is of the Morse type.

Leeds and Northrup Optical Pyrometer. — The principle and manner of using the instrument will be understood by reference to Fig. 3, in which *L* is a

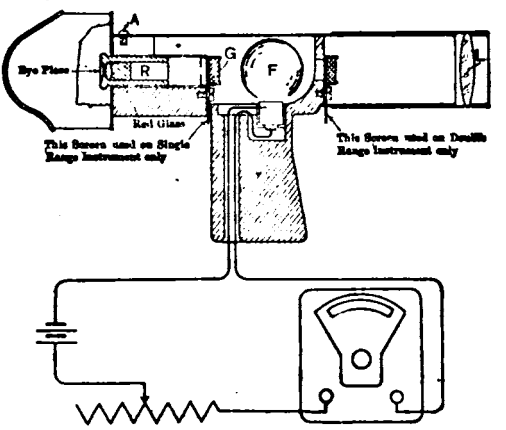


Fig. 3. Leeds and Northrup Optical Pyrometer.

lens, through which radiation from the body whose temperature is to be measured is brought to a focus at the point *F*. In the plane of the image produced by the lens is placed a tungsten lamp filament. The lamp filament receives current from a small battery contained in a portable case, also containing a rheostat and an accurate milliammeter. The incandescent filament and the image produced by the lens are observed through the eyepiece.

By means of the rheostat the current through the lamp is adjusted until the brightness of the filament is just equal to the brightness of the image produced by the lens *L*, whereupon the filament blends with or becomes indistinguishable in the background formed by the image of the hot object. This adjustment can be made with great accuracy and certainty, as the effect of radiation upon the eye varies some twenty times faster than does the temperature at 1600° F, and some fourteen times faster at 3400° F. When a balance has been obtained,

the observer notes the reading of the milliammeter. The temperature corresponding to the current is then read from a calibration curve supplied with the instrument.

The red glass R is in for all temperature measurements. An additional red glass G in Fig. 3 is put in when measuring higher temperature where the light emitted becomes dazzling. This also eliminates any question of matching colors or of the observer's ability to distinguish colors. It is further of value in dealing with bodies which do not radiate light in the same composition as that emitted by a black body, since the intensity of radiation of any one color from such bodies increases progressively in a definite manner as the temperature rises. The intensity of this one color can therefore be used as a measure of temperature for the body in question.

Measurement of Very High Temperatures. — In observing bodies at very high temperatures, i.e., above 2500° F., the light received through the lens of the telescope is too blinding for direct observation, even through the red glass of the eyepiece. The intensity of the image also becomes greater than that at which it is practicable to burn the filament.

Some method of reducing the intensity of the light from the hot body must therefore be employed at these temperatures. This is done by placing an absorbing screen between the objective lens and the lamp filament so that it reduces the light from the hot body, but does not affect that from the filament. With the proper screen in place, it is possible to make direct observations on the most brilliant light sources, as the electric arc or the surface of the sun.

The screen used in the Leeds and Northrup high-temperature optical pyrometer for cutting off part of the radiation from the hot body can be thrown into or out of the field of view by revolving with the thumb a milled disk projecting through an opening in the barrel of the instrument. With the absorbing screen in use, a different calibration curve is required. Inasmuch, however, as the range of the instrument without the absorbing screen overlaps by several hundred degrees the range with the absorbing screen, the accuracy of the two scales can always be checked by observing a hot body whose temperature lies within this range.

RESISTANCE PYROMETERS. — These instruments are based upon the variation of electrical resistance with temperature, and are suitable for measuring temperatures throughout the range from the lowest obtainable temperatures to about 1200° C. Platinum wire is usually employed as the resistor, though nickel may be used for temperatures up to 400° C.

Platinum Scale of Temperatures. — The platinum scale of temperatures is defined by the relation

$$p_t = \frac{R_t - R_0}{R_{100} - R_0} \times 100,$$

where R_0 and R_{100} are the resistances of the platinum wire at the temperature of ice and boiling water (760 millimeters mercury pressure) respectively, and R_t is the resistance at any other temperature t. For this scale to agree with the gas thermometer scale would require that the temperature coefficient of resistance of platinum (on the gas scale) be a constant equal to

$$c = \frac{R_{100} - R_0}{100\, R_0}.$$

As a matter of fact the temperature coefficient is not constant but the relation between temperature (on the gas scale) and resistance is

$$R_t = R_0 (1 + at - bt^2)$$

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where a and b are constants. Consequently the platinum temperature and the gas temperature differ by an amount

$$t - p_t = \delta\left(\frac{t}{100} - 1\right)\frac{t}{100},$$

where

$$\delta = \frac{10{,}000\,b}{a - 100\,b}.$$

The fundamental constants of a platinum thermometer are then R_0, c, and δ. These can be determined by measuring the resistance at three known temperatures, viz., melting point of ice, boiling point of water and boiling point of sulphur (444.7° C. on the gas scale). For the purest platinum $\delta = 1.50$ and $c = 0.0039$. The value of δ increases with the amount of impurity.

CORRECTIONS TO t FOR SMALL CHANGES IN δ

Centigrade scale				Centigrade scale			
	Δt for $\Delta\delta = 0.01$		Δt for $\Delta\delta = 0.01$		Δt for $\Delta\delta = 0.01$		Δt for $\Delta\delta = 0.01$
50	−0.002	300	+0.060	550	+0.247	800	+0.560
100	.000	350	.087	600	.300	850	.637
150	+ .008	400	.120	650	.357	900	.720
200	.020	450	.157	700	.420	950	.807
250	.037	500	.200	750	.487	1000	.900

Computations of t from p_t are made by the table on p. 1238, as if the thermometer had $\delta = 1.50$. The above corrections (Δt) are then applied to the computed values of t for the value of δ proper to the thermometer.

Example. Let $p_t = 470.00$, whence $t = 500.00°$ C, by table on p. 1238. If $\delta = 1.52$, the corrected value of t is 500.40° C.

For a full discussion of the platinum temperature scale and its relation to the gas-thermometer scale, see Burgess and Le Chatelier, *Measurement of High Temperatures*. The brief discussion given above is adapted from this treatise, from which also the tables are taken.

Forms of Resistance Thermometers and Pyrometers. — A complete outfit consists of the thermometer proper or "bulb," the indicating or recording instrument and two or three dry cells for operating the same. Where the indicating or recording instrument is to be in circuit continuously, it is best to operate it from a direct-current lighting circuit or storage-battery system.

With the proper switching device a number of bulbs at widely-separated points may be used with the same indicator or recorder.

Thermometer Proper or Bulb. — Since practically every problem in temperature measurement presents different conditions there can be no general type or form of resistance thermometers. The following descriptions are of some of the thermometers now on the market that have proved satisfactory for certain classes of work.

Resistance thermometers for use below 125° C. are of relatively simple construction, for in this case silk-insulated nickel wire may be used. Such a thermometer is shown in section in Fig. 4. This particular thermometer has an over-all length D of 10¼ inches, a length of winding C of 4½ inches and a

VALUES OF TEMPERATURE CENTIGRADE (t) IN TERMS OF PLATINUM TEMPERATURES (p_t) FOR THERMOMETERS WITH $\delta = 1.500$

p_t	t	Difference for 1° p_t	p_t	t	Difference for 1° p_t	p_t	t	Difference for 1° p_t	p_t	t	Difference for 1° p_t
0	0.000	0.985	250	255.99	1.066	500	534.89	1.170	750	844.26	1.313
10	9.867	0.988	260	266.67	1.070	510	546.62	1.175	760	857.42	1.319
20	19.762	0.991	270	277.38	1.073	520	558.40	1.180	770	870.65	1.326
30	29.687	0.994	280	288.13	1.077	530	570.22	1.185	780	883.95	1.333
40	39.641	0.997	290	298.92	1.081	540	582.10	1.190	790	897.32	1.340
50	49.625	1.000	300	309.75	1.084	550	594.03	1.195	800	910.76	1.347
60	59.639	1.003	310	320.61	1.088	560	606.00	1.200	810	924.28	1.355
70	69.683	1.006	320	331.51	1.092	570	618.03	1.205	820	937.87	1.363
80	79.758	1.009	330	342.46	1.096	580	630.11	1.210	830	951.54	1.370
90	89.863	1.012	340	353.44	1.100	590	642.24	1.216	840	965.28	1.378
100	100.00	1.015	350	364.46	1.104	600	654.43	1.222	850	979.10	1.386
110	110.17	1.018	360	375.52	1.108	610	666.67	1.227	860	993.01	1.394
120	120.37	1.021	370	386.62	1.112	620	678.97	1.232	870	1007.00	1.403
130	130.60	1.024	380	397.76	1.116	630	691.32	1.238	880	1021.07	1.411
140	140.86	1.027	390	408.95	1.120	640	703.73	1.244	890	1035.23	1.420
150	151.16	1.031	400	420.18	1.125	650	716.20	1.250	900	1049.47	1.428
160	161.49	1.034	410	431.45	1.129	660	728.73	1.256	910	1063.80	1.437
170	171.85	1.038	420	442.77	1.134	670	741.32	1.261	920	1078.21	1.445
180	182.25	1.041	430	454.13	1.138	680	753.97	1.267	930	1092.71	1.455
190	192.68	1.044	440	465.53	1.142	690	766.67	1.274	940	1107.31	1.464
200	203.14	1.048	450	476.97	1.146	700	779.44	1.280	950	1122.00	1.474
210	213.64	1.052	460	488.46	1.151	710	792.27	1.286	960	1136.79	1.484
220	224.18	1.055	470	500.00	1.156	720	805.17	1.293	970	1151.69	1.494
230	234.75	1.058	480	511.58	1.160	730	818.13	1.299	980	1166.68	1.503
240	245.35	1.062	490	523.21	1.165	740	831.16	1.306	990	1181.76	1.513
250	255.99	1.066	500	534.89	1.170	750	844.26	1.313	1000	1196.95	1.524

diameter A of 3/16 inch. The same type of thermometer is also made with a number of different lengths from 3¾ inches over-all to 12¼ inches over-all, and one form, designed to be particularly quick acting, is encased in a thin steel tube ¼ inch outside diameter. This type of thermometer is largely used for the measurement of the temperature of air, solids, concrete, water, and grains and fruit in transit. It may also be used as a wet-bulb thermometer.

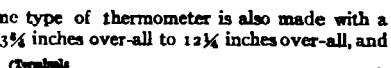


Fig. 4. Resistance Thermometer for Use up to 125° C.

The thermometer shown in Fig. 5 is a platinum resistance bulb for measurement of the highest precision. The winding is of pure platinum wound on a mica cross; the protecting tube is of royal Berlin porcelain. For shop use it is well to protect the porcelain tube with a seamless nickel case. Such a case will maintain its mechanical strength after long exposures to high temperatures. Thermometers of this type may be used up to 1000° C. This type of ther-

mometer is also provided with a special fireproof head and with a steel protecting case in addition to the nickel case. This is necessary where the thermometer is to be used in connection with case hardening.

The Leeds and Northrup Company make a bulb designed especially for measuring the temperature of generators, transformers, etc. The resistance winding of this bulb is about 3 inches long and is mounted on a flexible stem 30 inches or more in length, the width over-all is ½ inch and the thickness ⅛ inch. This resistance coil is wound non-inductively and is therefore unaffected by neighboring magnetic fields.

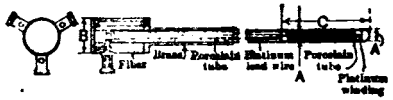


Fig. 5. Thermometer for Use up to 100° C.

Indicating Devices. — The application of the various bridge, potentiometer, differential galvanometer and ohmmeter methods (q.v.) to the measurement of the resistance of the platinum coil and the methods of compensating for the resistance of the leads are described in detail in Burgess and Le Chatelier's *Measurement of High Temperatures*. Two types of indicators are employed: (1) the balance type which requires the adjustment of a rheostat to produce zero deflection of the indicating instrument, the temperature then being read in terms of the balancing resistance, current or p.d., and (2) the direct-reading type in which the deflection of the instrument, read on a properly calibrated scale, gives the temperature directly.

THERMOELECTRIC PYROMETERS. — These instruments consist of a thermocouple and some device for measuring the e.m.f. generated due to the difference in temperature between the hot and cold junctions of the thermocouple, for which the relation between e.m.f. and temperature difference is known. The thermocouple consists of two parallel wires of different materials joined together at one end but insulated from each other throughout their length. The two ends which are joined form the hot junction and the two open ends are usually referred to as the cold junction, although they are not connected directly to each other. The two cold ends are, however, connected electrically through the device used for measuring the e.m.f. generated, thus forming a closed circuit.

Thermocouple Circuits. — The net e.m.f. tending to establish a current in such a circuit as described above is the algebraic sum of all the contact e.m.f.'s (*see Electricity and Magnetism, Principles of*) in the circuit. Wherever there is a change in the chemical nature or physical properties of the conductors forming such a circuit there exists such a contact e.m.f. These various contact e.m.f.'s are functions of the temperature of the transition points, but if the entire circuit is at the same temperature throughout, the net e.m.f. is zero (provided the circuit is formed solely of *metallic* conductors). If, however, *any* transition point is at a higher temperature than another, the net e.m.f. will in general not be zero. Consequently, when a thermocouple is used to measure the difference in temperature between the hot and cold junctions of the couple itself, care must be taken to eliminate the e.m.f.'s due to the temperature differences between the various other transition points in the circuit.

Transition points occur (1) at the junction of any two dissimilar metals; (2) wherever there is a change in the homogeneity of the structure of any of the metals in the circuit, and (3) wherever there is a change in the temperature of the metal, although it may be perfectly homogeneous. To avoid errors due to the e.m.f.'s at the transition points other than the hot and cold junctions of the couple itself, it is necessary to use for the latter metals which give a relatively *high* e.m.f. for a given temperature difference between the two junctions and

which are also *homogeneous* throughout, and to so dispose the rest of the circuit that the e.m.f.'s produced therein as the result of temperature differences neutralize one another.

Metals for Thermocouples. — For high-precision thermoelectric pyrometers platinum against platinum-iridium or platinum-rhodium alloys (containing 10 per cent iridium or rhodium) are usually employed. For industrial purposes cheaper metals and alloys are used, such as nickel, copper, iron and alloys of these metals; such couples are usually referred to as *base* metal couples, as contrasted with the *noble* metal couples formed of platinum, iridium, etc.

Thermocouples for Industrial Use. — For industrial use cheap and robust couples are required. Such couples may be made either entirely of the

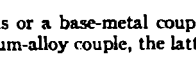


Fig. 6. Base Metal Couple

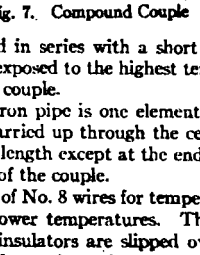


Fig. 7. Compound Couple

base metals or a base-metal couple may be used in series with a short length of a platinum-alloy couple, the latter only being exposed to the highest temperature. In Fig. 7 is shown one form of compound couple.

In the pipe type couple (Fig. 6) the outside iron pipe is one element of the couple and an alloy wire such as constantan is carried up through the center of this pipe insulated from it throughout the entire length except at the end where it is welded to the pipe forming the hot junction of the couple.

The double wire type couples are usually made of No. 8 wires for temperatures up to 1800° F., and smaller sizes of wires for lower temperatures. The ends are twisted and welded together and porcelain insulators are slipped over the wires. These couples are protected by either a heavy iron pipe or a nichrome pipe. The life of the latter at temperatures above 1800° F. is much greater than that of the iron pipe.

E.M.F.'s of Thermocouples. — By the e.m.f. of a thermocouple is meant the e.m.f. developed in a circuit consisting solely of the metals forming the thermocouple itself; i.e., the e.m.f.'s in the external circuit are not considered. If E_{sa} is the e.m.f. of a couple made of a metal a against any standard metal s, and E_{sb} is the e.m.f. of a couple made of a metal b against this same standard metal s, the e.m.f.'s in each case being for the same temperature of the cold junction (standard temperature is 0° C.) and for the same difference in temperature between the hot and cold junctions, then the e.m.f. of a couple made of a and b is, for these same temperatures

$$E_{ba} = E_{bs} + E_{sa} = E_{bs} - E_{as}.$$

(In this notation *rises* of potential are considered to be in the direction of the subscripts, that is, E_{ba} is the rise of potential from b to a). Consequently the insertion of a metal wire of any material in the circuit of a thermocouple does not change the net e.m.f., *provided this wire is of uniform structure and temperature throughout*. Consequently the hot junction may be soldered with any other metal which will not melt at the temperature to which the junction is exposed.

Electromotive Force Formulas. — No simple relation exists between the e.m.f. (E) of a thermocouple and the temperature difference (t) between

the hot and cold junctions. A number of approximate formulas, however, has been suggested. The following, due to Holman, is one of the simplest.

$$E = mt^n,$$

where m and n are constants, the cold junction being kept at 0° C. For convenience in plotting and calculation this may be written

$$\log E = n \log t + \log m.$$

Holman's formula when applied to couples made of platinum and its alloys of iridium and rhodium gives results accurate to about 2° C. for t between 200° C. and 1200° C. Typical values of n and $\log m$ are given below (Cambridge Scientific Instrument Company).

	n	$\log m$
Pt against (Pt 90%, Ir 10%).....	1.102	0.895
Pt against (Pt 90%, Rh 10%).....	1.189	0.526

The values of these constants, however, differ with different makes of couples, and in any particular case should be obtained from the maker as determined by calibration.

Another formula, due to Holborn and Day, is the following,

$$E = a + bt + ct^2,$$

where a, b and c are constants. Between 300° C. and 1100° C. this formula gives results accurate to 1° C. when applied to couples made of platinum and the various platinum alloys.

Ideal wire (*see Wires, Resistance*) and copper form a very satisfactory couple of relatively large e.m.f. suitable for a range of temperature between 0° and 400° C. With the cold junction at 0° C. the temperature of the hot junction and the e.m.f. are related as follows:

Temp. Hot Junct., °C.....	50	100	150	200	250	300	350
E.m.f., microvolts...	2.3	4.65	7.05	9.45	11.90	14.43	17.08

Thermoelectric Power (H) of Thermocouples. — The thermoelectric power of a thermocouple is defined as the increase in the e.m.f. developed per degree increase in the difference in temperature between the hot and cold junctions. This quantity, which is equal to $b + 2ct$ in Holborn and Day's formula, depends in general upon the temperature (t) of the hot junction; the values given in the table on page 1242 are close approximations within the range stated.

Measurement of E.M.F. of Thermocouples. — Two methods may be used to measure the electromotive force of a couple: the potentiometer method and the galvanometric method (*see Potentiometers; Galvanometers*). The first is the more accurate and is usually made use of in laboratories. The second method is simpler, but possesses the inconvenience of giving only indirectly the measure of the electromotive force by means of a measurement of current strength.

There are sources of error, however, inherent in the galvanometric method, such as effects of lead resistance and temperature coefficients of leads and galvanometer, which are difficult if not impossible of complete elimination even with the best apparatus available. The potentiometer method, on the other hand, may be made, in so far as the measurements of e.m.f. are concerned, as

THERMOELECTRIC POWERS OF THERMOCOUPLES
Microvolts per °C. increase in temperature, t in °C.

Thermocouple	Thermoelectric power	Temperature range, ° C.	Authority
Pt and 90% Pt, 10% Rh	$4.3+0.0088t$	0–1300	Le Chatelier
Pt and 90% Pt, 10% Ir	$11.3+0.0104t$	0–1000	Le Chatelier
Pt and Ni	$7.8+0.01325t$	300–1300	Burgess
Cu and Ni	$24.4+0.016t$	0–235	Pécheux
Cu and Constantan *	$42.3+0.058t$	0–320	Pécheux
Pt and Fe (forged)	$2.5+0.0210t$	700–1000	Le Chatelier

* 60% Cu, 40% Ni.

exact as may be desired, or so that the only outstanding uncertainties are inherent in the thermocouple itself. These uncertainties, such as inhomogeneity, conduction along the wires, variable zero and actual change of e.m.f., are sometimes overlooked, giving rise to illusory accuracy.

The application of these two methods to the measurement of the e.m.f.'s of thermocouples is described in detail in Burgess and Le Chatelier's *Measurement of High Temperatures*.

Cold-junction Correction. — When the galvanometer method is used, it is often not convenient to keep the junctions of the couple to the lead wires of the galvanometer at a definite temperature, although the galvanometer itself may be so far removed from the furnace that its temperature changes are slight. Except in the roughest kind of work, allowance has to be made for the cold-junction temperatures, which may be measured by an auxiliary thermometer.

Calling t_0 the cold-junction temperature for which the instrument reads correctly, t the observed temperature of the cold junction, the correction to apply to the observed temperature readings of the galvanometer, otherwise supposed to read correctly for a given thermocouple, usually lies between $\frac{1}{3}(t-t_0)$ and $(t-t_0)$, depending on the type of couple and the temperatures of both hot and cold junctions. This question has been treated in detail for several types of couple by C. Offenhaus and E. H. Fischer (*Electrochem. and Met. Ind., 1908, Vol. 6, p. 362*).

Elimination of Cold-junction Correction. — Bristol has also devised an automatic compensator for cold-end temperatures, shown in Fig. 8, consisting of a small glass bulb and capillary tube partially filled with mercury, into which a short loop of fine platinum wire dips. This is inserted in the thermoelectric circuit close to the cold junction. Changes in temperature cause the mercury to expand or contract, cutting in or out resistance in the circuit. This acts in opposition to the change in e.m.f. with temperature at the cold end, so that a balance may be established if the parts are properly designed.

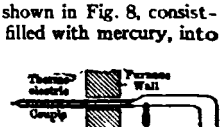


Fig. 8. Bristol's Compensator

In the Thwing instruments the elimination of the temperature variations of the cold ends of the couple, where they can be brought close to the galvanometer, is affected by a device consisting of a compound strip of two metals having unequal coefficients of expansion, so attached to the spring controlling the

pointer that the reading of the galvanometer when no current is flowing is the temperature of the surroundings.

Fig. 9 shows a simplified diagram of connections of the Leeds and Northrup split-circuit potentiometer system with automatic cold-junction compensator. The current from the battery *Ba* divides at *a* and *b*, one-half passing through the upper branch which includes the slide wire *S* and resistances *G* and *B*. The lower branch includes the nickel coil *D* and the resistance *C*. All the resistances, except the nickel coil *D*, are made of manganin wire having a zero temperature coefficient. The current in the two branches is kept constant by adjusting the rheostat *R* until the drop of potential across the coil *C* is equal to the e.m.f. of the standard cell *W*. The galvanometer *Ga* shows when a balance has been obtained. In the recording instrument, this adjustment is made automatically. The resistances *B* and *C* are high and are so chosen that the resistance in the two branches are equal.

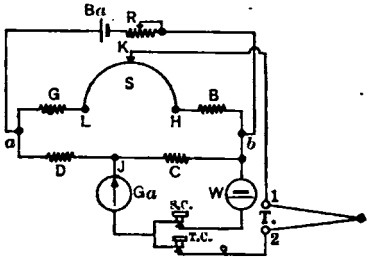


FIG. 9.

The nickel coil, *D*, is located near the cold junction of the thermocouple and has such a value that changes in cold junction temperature are compensated for by changes in the drop of potential across this coil caused by changes in its resistance with temperature.

The value of the resistance of the compensating coil *D* is calculated as follows: Let R = resistance of compensating coil *D* at reference temperature; c = change in e.m.f. of thermocouple per degree change in temperature of cold junction; K = temperature coefficient of nickel composing compensating coil per ohm per degree; i = current in branch including nickel coil; e = change in e.m.f. of thermocouple due to temperature change t of cold junction; e_1 = change in fall of potential across nickel coil due to temperature change t of cold junction. In order to have compensation e must equal e_1, regardless of changes in temperature of the cold junction, which condition is satisfied when

$$R = \frac{c}{Ki}.$$

The value of the resistance *G* is so chosen that the scale starts at 0° or at any other desired temperature. For example, suppose the temperature range is from 0 to 1000° C. The coil *G* will be equal to the nickel coil *D* at 0° *C*. Suppose both the hot junction and the cold junction are at 0° *C*. The e.m.f. of the thermocouple will be zero and the difference of potential between *K* and *J* will also be zero because the resistance of *D* equals that of *G*. If the temperature of the hot junction increases to 1000° C. and the cold junction stays at 0° C., the galvanometer will show a balance when the contact *K* is at the extreme right side of the scale (side marked *H*). Now suppose the temperature of the cold junction increases. The e.m.f. of the couple will decrease but the resistance of the nickel coil increases and causes a decrease in the e.m.f. across the points *J* and *K* that exactly compensates for the decrease in the e.m.f. of the thermocouple. The result is that the contact *K* remains at 1000° on the scale, which is the temperature at the hot junction.

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CALIBRATION OF PYROMETERS. — The methods employed are described in detail in Burgess and Le Chatelier's *High Temperature Measurements*. In general, the reading of the pyrometer is observed when the fire end is at the melting or boiling point of some solid or liquid. The melting and boiling points which possess the greatest reliability are given in the article on *Heat and Thermal Properties*.

COST AND RANGE OF TYPICAL PYROMETERS. — These items are indicated *approximately* in the table below. The precision stated is on the assumption of proper calibration and careful use.

Type	Range ° C.	Cost,* dollars
Ferry radiation pyrometer	800 and up	420–564
Thwing radiation pyrometer	800 and up	160–600
Fery absorption pyrometer	900 and up	130–150
Wanner pyrometer	900 and up	225–300
Leeds & Northrup optical pyrometer	650 and up	110–175
Resistance thermometer bulb	Up to 125	10–50
Resistance thermometer bulb	Up to 1000	40–80
Indicator for resistance thermometer	Optional	80–150
Recorder for resistance thermometer	Optional	150–700
Platinum Pt. Rh. Couples	Up to 1600	10 and up
Base metal couples	Up to 1200	5–20
Milli voltmeter indicator	Optional	50–200
Milli voltmeter recorder	Optional	150–700
Potentiometer indicator	Optional	120–200
Potentiometer recorder	Optional	200–700

* As of 1920.

BIBLIOGRAPHY. — Burgess and Le Chatelier's *Measurement of High Temperatures*, N. Y., 1912. In this treatise will also be found a complete bibliography of the entire subject of pyrometry. See also *Symposium on Pyrometry*, Am. Inst. Min. and Met. Eng., 1920, and *Pyrometer Practice*, Bur. Stands. Tech. Paper No. 170.

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RADIO COMMUNICATION. — (*See also Alternating Currents; Capacity and Charging Currents; Electricity and Magnetism, Principles of; Electron Theory; Inductance and Inductive Reactance; Skin Effect; Transient Electric Phenomena.*)

RADIATION. — Whenever current flows in an ordinary electric circuit magnetic and electric fields are set up in and around the circuit; the magnetic field is proportional to the current flowing and the electric field is proportional to the difference in electric potential in various parts of the circuit.

These two fields represent a certain amount of energy stored in the space where they exist. The magnetic energy depends upon the self-inductance of the circuit and the current flowing, whereas the electric energy depends upon the capacity (electrostatic) of the parts of the circuit, considered as a condenser, and the potential difference. When the current or potential difference changes the energies change and, if the current and potential difference become zero, the greater part of the magnetic and electric energies are returned to the circuit.

When the current in the circuit is a low-frequency alternating current, practically all the energy which goes out into space is returned when the current and potential become zero. When the frequency is high (and strictly in every case irrespective of the frequency), part of the energy represented by the two fields, is sent out into space and never returns to the circuit. This energy is said to be radiated; as the radiated power varies (for a given circuit) as the square of the frequency, this action may be neglected in circuits where the frequency is less than several thousand; in radio circuits the frequency ranges from 20,000 to 1,000,000 or more, and at these high frequencies the radiated power may constitute the principal loss in the circuit.

ELECTROMAGNETIC WAVES. — The radiated energy travels in the form of electromagnetic waves; such a wave has half of its energy magnetic and half electric, and travels with the velocity of light. If the intensity of the magnetic field is H and that of the electric field is F (these two intensities being so related that magnetic and electric energies per unit volume are equal) the electromagnetic wave becomes self-sustaining by virtue of the fact that an electric field of intensity E travelling with the velocity of light generates at right angles to itself, and at right angles to the direction of wave motion, a magnetic field of intensity H; or conversely field H, travelling with the velocity of light sets up, at right angles to itself and the direction of motion, an electric field F.

The arrangement of electric and magnetic fields around a radiating antenna is indicated in Fig. 1, the magnetic field being shown by dots and the electric

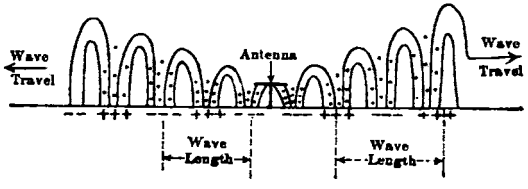


Fig. 1.

field by lines; this arrangement of fields is practically circular around the antenna. The "feet" of the waves slide over the earth's surface (this being considered a conductor) so that in the earth's surface there are around the antenna circular distributions of electric charges, alternately positive and nega-

tive, which bands of charge spread out from the antenna with the velocity of light.

Wave Length. — The waves of radiation travel out from the antenna at fixed velocity, so that the distance between the "feet" remains constant; the distance from a band of positive charge in the earth's surface to the next positive band is termed the wave length. In radio practice the wave lengths emitted vary from perhaps 50 meters to as much as 20,000 meters. The longer waves are used in the large stations engaged in transoceanic communication while the shorter may be used in aeroplane radio sets or in small portable field outfits. The standard wave length used for inter-ship communication is 600 meters; occasionally 300 and 450 meters are used in this work.

The wave length and frequency in any wave propagation are related by the equation $f\lambda = V$, in which f is the frequency, λ is the wave length, and V is the velocity of propagation. For any electromagnetic disturbance, whether light, heat, X rays or radio waves, the velocity of travel is 3×10^8 meters per second. Hence the wave length, in meters, is given by

$$\lambda = \frac{300,000,000}{f} \quad \text{meters.}$$

The frequency of currents used in radio antennæ lie between 15,000 for the very large stations and 2,000,000 for small portable sets. Ship sets nearly always use a frequency of 500,000 cycles per second.

Energy in Electromagnetic Wave. — If H is the intensity of the magnetic field in gilberts per cm. and F is the intensity of electric field in e.s. units (statvolts per cm.) at any point in the wave front, the energy per cu. cm., is

$$\frac{H^2}{8\pi} + \frac{F^2}{8\pi} = \frac{H^2}{4\pi} = \frac{F^2}{4\pi},$$

the two energies being equal.

As the two energies have a sinusoidal distribution in the wave disturbance, the average value of the energy density will be one-half the maximum density; if therefore F_m is the maximum electric gradiant in the wave front the average energy per cu. cm. is $\frac{F_m^2}{8\pi}$ ergs. The energy passing through one sq. cm. per second is therefore equal to $\frac{F_m^2}{8\pi} \times 3 \times 10^{10}$ ergs, or the radiated power associated with one sq. cm. of wave front is $\frac{3000}{8\pi} F_m^2$ watts. When the electric gradient F_m is measured in *volts per cm.* then

$$\text{Radiated power per sq. cm. of wave front} = \frac{F_m^2}{240\pi} \quad \text{watts.}$$

Form of Wave Front. — As the wave travels out from the antenna it gradually increases in height, as indicated in Fig. 1. If the surface of the earth is a good conductor the wave front remains upright; if the atmosphere is highly absorbing (ionization, etc.) the wave front tips backwards, whereas if the atmosphere is non-absorbing and the earth's surface is a poor conductor the wave front tips forwards.

It seems likely that the waves do not extend very high; in the upper rarified atmosphere the ionization is intense, so that the air becomes a fair conductor. Such a conducting layer of air will act as an upper boundary beyond which the waves are able to penetrate with difficulty. Radio communication may there-

fore be regarded as carried on by wave propagation between the earth's surface and this upper layer of conducting air.

Attenuation. — As the electromagnetic wave travels over the earth's surface, the intensity of both electric and magnetic fields continually diminish, due to two factors; the wave front becomes larger in area with increasing distance from the transmitting antenna, thus decreasing the energy density in the wave front, and there is also some energy absorbed in the atomosphere and the earth's surface as the wave progresses. Measurements of the attenuation are difficult to make, and experimental results on this effect are meagre. Duddell and Taylor, in 1905, reported the results of tests over comparatively short distances, and L. W. Austin has reported more extensive tests carried out in 1909. Duddell's results indicated that the field strength in the wave front varied inversely with the distance from the sending station, whereas Austin's experiments showed the field strength falling off more rapidly than this. He deduced from his results a formula which is now regarded as the best obtainable. It is

$$I_r = \frac{A}{d}\, \epsilon^{-\frac{ad}{\sqrt{\lambda}}},$$

in which I_r = current set up in the receiving antenna; d = distance between transmitting and receiving stations, in km., λ = wave length in km.; a = a constant, ordinarily equal to 0.0015; A = a constant, depending upon heights of the two antennæ, current in the transmitting antenna, etc.

The absorption constant, a, depends upon the amount of ionization present in the air, and condition of the surface over which the wave has travelled, etc. It is least for transmission over sea at night, and maximum in daytime over mountainous country thickly covered with vegetation.

Reflection and Refraction. — Radio waves reflect and refract in the same way as do light waves, allowance being made for the vast difference in wave length; to these two effects many vagaries in radio transmission are undoubtedly due. Thus two ships on opposite sides of a mountainous island are not able to communicate at all, yet if each steams away from the island, thus increasing the distance between them, the transmission becomes normal; such effects are noted by vessels off the shores of Cuba. This effect is probably due to peculiar reflections of the waves by the semi-conducting minerals in the hills over which the waves must travel in crossing the island.

In other cases a very small amount of power may suffice to establish communication over vast distances; it seems quite likely that the upper layers of partly ionized atmosphere concentrate the energy of the electromagnetic waves just as mirrors and lenses concentrate light waves. Of course such effects cannot be relied upon, but they do give at times "silent zones," where the signal disappears, and other zones where the signal may be much more intense than the transmitter power and distance would seem to justify.

Daily Variation in Transmission. — There is a very great difference in radio transmission at different times of day, especially if the line of communication runs east and west. This was first noticed at the Marconi stations at Glace Bay and Clifden. The transmission follows a curve about as shown in Fig. 2; when the line of sunset or sunrise was between the two stations the transmission was very poor. It seemed that the line of sunrise or sunset acted as a barrier across which the waves could not easily pass. This effect was more marked on short waves than on long ones, in fact transmission is always more uncertain on short waves than on long ones. Some exceptions to this have, however, been noted, such as those reported by Taylor and Blatterman, who found 500 meters better than 1500 meters in the night time, but not in the daytime.

The variation in signal strength at a receiving station may occur very suddenly, thus at Chelmsford the received current from Clifden would double in 5 minutes. Other instances are on record of even more rapid changes in signal strength, the transmitting station sending out a constant amount of power. Such effects are often spoken of as the " fading " of the signal.

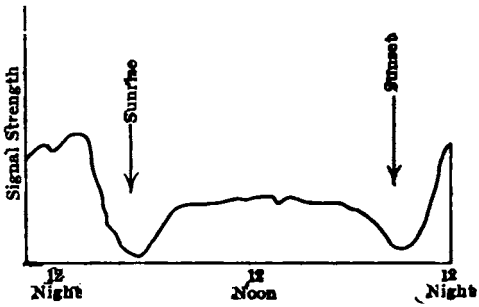


Fig. 2.

Seasonal Variation. — L. W. Austin has reported the results of a long series of tests of transmission over distances of about 100 miles, which show that there is a very large variation in the transmission throughout the year. The transmission was over land, with a wave length of 1000 meters. The average signal in the winter showed about 6 times as much energy as the average signal in summer.

Transmission through Water and Earth. — Calculation of the attenuation of an electromagnetic wave penetrating water would lead to the belief that the penetration can occur only with great loss, and such proves to be the case. The reception of radio signals by a submerged submarine is only possible if long waves are used, and suitable amplifiers are used with the receiving set. It is possible, however (with a good amplifier), for a submarine submerged 30 to 40 feet to detect signals from a long-wave, high-powered station thousands of miles away. Thus submarines on the Atlantic coast of the U. S. are able to pick up signals from Nauen, even though submerged.

Experiments have been reported of picking up radio signals with all the receiving apparatus at the bottom of a mine shaft, indicating that the waves penetrate a considerable distance into the earth's surface; not much reliable information on the subject is at hand.

ANTENNÆ. — The original experiments in radio transmission, by Hertz, used ungrounded sending and receiving systems; this is seldom the case in modern radio sets. Practically the only case of successful ungrounded transmitting antennæ is that of air craft. Attached to the upper plane is a network of wires and through the floor of the cockpit of the plane is suspended a wire generally having a weight on the end. This trailing wire and the network on the wing form the two parts of the antenna. Such antenna systems permit communication between two aeroplanes several miles apart, or between a plane and ground station perhaps 50 miles apart. As mentioned below, an ungrounded coil is often used for a receiving station, but practically never as a transmitting antenna.

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Grounded Antennæ. — In Marconi's first successful experiments a single vertical wire was used for antenna, the lower end being connected to ground through the spark gap, as shown in Fig. 3. The high voltage secondary of a spark coil was connected across the gap as indicated by the dotted line. When the coil was operating the antenna was charged to a high voltage by the opening of the interrupter in the primary circuit, thus storing energy in the electric field of the condenser formed by the wire *M* and the earth. When the voltage on *M* rose to a sufficient value, the spark gap broke down, and an oscillatory current was set up in the antenna, the frequency of this current being controlled by the height of the wire *M*. Such a form of antenna radiates very rapidly, so that the oscillatory current for each discharge of the spark gap is of very short duration, perhaps 5 or 10 cycles.

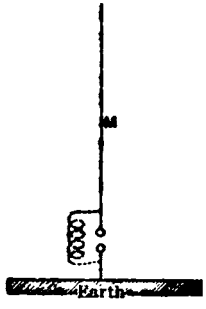


Fig. 3.

Forms of Voltage and Current Distribution. — When a charged antenna is left free to oscillate, the charge on the antenna so flows and rearranges itself that the intensities of potential and current at various parts of the wire follow approximately a sine law distribution. It is evident that in any case the potential of the antenna (with respect to earth) must be zero at the ground end and that the current in the antenna must be zero at the top, or end, of the antenna.

Typical forms of distribution are shown in Fig. 4. At (*a*) are shown the current and potential curves for a simple vertical wire, similar to the original Marconi antenna; such a condition is called *quarter wave length distribution* because one-quarter of a complete wave is developed for each of the curves. In (*b*) and (*c*) of Fig. 4 are shown the current and voltage forms when a series inductance has been introduced in the base of the antenna; (*b*) shows the effect for a small inductance and (*c*) that for a much larger one. Sometimes it is necessary to use a condenser in the base of the antenna, for which case the current and potential distributions are somewhat as shown in (*d*) Fig. 4. The node of voltage here shown is not a true node; the phase of the voltage does reverse on the two sides of the point, but the magnitude of the voltage does not go through zero.

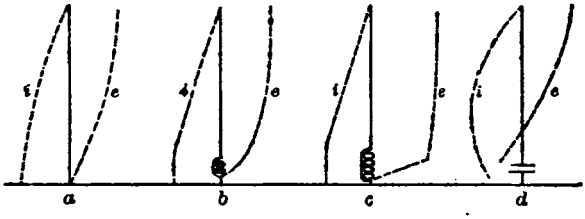


Fig. 4.

Forms of Antennæ. — There are three ordinary forms of transmitting antennæ, as illustrated in Figs. 5, 6, and 7. Fig. 5 represents a *T* antenna which is the type generally used for ship sets, because of the ease of erection from the two ship's masts. It is practically non-directive, sending about the same amount of radiated power in all directions.

The form of antenna shown in Fig. 6, called the inverted *L*, is used for stations

designed to communicate with a fixed receiving station; the large Marconi stations for transoceanic communication are of this type. In the largest stations these antenna may be as much as 500 feet high, 1000 feet wide, and more than a mile long.

High powered stations designed to communicate with stations in various directions, use an umbrella shaped antenna, Fig. 7. This type radiates equally well in all directions, and has the possible mechanical advantage of requiring but one mast. These tall masts are from 600 to 800 feet high, generally made of steel lattice construction. This mast may be in three or four sections jointed flexibly to one another, radial guys running out from these junction points. It is practice to insulate these masts from the ground, the base of the mast being supported on a marble ball, or similar construction. The guys of these high power stations are generally broken up into insulated sections, to keep the induced currents in them low.

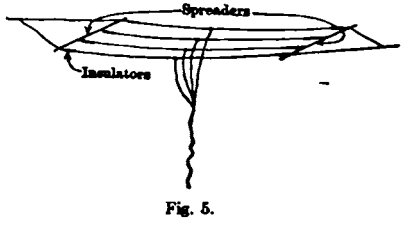


Fig. 5.

Receiving Antennæ. — A few years ago it was customary to use a large antenna for receiving, but to-day such is seldom the case. The present limit on radio reception is the amount of atmospheric disturbance present, this producing a hissing and crackling noise in the operator's telephones, so that the signal is blurred and unreadable. The large receiving antenna "picks up" a stronger signal than a small one, but it also picks up more of the atmospheric disturbances, so that a signal received on the small antenna, after being suitably amplified, is just as readable as that from the large antenna. In fact, with a properly designed amplifier, the signal is amplified more than the disturbing noises, so that the smaller antenna is actually more serviceable in receiving than the large one.

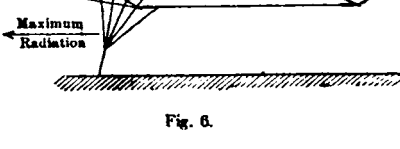


Fig. 6.

Coil Antenna. — The coil antenna is a special form of antenna which is never used for transmitting but which is very useful for receiving. It consists of a few turns (sometimes constructed as shown in Fig. 8) and the receiving apparatus is connected to the terminals *a* and *b*, there being no ground connection at all to the receiving circuit. Such a coil must be connected to a powerful amplifier if the

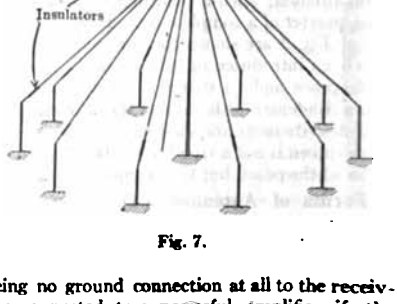


Fig. 7.

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signals to be received are from a distant station, as the coil picks up but little energy from the radio wave. The size of coil, as well as the number and spacing of turns, depends upon the wave length to be received; for 600 meters a coil 4 feet square of 12 turns spaced ¾ inch from each other is suitable, whereas for 10,000 meters a coil 20 feet square of 50 turns spaced 1½ inches is about right. The spacing between the turns must be kept sufficiently great, otherwise the capacity between the turns will be so high that tuning with an attached condenser will be poor; in fact if the turns are too close the natural period of the coil will be greater than that of the signalling current, and the reception will then be very poor.

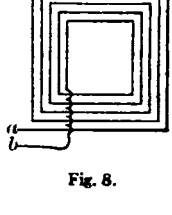


Fig. 8.

Ground Antenna. — A long insulated wire laid along the ground, or even better, at the bottom of a shallow body of water, forms a good receiving antenna, if it is opened at its middle point and the receiving apparatus connected in. The wire should be laid in the direction from which the desired signal comes, as this type of antenna is fairly directive. If laid in salt water the wire should not be covered more than a foot or two, whereas in fresh water the depth may be several feet, without too much attenuation of the signal.

Capacity of an Antenna. — The electrostatic capacity of an antenna depends upon the area covered by the net work of wires, and upon the height from ground, and to a lesser extent upon the size and number of wires used. For an antenna of the forms shown in Figs. 5 and 6, Austin has found the empirical formula,

$$C = \left(4\sqrt{a} + 0.885\,\frac{a}{h}\right) \times 10^{-5},$$

in which C = capacity in microfarads, a = area of the antenna (width of spreaders multiplied by the distance between them) in square meters; h = height of the antenna from ground, in meters. If the length, l, of the antenna is much greater than the width, b, the value of C must be multiplied by the factor $\left(1 + 0.015\,\frac{l}{b}\right)$.

The ordinary ship's antenna has a capacity * of about 0.001μf, a small one such as that carried by a submarine about 0.0005μf while those carried by the battleships may have as much as 0.003 μf. The large land stations may have a capacity of 0.01μf or more.

The capacity of an antenna, being distributed, is really a function of the frequency, but if the loading coil used has sufficient inductance to increase the wave length to about four times the natural wave length, the antenna capacity may be treated as lumped and thus independent of the frequency.

Wave-Length Radiated from an Antenna. — If the antenna is connected directly to the ground (no loading coil used), the wave length radiated is very closely 4 times the distance from the ground, up the lead wire (vertical part of the antenna) and so out to the extreme end of the antenna; actually it may be 10 per cent larger than this value. An antenna of the T-form, having a height of 50 meters, and a length of top part of 150 meters, would have a wave length about $4 \times \left(50 + \frac{150}{2}\right) \times 1.1 = 550$ meters. This would be called the "natural wave length" of the antenna. If the lead wire is now attached to the end of the

* The abreviation μf is used for microfarad.

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top part, thus making an inverted L antenna, the natural wave length would be $4 \times (50+150) \times 1.1 = 880$ meters.

Loading Coil and Condenser. — It is generally not feasible to use an antenna radiating its natural wave length; generally an antenna is worked at from 2 to 4 times its natural wave length. This is accomplished by putting a suitable inductance (called a loading coil) in the base of the antenna, thus increasing the inductance of the oscillating circuit over that inherent in the antenna itself. For such a case the wave length radiated from the antenna is easily calculated from the formula,

$$\lambda = 1885\sqrt{LC} \qquad \text{meters,}$$

in which L is the inductance of the coil in microhenries, and C is the capacity of the antenna in microfarads.

By putting a condenser in series with the base of the antenna, and using only a small loading coil (at least a small coil is nearly always necessary to the operation of the average set, as will appear later), it is possible to make the antenna radiate at less than its natural wave length; such operation is carried out only in emergencies.

Antenna Resistance. — It is impossible to measure the amount of high frequency power supplied to an antenna by a wattmeter or similar test; the power in the antenna is always calculated from the known resistance of the antenna and the reading of the hot wire ammeter in the antenna circuit. A knowledge of the antenna resistance is thus important; in fact it is probably the most important single factor in the whole radio system.

In Fig. 9 are shown two typical antenna resistance curves; that indicated by A being for a ship, and the other B for a land station, the two antenna being the same size; λ_0 indicates the natural wave length of the antennæ. The form of this curve is due to the various components which change in different ways as the wave length is increased. The *radiation resistance* varies inversely with λ^2, and the principle resistance causing loss of power, due to dielectric hysteresis in the earth's crust and objects in the electric field of the antenna, varies directly with the wave length. This wasteful resistance exists to a greater extent in a land station than in a ship station, hence the higher slope of the curve at the longer wave lengths.

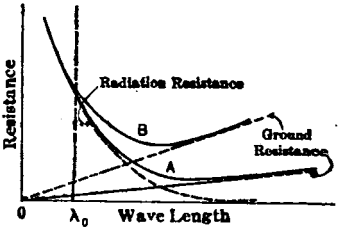


Fig. 9.

Importance of Good Ground. — With a well-grounded antenna at short wave lengths, the greater part of the energy supplied to the antenna is radiated, as indicated by the relative values of the ground resistance and radiation resistance in Fig. 9; at the longer wave lengths, however, the radiation resistance decreases very rapidly, and the ground resistance increases, so that most of the power supplied to the antenna is used up as heat and so wasted. It will thus be realized that the ground resistance must be kept low if the antenna is to be efficient. Elaborate networks of copper wire are often buried in the ground underneath an antenna, and heavy wires carried down to the permanently moist earth to minimize part of the ground resistance effect. From measurements made by J. M. Miller it would appear that wooden posts, trees, etc., close to an antenna absorb a great deal of power.

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Counterpoises. — Where a good ground connection is not possible, it is found that an insulated network of wires, suspended on insulators a few feet above the ground, serve well as a ground connection. The network should have a spread considerably greater in area than the antenna itself, if possible.

Radiation Resistance. — The radiation resistance of an antenna can be obtained from experimental observation, or it can be calculated from the dimensions of the antenna. Various formulæ have been given which differ somewhat among themselves, generally due to different assumptions as to what the height of the antenna is; some formulæ use the "effective" height and others use the actual height. The following formulæ have been given by J. H. Dellinger. For a flat top antenna, of height h,

$$R = \left(39.7 \frac{h}{\lambda}\right)^2 \text{ ohms.}$$

For a square coil of N turns, length of side, a,

$$R = \left(13.3 \frac{a}{\lambda}\right)^4 N^2 \text{ ohms.}$$

In these formulæ the dimensions must of course all be expressed in the same units.

From the above it is readily seen that a coil is not a good radiator unless its dimensions approach those of the ordinary antenna; it has been used successfully as a transmitter only for very short waves. The above formulæ also give an idea of the comparative amounts of energy the two types of aerial will pick up when used at a receiving station; they do not give an idea of the actual relative merits of the two, however, because the coil aerial may be made with a much lower resistance than the ordinary type, and hence will produce a greater relative response in the detecting device than would be indicated by the above formulæ.

The formulæ show that the maximum radiation resistance which a straight vertical grounded wire can have is about 50 ohms (the value of h/λ for quarter wave length oscillation is about 0.17) and this is the same for all vertical wire antennæ, no matter how high they may be.

VACUUM TUBES. — When a metal is heated to a high temperature in a vacuum it gives off free electrons, i.e., particles of negative electricity (*see article on Electron Theory*). When the heated metal is made one electrode, and a second unheated electrode is provided, it is found that the space between the two electrodes becomes a relative good conductor to a current flowing through the tube in the direction from the cold electrode to the hot electrode, but that practically no current will flow in the reverse direction. Such a device is therefore an almost perfect rectifier for alternating currents. The Fleming valve and G. E. kenotron are typical rectifiers of this type.

The electrode to be heated is usually made in the form of a filament, which is heated by sending a current through it from a storage battery or other source of e.m.f. The heated electrode is therefore usually referred to as the "filament" and the other electrode as the "plate." The current from the plate to the filament is called the plate current (and must not be confused with the current passed through the filament to heat it).

Space Charge. — Experiment justifies the assumption that for a given temperature of the filament, there is a definite rate at which electrons are given off, or evaporated, from it. When there is no potential difference established between the filament and plate (the plate and filament being insulated from each other), a condition of equilibrium is reached when the number of electrons

evaporated in a given time interval is exactly equal to the number of electrons which are forced back into the filament by the mutual repulsion between the electrons which fill the space in the tube. That is, the tube may be thought of as filled with a negative charge, exerting a pressure tending to prevent a further evaporation of electrons, just as the vapor in a closed vessel partially filled with water exerts a pressure on the water tending to prevent further evaporation of the water. This negative charge is conveniently referred to as the "space charge."

Two-Electrode Tubes. — When a difference of potential is established between the plate and the filament, the plate being the anode (positive), the electrons forming this space charge are attracted to the plate, pass through the external circuit and re-enter the filament, and are again evaporated. However, since for a given temperature there is a limit to the rate at which the electrons can be evaporated, it follows that when the potential difference between the plate and the filament is increased to such a value that the plate current is equal to the rate at which negative electricity is evaporated from the filament, then any further increase in this potential difference cannot produce an increase in the value of the current. This limitation to the value of the current is said to be caused by "saturation," and this limiting current is called the "saturation current" for the given filament temperature.

When the applied potential difference is small, and the resulting current is small relative to the rate of evaporation of the electrons, it can be deduced from fundamental principles that the resultant effect of the applied potential difference and the repulsive action of electrons forming the space charge is such as to give a current which depends solely on the applied potential difference and which is independent of the temperature of the filament. Under these conditions the current is said to be limited by the space charge.

Consequently, for high filament temperatures and low potential differences the plate current is the same irrespective of the temperature of the filament

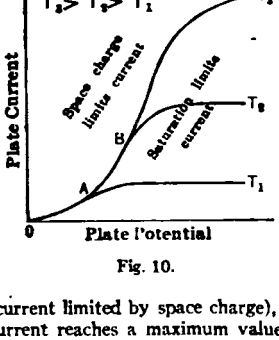


Fig. 10.

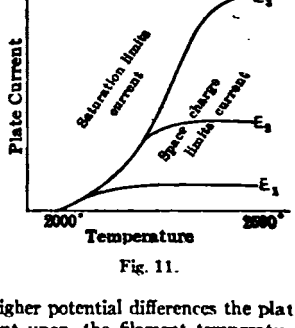


Fig. 11.

(current limited by space charge), but for higher potential differences the plate current reaches a maximum value dependent upon the filament temperature only (current limited by saturation); see Fig. 10. Or, looked at from another point of view, for high potential differences and low temperatures the plate current is the same irrespective of the potential difference (current limited by saturation), but for higher temperatures the plate current reaches a maximum value dependent upon the potential difference only (current limited by space charge); see Fig. 11.

The two electrode tube is not used to a great extent to-day; it may be used

as a rectifier in such installations as the Cottrell process for dust precipitation, and during the war was used to some extent as a voltage regulator for small self-excited, variable-speed generators. It seems likely that it may find further application in this field.

Three Electrode Tube, or Triode. — The thermionic tube becomes a much more effective device if a third electrode is interposed between the plate and filament, this electrode being in the form of a mesh or grid, so that electrons may flow through it on their way to the plate. Fig. 12 shows diagrammatically the construction of a triode. Such a tube was first put out by DeForest under the trade name of "Audion"; to-day many types of three electrode tubes are in use in both wire and radio comunication. Eccles has suggested the name "triode" for a three electrode functioning as a pure electron device, and such a name seems better than the various trade names now used. According to the service for which they are intended these triodes vary in size from a peanut to a bulb 8 inches in diameter or more; the plates and grids are flat in some and cylindrical in others; molybdenum, tungsten and nickel are all used for the construction of grids and plates.

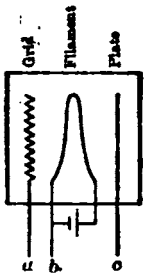


Fig. 12.

Uses of the Triode. — The triode is the most important factor in any radio system; it is only due to this device that radio has made such progeess during the last few years. It performs the functions of *rectifier*, or *detector*, in every modern receiving station; it is used singly, or several in cascade, as an *amplifier* of radio and other signals; it is used in small transmitting stations as a *converter* or generator of high-frequency power from a continuous current source; and in radio telephone outfits it is used extensively as a *modulator* of the radiated high-frequency power.

Action of the Grid. — The feature of fundamental importance in the triode is that under proper conditions a variation in the voltage between grid and filament will produce variations in the plate current *many times greater* than would be produced by equal variations in the voltage between the plate and filament.

The action of the triode is most easily explained by noting that the grid, situated in the space between the filament and the plate, may assist the space charge in limiting the plate current or may nullify the space charge effect and thereby increase the plate current, according as its potential is negative or positive. (In the literature on electron stream devices it is customary to speak of the plate and grid potentials with respect to the negative end of the filament.) The controlling action of the grid depends upon the fineness of its meshes, and upon how completely it surrounds the filament. According to Miller, the grid exerts more control the closer it is to the plate, other things being equal.

Characteristic Curves of the Triode. — In Fig. 13 are given typical curves of a triode showing how the plate and grid currents vary as the grid potential is varied, for several values E_1, E_2 and E_3 of plate potential. The source of the plate current is connected to c and b in Fig. 12, and the source of the grid current to a and b. For small detector tubes the plate current would be less than one milliampere and the grid current a few microamperes; for telephone repeater tubes, or for small power tubes for radio sets, the plate current is about 50 milliamperes; while for the largest power tubes the plate current

may be an ampere or more, the grid current being perhaps one hundredth as much.

It will be noticed in Fig. 13 that for a given grid potential the grid current increases as the plate potential decreases; this is due to the relatively greater

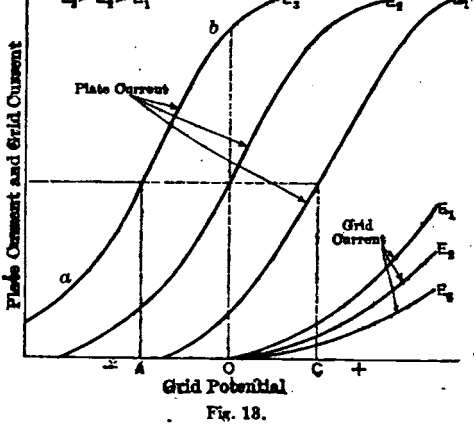


Fig. 18.

attractive force of the grid on the electrons passing through it, as the plate potential is lowered. For negative potentials the grid of an ordinary triode takes so little current that it requires a sensitive galvanometer to measure it.

The maximum plate current is nearly the same for all plate voltages, it requiring a higher positive grid to reach this maximum current, however, when the plate voltage is low. For very low plate voltage this maximum current is never reached; as the grid is made more and more positive it takes more current, thus depriving the plate of part of the electrons, and it may do this to such an extent that the plate current actually decreases with increasing grid potential, for the highest grid voltages.

Tungsten Filament and Oxide Coated Filaments. — In the U. S. practically all the triodes are manufactured either by the G. E. Co. or the W. E. Co. The G. E. tubes go by the trade names of kenotron, pliotron, dynatron, pliodynatron, etc. All of these G. E. tubes use a pure tungsten filament as the electron-emitting element, and tungsten or molybdenum for the grids and plates; the tungsten filament must be at a dazzling white heat before much electron emission occurs and so, of course, considerable power must be used in heating the filament.

For the tungsten filaments Dushman has given the following table of safe operating temperatures, etc., the life of the filament being supposedly 2000 hours.

To get the emission stated in this table the surface of the tungsten must be very clean; there must be no adsorbed gas on the surface.

The tubes made by the W. E. Co. use a platinum ribbon filament coated with certain oxides, a particular cement being used to hold the oxide on; to assist in holding the coating the ribbon is twisted on itself several times per centimeter. The type of emitting surface is frequently called a Wehnelt cathode, as Wehnelt first pointed out the use of the oxide to get more emission

Diameter of filament, cm.	Safe temperature, absolute °C.	Emission in amperes per cm. length	Power to heat filament in watts per cm. length
0.0125	2475	0.03	3.1
0.0175	2500	0.05	4.6
0.0250	2550	0.10	7.2
0.0375	2575	0.20	11.3

at a given temperature. Ordinarily about one milligram of coating is used per square centimeter, but recent experiments seem to indicate that this is much more than necessary.

The advantage of the oxide coated filament is the low temperature at which liberal emission occurs; for a given emission per square centimeter the power required to heat an oxide filament is only about one-half as much as for the pure tungsten filament. An oxide filament is never operated hotter than a bright yellow color; quite appreciable emission occurs when the filament is scarcely visibly hot. The only apparent disadvantage of the oxide filament is the difficulty with which very high vacuum is obtained in the tube without spoiling the filament.

Effect of Gas in a Tube. — An electron tube must be freed from gas sufficiently well to make its characteristic curves permanent and reproducible; if appreciable gas is present in the tube this is not so. All sorts of eccentricities were noted in the early, poorly evacuated audions, so that their inventor, DeForest, regarded their action as very mysterious. It is now known that all these peculiarities were due to the kind and amount of residual gas in the tube, and its effect upon the emission of electrons, as well as certain effects produced by ionization of these gases. Certain gases, such as argon, mercury vapor, hydrogen, etc., have very little effect on the electron emission from tungsten, but oxygen or water vapor (in pressures as low as 10^{-6} mm. of Hg) have a marked effect, much reducing the emission. Water vapor may be absorbed in the glass walls of the tube; heating the glass slightly will release this water vapor and it attacks the surface of the filament, changing the emission as much as 10 times when heating the walls only 10 degrees. Mercury vapor as high as 10^{-1} mm. has scarcely any effect on the emission. The best work on the effect of various problems connected with electron emission has been done by Langmuir, who was the first to produce the tube with very pure tungsten parts and very high vacua.

In detector tubes the effect of a slight amount of gas is unimportant; if ionisation occurs to an extent sufficient to show the characteristic blue glow, the plate voltage should be reduced until the glow disappears and the tube will generally function as well as before.

In a modern tube there is not sufficient gas to make it erratic in its action. The presence of a gas may be detected by determining the grid current vs. grid potential curve. If such a curve shows an appreciable grid current with reversed grid potential (grid negative with respect to the negative end of filament), it may be concluded that a gas is present.

Amplification Factor of a Triode. — As shown in Fig. 13 the plate current depends upon both the plate and grid potentials. For the working range of the tube, the plate current is a function of the sum of the plate voltage E_p and the product of the grid voltage E_g and a factor greater than unity, i.e., the plate current is a function of $(E_p+\mu_0 E_g)$, where μ_0 is a factor greater

than 1. This factor μ_0, which expresses the relative value of E_g and E_p in controlling the plate current, is called the voltage amplification factor of the tube; it is nearly constant throughout the working range of the tube but does depend to some extent upon the filament current and plate and grid potentials. It is greater the finer the grid mesh and in actual tubes may have a value between 1 to 2 (old DeForest audions) to as much as 200. The ordinary value of μ_0 lies between 3 and 40, the latter value being infrequent. The ordinary detecting and amplifying tube used so much at present has a μ_0 of about 7.

Langmuir has expressed the relation between the plate current and the plate and grid potentials by the equation,

$$I_p = A(E_p + \mu_0 E_g)^{3/2},$$

where A is a constant. Van der Bijl, to whom is largely due the development of the W. E. tubes, gives the relation,

$$I_p = A(E_p + \mu_0 E_g + e)^2,$$

where e is a small quantity determined by the surface characteristics of the three electrodes in the tube (called the contact difference of potential), and other factors. Actually, the exponent of the term in the parentheses is neither 3/2 nor 2, but is a variable depending upon the grid and plate voltages.

For small changes in plate current, as occur in the ordinary amplifier circuit the relations of current and potentials may be written,

$$\Delta I_p = K(\Delta E_p + \mu_0 \Delta E_g),$$

where K is a constant. This relation was first given by Latour. This equation is the one on which practically all tube theory is based; it is not correct for detection, as it neglects the factor upon which detection depends. It also leads to certain vague conclusions when dealing with triodes as power converters.

Internal Resistance of Tube. — The circuit to which a tube is connected should always be designed to fit the tube resistance. There are two internal resistances which control the design of the connected circuits, viz., the resistance from the grid to the filament (input circuit), and the resistance from the plate to the filament (output circuit). The input circuit resistance is in nearly all cases very high; if the grid is maintained at some negative potential, as is generally the case, the input circuit may be treated as though it had infinite resistance, except when used with very high frequency, in which case the capacity of the input circuit may be of importance.

The resistance of the output circuit varies with the type of triode and with the voltage used in the plate and grid circuits; it generally lies between 5000 and 100,000 ohms for tubes used to-day. The continuous-current resistance is seldom of importance, the alternating-current resistance being the factor, knowledge of which is necessary. This a-c. resistance is about one-half the c-c. resistance. The c-c. resistance is given by the relation,

$$R_c = \frac{E_p + \mu_0 E_g}{I_p}.$$

The a-c. resistance is,

$$R_a = \frac{\Delta E_p}{\Delta I_p},$$

when E_g is held constant.

Triode as a Converter from C-c. to A-c. — Innumerable circuits have been devised for making the triode function as a converter of c-c. power

to a-c. power, one of the simplest being that shown in Fig. 14. The filament is heated by battery A and the plate voltage furnished by generator B; a condenser C serves as a by-pass for the high-frequency fluctuations in the plate current which occur as soon as the triode starts to function. The coil L_1 and condenser C_1 form an oscillatory circuit of resistance R. The grid is connected to the negative end of the filament through an inductance L_2, which is coupled magnetically to L_1, the mutual induction being indicated by M.

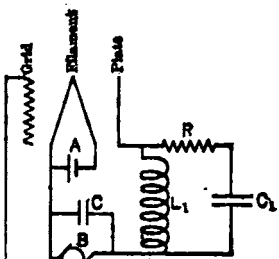


Fig. 14.

When certain conditions have been satisfied the combination will generate alternating current in circuit $L_1 - C_1$, the frequency of the current being fixed by the natural period of this circuit. The plate current itself fluctuates from zero to twice its normal value and in the $L_1 - C_1$ circuit the magnitude of current is limited (in a suitably designed circuit) only by the resistance R. It is to be noted that C_1 and R might be the capacity and resistance of an ordinary antenna.

The required conditions for producing oscillations in the oscillatory circuit may be found by assuming a damped oscillatory current to flow in the circuit, and solve for the condition which gives a damping factor of zero; such a condition means of course the continuous generation of alternating current in this circuit. It may be proved in this manner that the condition for oscillations being maintained by the triode is given by the inequality:

$$M \text{ negative and greater in magnitude than } \frac{1}{\mu_0}(L_1 + CRR_p),$$

where R_p is the alternating current resistance of the plate-filament circuit. The required negative value of M means that the coils L_1 and L_2 must be so related that when the plate voltage rises the action of L_1 on L_2 is to make the grid potential fall, in other words, that as the circuit is in oscillation the plate and grid voltages must have opposite polarities with respect to the filament.

Power Obtainable from a Triode Converter. — A triode is rated in terms of the power safely dissipated by the plate; if this is too much the plate overheats, drives gas out from itself, and so the vacuum is spoiled. With ordinary adjustments of circuits the amount of power obtainable in the form of alternating-current power is about the same as the safe rating of the plate. For this condition the efficiency of the converter is 50 per cent, neglecting the amount of power required to heat the filament. With suitably designed circuits, however, and with sufficiently high voltage on the plate (that is, high voltage generator in the plate circuit), it is possible to get from the tube about four times as much power as the plate is rated to stand. For such an efficiency the plate circuit generator must be a 2500 volt machine or more.

Triode as Amplifier. — The equation for the plate current of a triode shows that the grid is μ_0 times as effective in controlling this current as is the plate voltage itself. For small changes in grid and plate potentials the change in plate current may be written,

$$\Delta I_p = \frac{1}{R_p}(\Delta E_p + \mu_0 \Delta E_g).$$

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From this it is seen that the change in plate current for an increment in grid potential is as large as if the grid potential had been held constant and an increment of voltage change in the plate voltage μ_0 times as large were introduced, so that an alternating e.m.f., E_g, introduced in the grid circuit (input circuit) may be regarded, in so far as effect on plate current is concerned, as the equal of a voltage $\mu_0 E_g$ introduced in the plate circuit.

Neglecting the continuous components of voltages and currents in the tube circuits, and dealing only with the alternating components (r.m.s. values), for a voltage of E_g in the grid circuit there is produced in the plate circuit a current

$$I_p = \frac{\mu_0 E_g}{R_p},$$

in which R_p is the a-c. resistance of the plate circuit of the triode. If an external resistance R is introduced in the plate circuit as indicated in Fig. 15 (heating battery and plate battery left out as they play no part in the a-c. laws), there are in the plate circuit two resistances in series and the equation for plate current becomes,

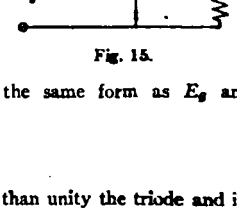


Fig. 15.

$$I_p = \frac{\mu_0 E_g}{R_p + R}.$$

I_p will of course be an alternating current of the same form as E_g (if the distorting effects of the variable R_p are neglected) so that the drop across the external resistance R is of the same form as E_g and equal to

$$E_g \times \frac{\mu_0 R}{R_p + R}.$$

Evidently if the fraction $\mu_0 R/(R_p+R)$ is greater than unity the triode and its attached circuit constitute a voltage amplifier, giving across R a voltage similar in form to E_g, and in practice from 2 to 20 times as large.

In case a reactance is used in place of R, the feasible amplification is somewhat more. Neglecting the resistance of the reactance introduced in the plate circuit, the amplified voltage across the reactance is,

$$E_g \times \frac{\mu_0 X}{\sqrt{X^2 + R_p^2}}.$$

If X is two or three times as large as R_p the amplified voltage will be sensibly μ_0 times as large as the input voltage.

Instead of inserting a reactance coil in the plate circuit the primary of a suitably designed transformer may be used. Such a transformer is generally built with a step-up ratio of about 5, so that the possible amplification is thereby increased. These repeating transformers must be built with a very large number of turns to match the resistance of the ordinary amplifying tube; and further, the natural period of the secondary must be kept much lower than that of any frequency to be amplified. It is this fact which keeps down the useful step-up ratio. If the transformer has a ratio of 5 the maximum obtainable amplification of the triode and attached transformer is equal to $\frac{5}{2}\mu_0$.

The output voltage of one triode may be impressed on the input circuit of another triode similarly arranged and the output of this triode impressed on the input of a third, etc. Thus if each stage of amplification (triode and attached circuits) gives a voltage amplification of A, and x stages are used, the theoretical

amplification is A^3 times in voltage. In practice a voltage amplification of 5000 is possible but seldom used; the amplifier tends to become unstable, and special precautions must be observed in using it if the amplification is more than about 500.

In Fig. 16 is shown a three-stage resistance coupled amplifier using common batteries for all filaments and plates; in this type of circuit the grid of each

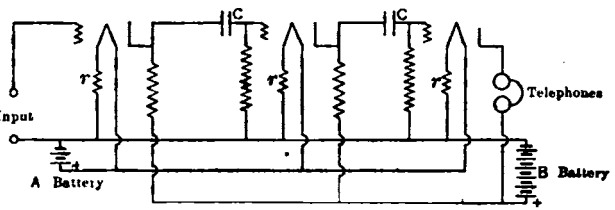


Fig. 16.

triode must be insulated from the plate circuit of the preceding one to prevent the high plate voltage from being impressed on the grid. This is the function of the condensers C, C, etc. The small resistances r, r, inserted in the negative leg of the filament serve to keep the average potential of the grids negative with respect to all parts of the filament, a necessary condition for efficient amplification.

In Fig. 17 is shown a three-stage transformer coupled amplifier. With tubes having μ_0 of 7 and transformers having a 5 : 1 step-up ratio three stages is all

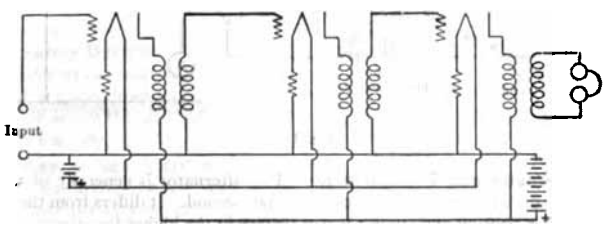


Fig. 17.

that could be used without the amplifier being very noisy and possibly not at all workable.

A regenerative coupling is possible and sometimes used with resistance coupled amplifiers; a small variable condenser serves to connect (electrostatically) the last plate to either the grid or plate of the first tube, thus tending to make the effective resistance of the amplifier as a whole zero, that is, tending towards infinite amplification.

DAMPED-WAVE TELEGRAPHY OR SPARK TELEGRAPHY.—Up to about 1915, spark telegraphy was the nearly universal method of carrying on radio communication; it is rapidly being superseded by continuous, or undamped, wave telegraphy, because of greater distance obtainable, more freedom from interference, etc. If seems likely that within a few years spark telegraphy will be done away with entirely. At present most of the radio

stations in the world still use the damped wave system; especially is this true of the smaller stations such as those on board ship. A knowledge of the function and operation of a spark station is therefore still essential.

In brief, this system comprises a source of power (generally a motor-driven alternator and step-up transformer to get a power supply of about 15,000 volts; suitable condensers are charged to this high voltage and then are discharged through a few microhenries of inductance, by the breaking down of a spark-gap in the circuit. This discharge is oscillatory, of frequency fixed by the inductance and capacity used. This oscillatory circuit is magnetically coupled to the antenna, and so a high-frequency oscillation is induced in the antenna for every break down of the spark-gap. The average set permits about 1000 sparks a second; therefore 1000 damped, high-frequency wave trains are emitted from the antenna per second.

At the receiving station the circuit is so arranged that the listening operator's telephone is actuated by one pulse of current per wave train arriving at the antenna. Thus the phone diaphram is impulsed 1000 times per second, so that the operator hears a musical note as long as the transmitting station is sending.

Typical Transmitting Circuit and Function of Parts. — In Fig. 18 is shown the general layout of a spark transmitter.

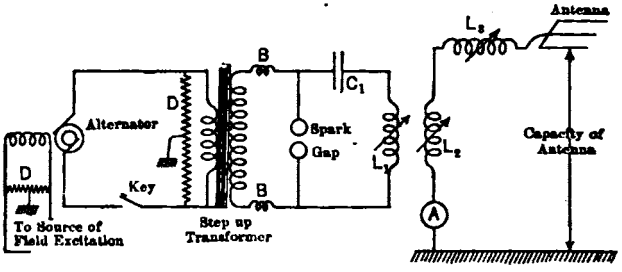


Fig. 18.

Alternator and Transformer. — The alternator is generally of the inductor type giving a frequency of 500 cycles per second. It differs from the small alternator for lighting and similar power service in the higher frequency and the very high internal impedance of its armature windings; the short-circuit current of a radio alternator is only slightly in excess of the full-load current. The step-up transformer is of the open or closed core type, more modern sets having the closed core; it steps the voltage up from perhaps 125 to 15,000 volts. *B–B* are high frequency choke coils (generally built in with the transformer) to keep the high-frequency currents from penetrating the secondary winding and breaking down the insulation.

Spark Gap. — The spark gap may consist of a couple of discs of non-arcing metal, such as zinc, but, because of the noise and difficulty of maintaining the adjustment of this type of gap, as well as the bad quality of signal radiated, such a gap is seldom used except in emergency sets.

A rotating disc, having studs mounted on its periphery which come close to a couple of stationary studs as the disc revolves, is more often used; it is called a rotating gap. If the rotating studs come in proximity to the stationary studs (so that a spark may pass) once per alternation of the power supply it is called a rotating synchronous gap; otherwise it is called a rotating non-synchronous

gap. The synchronous gap is used more often than the non-synchronous, the rotating disc being mounted on the end of the alternator shaft, thus ensuring synchronism. The disc is so shaped that as it rotates it plays a blast of air on the stationary studs to keep them cool. The U. S. Government station at Arlington from which standard time signals are sent out, uses this type of gap.

Condensers. — C consists of either copper plated glass jars or mica condensers, the latter gradually replacing the jars because of less dielectric loss, more compact structure, and less likelihood of breaking. The copper-plated jars were made of standard size, having 0.002 microfarad capacity. A 1000-cycle spark set requires four of these jars per kw. rated capacity. The mica a-c. condensers are made more generally in units of 0.004 microfarad.

In order to obtain uniform sparking of a set, the reactance of the alternator armature plus the leakage reactance of the transformer must constitute, with condenser C, a resonant circuit the frequency of which is about 20 per cent lower than the frequency generated by the alternator. In calculating this effect the transformer inductance and condenser capacity must be suitably changed to reduce the circuit to a 1–1 transformer condition.

Oscillation Transformer and Loading Coil. — The two coils L_1 and L_2 placed in proximity to each other constitute the oscillation transformer; the coil L_1 in combination with condenser C and spark gap make up the closed oscillatory circuit and fix the frequency sent out. The extra coil in the antenna circuit L_3 is called the antenna loading coil. All of these coils L_1, L_2, and L_3, as well as the mutual inductance between L_1 and L_2 are generally variable either by sliding contacts or taps.

Ammeter. — In the base of the antenna, just where it connects to ground, is placed a hot wire ammeter A to indicate the amount of current flowing in the antenna circuit. For measuring these high-frequency currents in radio circuits only two types of ammeter are available, the hot-wire type and the thermocouple and c-c. millivoltmeter type.

Safety Devices. — Various safety devices consisting of high resistances and condensers are placed across the low-voltage lines to keep any high-frequency induced voltages from damaging the insulation of field, armature, etc. A high resistance across the alternator terminals, grounded at its middle point, is shown at D, in Fig. 18.

Key. — Signals are sent in the form of dots and dashes (Continental Morse; see article on *Telegraphy*) by suitably manipulating the key in the transformer primary circuit. In the case of a high-powered station, or station using distant control, this key is of the relay type. Sometimes multiple relays are used putting several gaps in series. The spark gap and relay key are the two parts of a spark transmitter which require the most attention to maintain.

Coefficient of Coupling. — The closed oscillating circuit L_1–C is coupled to the open oscillating circuit (the antenna) by the mutual inductance between L_1 and L_2. The coefficient of coupling of the two circuits is given by

$$k = \frac{M}{\sqrt{L_1(L_2+L_3)}}.$$

The permissible value of k varies from perhaps 10 per cent in a rotating gap to 20–25 per cent with a quenched gap (described below).

Wave-Length Radiated. — Were the circuit L_1–C of Fig. 18, not influenced by the circuit L_2–L_3, it would oscillate at a frequency fixed by the formula,

$$f = \frac{1}{2\pi\sqrt{L_1C}},$$

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where L_1 and C are expressed in henries and farads. When L_1 and C are expressed in microhenries and microfarads, this formula becomes

$$f = \frac{10^6}{2\pi\sqrt{L_1 C}}.$$

The corresponding wave-length is then

$$\lambda = 1885\sqrt{L_1 C} \qquad \text{meters},$$

when L_1 and C are expressed in microhenries and microfarads.

In the operation of a set it is necessary to make the natural period of the antenna circuit the same as that of the closed circuit; this is called *tuning* the two circuits. If this has been done it might be supposed that the wave-length radiated from the antenna would be given by the formula $\lambda = 1885\sqrt{L_1 C}$, but actually such is not the case. By use of a wave meter (described later) it is found that two separate wave-lengths are radiated simultaneously and neither one of them is the same as that expected, one being higher and the other lower. Investigation shows that the values of these two wave-lengths depends upon the coupling, and exact analysis predicts that the wave-lengths should be given by the relations,

$$\lambda' = \lambda\sqrt{1+k},$$
$$\lambda'' = \lambda\sqrt{1-k},$$

in which λ' and λ'' are the two radiated waves and λ is the wave-length for which each of the circuits is turned, and k is the coefficient of coupling. Thus a set tuned for 600 meters in both the closed and in the open oscillating circuits, and having a coupling coefficient of 20 per cent, would radiate simultaneously 657 meters and 536 meters.

Quenched Gap.—Elimination of the Double-Wave Radiation.—The two waves are generated because the transmitting system comprises two more or less independent oscillatory circuits; such a combination will always have two natural periods, and will oscillate at both of them at the same time. The high-frequency energy is first resident in the closed circuit, then by coupling in the oscillation transformer it is transferred to the open circuit, and then again flows back to the closed circuit, and continues this to and fro flow until all the energy is used up, as heat or otherwise. The forms of currents in the two circuits for such a state of affairs are shown in Fig. 19; such a "beating" current is actually made up of two currents of different frequencies.

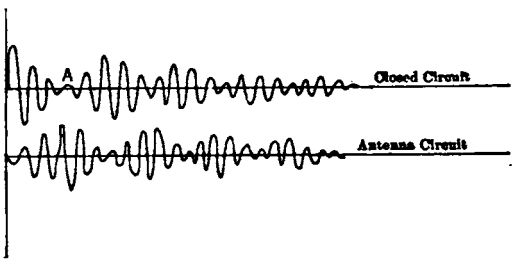


Fig. 19.

At time *A*, Fig. 19, all the energy has left the closed circuit and is in the antenna circuit; if, at this time the circuit L_1–C should be opened the energy

could not get back into the closed circuit and the antenna would be left free to oscillate at its own natural frequency, and but one wave will be radiated; such an occurrence is shown in Fig. 20. The time available for opening the circuit L_1–C is so short as to make a mechanical break impossible; by suitably designing the spark gap, however, the deionization of the gap, which can take place

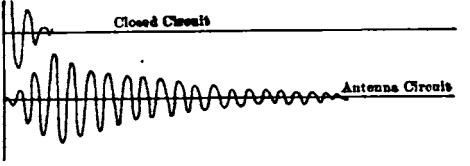


Fig. 20.

in perhaps 10^{-6} seconds, serves as a switch to open the circuit at the proper time, and so perform the required operation of preventing the two waves being formed.

A gap built suitably to accomplish this result is called a "quenched" gap; it consists of an assembly of very short gaps connected in series, each gap not more than about 0.02 cm. long. It is generally made up of a series of copper discs, separated by suitable insulating washers, or gaskets, so that the spark takes place in an air tight cavity. Two sections of such a gap are illustrated in Fig. 21; the sparking surface is of electrolytic copper or silver, let into the faces of the cast copper discs. Ten or fifteen of these discs are clamped together in a frame work of insulated construction to form the ordinary quenched gap. As many of the gaps as desired can be used by clip connections on the flanges. An air blast from a small fan serves to keep the gap cool, the air circulating around the flanges. Small gaps may have liberally designed cooling flanges and so be self-cooled; such a type of gap is used in ½ kw. sets and smaller.

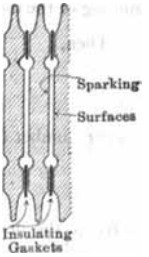


Fig. 21.

To maintain the quenching action the insulating gaskets must be made air tight, so after the oxygen, originally in the sparking cavity when the gap is assembled, is once burned out, no more oxygen can get in. If it does, an oxide layer of increasing thickness forms on the sparking surfaces and the gap ceases to quench.

Decrement. — Number of Waves in a Train. — After the circuit L_1C opens, the current in the antenna (Fig. 20) dies away, as the energy is radiated and wasted as heat, the decay being in accordance with the exponential law. The antenna current, after the gap has opened the closed oscillating circuit is of the form,

$$i = I_0 \epsilon^{-\alpha t} \sin \omega t,$$

in which I_0 is slightly larger than the highest current actually occurring in the antenna; it is equal to the actual maximum current multiplied by $\epsilon^{\frac{\alpha T}{4}}$, where T is the natural period of the antenna circuit. The constant α, called the damping constant, has the value,

$$\alpha = \frac{R}{2L}.$$

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The constant ω, called the angular frequency, has the value

$$\omega = 2\pi f = \frac{1}{\sqrt{(L_1+L_2)C}},$$

where C is the capacity of the antenna.

The current may also be written,

$$i = I_0 \epsilon^{-n\delta} \sin \omega t,$$

where

$$\delta = \frac{\alpha}{f},$$

and

$$n = ft = \frac{t}{T}.$$

The quantity n is the number of complete periods or oscillations in the time t. The constant δ is called the "decrement" of the wave train, and is equal to the logarithm (to the base ϵ) of two successive maxima of current, in the same direction, the ratio being taken greater than unity.

The decrement of a spark station is a very important characteristic; if it is too high the transmitting station causes too much interference with other stations in the vicinity. The upper permissible value of the decrement is fixed by law as 0.2; in a good average spark station it is about 0.1, and in the very large stations it may be as low as 0.02–0.03.

In radio theory it is practice to regard a wave train as ended when the current has decayed to 1 per cent of its original value. Let I_N be the current at the beginning of the oscillation for which the current has a maximum value equal to $\frac{I_0}{100}$. Then,

$$I_N = \frac{I_0}{100} = I_0 \epsilon^{-(N-1)\delta}.$$

Then the number of waves in the train is,

$$N = \frac{4.60 + \delta}{\delta}.$$

The larger the decrement the fewer the waves in the train; e.g., for $\delta = 0.2$, $N = 24$, and for $\delta = 0.02$, $N = 231$.

Adjustment of a Transmitting Set. — With the spark gap set to discharge at about one-half normal voltage, and with the antenna circuit open, L_1 is varied until the L_1–C circuit is generating the desired wave-length, as indicated by a wave meter (described later) held near L_1. Then with the coupling between L_1 and L_2 very weak the antenna circuit is closed and, with medium value of L_2 connected in the circuit, L_2 is varied until the antenna ammeter indicates maximum current; the antenna is then tuned to the closed circuit, which is generating the desired wave-length. The coupling between L_1 and L_2 should be now increased and the indication of the antenna ammeter noted; this reading will increase rapidly at first (with increasing coupling) and then will increase more slowly. The coupling should not be increased past the point where the rapid increase in antenna current ceases. In case a quenched gap is used the coupling may be increased until, after the current has increased with coupling, it shows a slight decrease with further increase in coupling; the coupling should be left slightly less than that value which shows the decrease in antenna current.

If this procedure is followed, but one wave will be radiated, whereas if tighter

coupling is used the ammeter in the antenna will (or may) show more current yet *the radiation at the desired wave-length will actually be less.* If too loose coupling is used the set is inefficient, too much of the high-frequency power being used up in heating the closed oscillating circuit, especially the spark gap.

To vary the power output of the set the gap should be changed in length (or, if a quenched gap, the number of active sections reduced), and the field excitation of the alternator suitably reduced to keep the musical note of the set constant. If too much or too little voltage is used with a given length of gap, the note of the set will change from its normal quality, too little voltage dropping the note an octave or two and too much voltage making the note impure, due to several discharges of the condenser per cycle, instead of two, the proper number.

Receiving Circuit. — Fig. 22 shows a typical receiving circuit; the antenna circuit is tuned by the variation of L_2 and L_3 and the closed oscillating circuit by varying the condenser C_1. It will be noted that there are the same elements in this receiving circuit as there are in the spark-transmitting circuit; the receiving coils and condensers, however, are of much lighter construction than the same parts of the transmitting set, because of the very small currents in the receiving system. In the transmitting station the currents are measured in amperes and potentials in kilovolts, whereas in the receiving system the potentials are less than a volt and the currents measurable in microamperes.

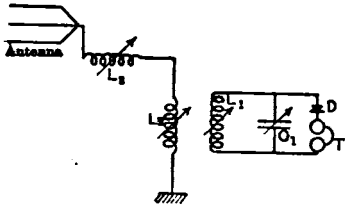


Fig. 22.

Across the tuning condenser C_1 is shunted a pair of head phones in series with some sort of rectifying device. When the two circuits are properly tuned to an incoming signal a musical note is heard in the phones, the pitch being fixed by the number of sparks per second of the transmitting station. The following procedure is followed in tuning the receiving circuit. With the condenser C_1 set at a low value and tight coupling between L_2 and L_1, the tuning of the antenna circuit is varied until the signal is heard; then, with decreased coupling between L_1 and L_2, C_1 is varied until maximum signal is heard. Because of the effect of one circuit on the other, as the coupling is weakened, both circuits must be slightly retuned. Having both circuits properly tuned it will be found that a certain value of coupling gives maximum signal strength; this will generally be quite loose coupling, depending somewhat upon the type of rectifier used and the decrement of the incoming wave.

The sharpness of tuning depends upon three factors, the decrement of the transmitting station, decrement of the receiving station, and the amount of coupling used in the receiving circuit, an increase of any one of these factors generally increasing the broadness of the resonance curve. As coupling is decreased from a high value the tuning increases in sharpness until a certain critical coupling is reached; further decrease in the coupling decrease the signal strength but does not increase the sharpness of tuning.

Rectifier or Detector. — The incoming wave train sets up oscillatory currents, of radio frequency, in circuit L_1–C_1; if the telephone were connected directly across C_1 nothing would be heard, because neither the phones nor the ear can respond to a radio-frequency current. By interposing the detector D,

which permits the passage of current more readily in one direction than in the other, the telephone diaphragm is impulsed in one direction (either in or out) for *each wave train in the receiving circuit*, thus giving a note in the telephone fixed by the number of sparks at the transmitting station; this note, it must be noticed, is entirely independent of the frequency of the radio current, that is, of the wave length used.

Crystal Rectifiers were used almost exclusively as detectors up to a few years ago, but since then the three-electrode vacuum tube (triode) has gradually displaced them, until to-day crystal detectors are used only in second-class outfits. Typical curves of carborundum and galena, two of the widely used crystals, are shown in Fig. 23. The rectifying effect depends upon the sharpness of curvature of the volt-ampere characteristic, so that carborundum was generally used, with a polarizing battery of voltage equal to *O–A* (Fig. 23) for best results. The crystals were generally used by casting them into a metal box by a low-melting alloy, such as Wood's metal, and making the top contact to a sensitive surface of the crystal by means of a finely pointed spring wire, sometimes called a "cat's whisker." Sometimes the rectifying contact was obtained by using two crystals touching one another, such as zincite and chalco-pyrite. In general the more sensitive the crystal rectifier the more easily it gets out of adjustment, or is spoiled at that one contact point by a very intense signal or atmospheric discharge.

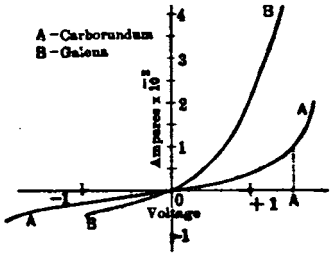


Fig. 23.

Triode as Detector. — The triode is immeasurably superior to the crystal detector, due to its reliability and still more to the possibility of suitably arranging the circuits attached to it to magnify the signal strength. The normal connection of the triode as a detector is shown in Fig. 24; with the connection as given by the full lines the triode is about 5 times as sensitive as an ordinary crystal. But if the plate circuit is opened at *X* and the coil L_4 inserted as indicated by the dotted lines, the signal strength may be amplified hundreds of times by the so called "regenerative action" (due to Armstrong). As the coupling between L_1 and L_4 is increased, the signal increases in strength about as indicated in Fig. 25. Beyond a certain value of coupling, the musical quality of the signal disappears and the signal becomes "mushy" or scratchy in sound, although very loud; this region is indicated in Fig. 25 by the dotted portion of the curve. With the critical value of coupling (*O–A* in Fig. 25), signals

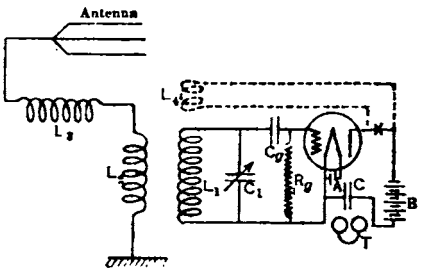


Fig. 24.

which are entirely inaudible with slightly less coupling become quite loud and readable, although not of musical quality.

The coupling between L_1 and L_4 (if of right polarity), tends to produce oscillations in the L_1–C_1 circuit, as pointed out in the section on triodes; in the region shown by the dotted line in Fig. 25 the tube is oscillating and the scratchy quality of the note is due to the irregular interfering action of the continuous oscillations in the L_1–C_1 circuit, and the damped-wave signals induced in this circuit by the signals received by the antenna.

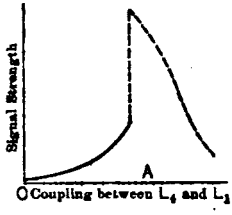


Fig. 25.

With slightly less than the critical coupling between L_1 and L_4 the decrement of the complete receiving circuit approaches zero, thus very much increasing the selectivity, or sharpness of resonance of the set; the tuning in this condition is limited in sharpness only by the decrement of the transmitting set.

A normal value of the grid condenser C_g of Fig. 24 is about 200 micro-microfarads, of the grid leak resistance R_g about 1 megohm, and for the by-pass condenser C about 5000 micro-microfarads.

CONTINUOUS, OR UNDAMPED TELEGRAPHY. — Continuous-wave telegraphy (often abbreviated C. W.) is rapidly superseding the older spark-wave system; it is the logical form of power to use for radio communication and the only reason that spark telegraphy gained the field at first was the difficulty of building a high-frequency generator which was reliable and could give several hundred kw. of power. Instead of sending out a group of discontinuous wave trains, as is done in spark telegraphy, the continuous-wave transmitter excites the antenna continuously with high-frequency power as long as the sending key is closed. This is indicated in Fig. 26; at A is shown the antenna excitation for a dot by spark telegraphy and at B the antenna excitation for a dot by continuous-wave telegraphy. For slow sending a dot might last 0.1 second; this would take 100 wave trains from a 1000-spark transmitter and would require 10,000 cycles of current, of fixed amplitude, for a 3000-meter continuous-wave transmitter.

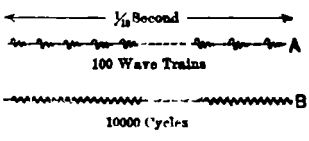


Fig. 26.

Advantages of Continuous-Wave Communication. — For a given radiated power the insulation of an antenna for continuous wave is much simpler than for spark waves, the voltage for which the insulators are built being perhaps 1/10 as great; a given amount of power in the form of continuous wave will permit communication over much greater distance than the same amount of damped-wave power, due principally to the receiving circuit used; the interference between continuous-wave stations is much less than that between spark stations.

Types of Generators Used. — There are now available three types of generators which will furnish 100 kw. or more of high-frequency power, at frequencies of 40,000 or more; namely, the inductor type of generator, the reflector type, and the Poulsen arc.

The Inductor Type of Alternator, first built by Fessenden, and now called the Alexanderson alternator, consists of stationary armature and field

coils, the revolving member being a disc of high-grade steel, carefully machined and balanced. Near its periphery the disc is cut through with closely placed radial slots, the slots being filled in with some non-magnetic alloy to make the disc smooth to cut down the windage loss. The armatures are placed one on either side of the revolving disc, these armatures being built of very finely laminated iron; they are ring shaped, having radial slots in their inner faces, in which the winding (one conductor per slot) is fitted. At the lower frequencies this machine can be built for an output of 100 kw. or more; it has been built to generate directly 200,000 cycles per second with an output of a few hundred watts, but is very inefficient (10 per cent) at these excessive frequencies. At the radio frequencies which these machines generate the iron loss per unit volume of material is very high, so that special means have to be taken to keep the machine from overheating. In the Alexanderson generator water pipes are fitted throughout the structure to keep the material at a safe temperature. The generator is motor driven, the motor being equipped with very sensitive speed controlling devices; this is necessary not only for the sake of efficient reception, but because all these high-frequency alternators require that the attached circuit be accurately tuned if much output is to be obtained, and any speed variations would spoil the adjustment of tuning.

The Reflector Type of Alternator was first suggested as possible by Boucherot in 1893, but no machine of this type proved commercially practicable until the advent of Goldschmidt's generator of this type put out in 1907. The reflector type utilizes the effect of armature reaction in a single-phase generator in inducing in the field winding a current of double the frequency of the armature current. Suppose a single-phase, 60-cycle alternator is loaded, thereby producing armature reaction on the field. It will be found that a 120-cycle e.m.f. has been generated in the field winding and, if a suitable path is provided for it, a 120-cycle current will flow in the field coils. Now an alternator turning at 60-cycle speed and having a field coil excited with 120-cycle current will generate in its armature a 180-cycle e.m.f., and if suitable paths are provided, current of this frequency will flow in the armature. This 180-cycle current will produce, by armature reaction, a 240-cycle e.m.f. in the field coils, which will produce 240-cycle current in the field circuit if suitable low impedance paths are provided. By using this idea of reflecting the frequency back and forth between the armature and the field, each time gaining the frequency of rotation of the machine, the frequency may be effectively quadrupled at least, possibly more.

In Fig. 27 the circuit arrangement of a Goldschmidt alternator connected to an antenna is shown. The key serves to vary the continuous current excitation, through coil L_1. In the armature coil L_2 is generated a frequency of 10,000, corresponding to the rotational speed of the machine. The combinations L_2–C_2 and L_4–C_4 are each resonant to this frequency. Due to this armature current of 10,000 cycles an e.m.f. of 20,000 is generated in L_1 and as the combinations L_1–C_1 and L_3–C_3 are each resonant to this frequency, a current of 20,000 circulates in the field coil L_1. This induces an e.m.f. of 30,000 in L_2, and as circuit L_5–C_5–C_6 is resonant to this frequency, 30,000 cycle current flows in the armature coils. This finally induces a 40,000 e.m.f. in the field coil, and as the circuit L_1–C_1 in series with the antenna capacity is resonant at 40,000 cycles, this frequency flows in the antenna and is used for radiating the signal. The tuning of each of these circuits is somewhat dependent on the tuning of the others, so the final tuning of the various branches has to be done experimentally after the machine is installed. Choke coils in the field-supply circuit prevent this path from short-circuiting the high-frequency currents.

The construction of this machine is a very difficult piece of work; the lami-

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ores of field and armature are built of plates 0.002 inch thick with 0.001 per between laminations; the rotor is 3 feet in diameter and weighs

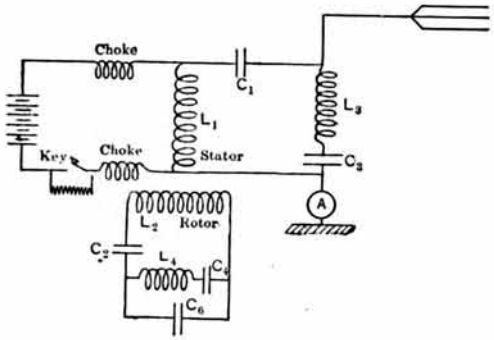


Fig. 27.

urns 4000 r.p.m. with an airgap of about 0.03 inch. In this machine, Alexanderson machine, it is very essential that the speed be kept to accomplish this a resistance is automatically inserted in the field ving motor whenever load is put on the generator.
gh reliable figures are not available, it seems likely that the efficiency achines is of the order of 50 per cent at full load.

he Poulsen Arc is an outgrowth of Duddell's singing arc (*see Arc*, It is shown connected to an antenna in Fig. 28. The commercial been made in sizes up kw. input; the efficiency somewhat less than cent, the output of e arcs are of the order w. of high-frequency The c-c. generator of volts e.m.f. is con- the arc through a resistance and choke ter the arc is struck ts to oscillate, the esistance is gradually The current through s unstable, and when s operating properly between nearly zero t twice that supplied -c. generator. The

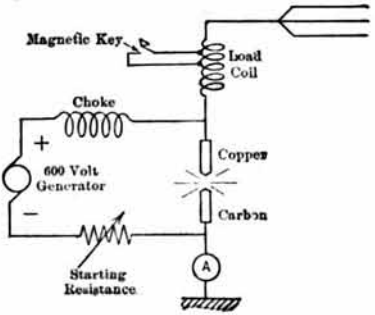


Fig. 28.

om the generator is held nearly constant by the choke coils, so that tions of the current from the average value flow in the antenna as uency current, the frequency being determined by the natural period of na circuit.

ction properly the arc must burn in a light gas, such as hydrogen or ng gas; the hollow copper anode must be water cooled, as must the

whole chamber in which the arc burns; the carbon cathode must be rotated slowly, the gap length must be proper (about ⅛ inch), and the arc must burn in a transverse magnetic field of proper intensity. The action of the arc becomes poorer as the natural period becomes less, the arc in fact is inapplicable for wave-lengths of less than 800 meters. Although the voltage across the arc may be only 50–60 volts when it is not oscillating, the peculiar action of the arc combined with the action of the choke coil results in an average voltage (as read on a c-c. meter) of about 500 volts when normal oscillations are occurring.

The interruption scheme of sending, such as used with the high-frequency generators just described, cannot be used with the arc, because when once it starts to oscillate the operation of the arc must not be stopped, otherwise the starting resistance must be re-inserted and the starting operation be repeated. Because of this condition the transmitting scheme of the arc station is peculiar to this type of transmitter. The arc operates all the time after it is started, the sending key merely changing slightly the natural period of the antenna circuit. Thus when the sending key is not depressed the arc is sending out radiation on a certain wave-length, and when the key is depressed the antenna radiates the same amount of power as before but at a wave-length perhaps 2 per cent higher or lower. The scheme of reception makes it possible to read the signal satisfactorily.

It will be seen that the arc station thus "uses up" two wave-lengths, whereas the two types of machines just described use but that one on which their signal is transmitted; this is one objection against the arc transmitter. Another arises from the fact that, owing to the continuous full load output of the arc (whether sending or not), its operating efficiency may be much lower than that of a generator.

Saturated Iron Cores have been used as frequency doublers and triplers to some extent, and the Marconi *multiple timed spark* scheme of generating continuous oscillations are used somewhat by the Marconi Co.; neither of these schemes has much engineering merit as a commercial device.

The Oscillating Triode (triode used as a converter; see section on *Triode* above) is used in practically all continuous wave transmitters of small output, say less than 1 kw.; in special tests it has been used in batteries to give several kw. output, but in the present state of its development it cannot be regarded as a competitor of the other schemes outlined, unless the required wave-length is less than about 800 meters, in which case the triode is the only available scheme.

A typical **triode circuit** is shown in Fig. 29. The oscillations are started and stopped by opening the grid circuit. It is best not to leave the grid "free," as would be the case if the key only were used; a good scheme is to have a battery of small dry cells connected across the key through a high resistance *R*. When the key is open this battery forces the grid to such a high negative potential that the plate current is brought to zero; the resistance *R* prevents short-circuiting the battery when the key is closed.

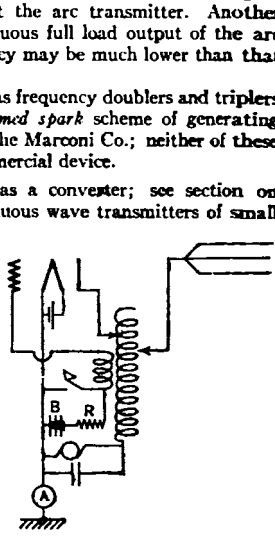


Fig. 29.

Sometimes a triode transmitter is used to send *modulated* continuous-wave signals. When the key is pressed it not only starts the triode to oscillate, but closes a buzzer circuit which opens and closes the antenna circuit at buzzer

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frequency, that is, at an audible frequency. The signals sent out by this method can be received by the ordinary crystal detector set, the transmission being practically the same as a spark station with very low decrement.

Reception of Continuous-Wave Signals. — Beat Reception. — As already pointed out, a continuous-wave signal arriving at a spark station receiving set will give no audible response in the telephones because there is no "wave-train frequency" or "spark frequency" to give the audible note. The scheme used universally to make a continuous wave signal audible is one due to Fessenden; it depends upon the creation of a "group," or "wave-train frequency" right at the receiving station, and is known as "beat reception." If a frequency of 100,000 is impressed on the receiving set by the incoming signal, and if there is already in the receiving set a continuous oscillation of 99,000 (or 101,000), these two frequencies together result in the actual current in the receiving circuit having variations in its amplitude, these variations having a frequency equal to the difference in the two frequencies present, in the above case 1000 variations or beats per second.

Originally Fessenden used a small oscillating arc to continually excite the receiving circuit, but to-day an oscillating triode is always used. The circuit is arranged as shown in Fig. 24, the coupling between L_1 and L_4 being adjusted to produce oscillations. The frequency of these oscillations will be fixed by the natural frequency of the L_1–C_1 circuit, and can be varied at will by changing C_1. Thus the beat frequency can be made just what the individual operator desires.

The triode rectifies this beat frequency just as it does the wave-train frequency from a spark station, and the operator hears the musical note of the beats; the musical note of such a signal is thus not independent of the wave-length of the transmitting station, as it is for a spark station.

This beat method of reception gives a wonderful degree of selectivity, thereby tending to prevent interference between different stations. Suppose one continuous-wave station is sending on 600 meters and another in the vicinity is sending on 605 meters. If the receiving station set is oscillating at 501,000 cycles per second the 600-meter signal will give a note in the phones of 1000, whereas the 605-meter signal will give a muscial note of about 5000 per second, practically out of audibility, whereas the desired signal note (1000) is in the most sensitive region of the ear and telephone. From what has already been said of tuning, it is evident that two spark stations sending on 600 meters and 605 meters would interfere very much, one could not be tuned out with tuning-out the other also.

Even if the two continuous-wave stations differed by only one meter in 600 they would still be easily distinguishable. The undesired signal may be made to produce with the local oscillations a beat frequency of zero; that is, the local receiving circuit may be made to oscillate at exactly the same frequency as the transmitter of the undesired signal. The desired signal would then produce a beat frequency of about 1000 per second and the interfering signal be entirely inaudible, no matter with what intensity it is arriving at the receiving antenna.

Autodyne and Heterodyne Reception. — When the detecting tube itself is used to produce the local oscillations the scheme is called "autodyne reception," and when another triode, separate from the detecting tube, is used to produce the local oscillations it is called "heterodyne reception." This distinction in names is not widely used in the literature, however, the term heterodyne being used for both methods very frequently. It will be noticed that in autodyne reception the local circuit L_1–C_1 cannot be tuned exactly to the incoming frequency, as the beat frequency for this adjustment would have

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zero value and so the signal be inaudible. In the heterodyne scheme the local circuit L_1–C_1, as well as the antenna circuit, can be exactly tuned to the signal frequency, and furthermore the amount of local oscillation impressed on the detector circuit (generally by mutual induction) can be regulated, and thus maximum response in the detector be obtained.

The amplitude of the local frequency impressed in the detector circuit should be slightly less than that existing when the tube is used for autodyne reception with the minimum value of M which will sustain oscillations. In other words, the local frequency should carry the plate current variation (Fig. 13) as far as possible without forcing it over the upper and lower knees of the curve, say from a to b of curve E_3.

RADIO TELEPHONY. — Radio-telephone conversation may be carried on by means of a suitably *modulated* high-frequency radiation. Some sort of continuous-wave, high-frequency generator is connected to the antenna, and thus radiates continuous-wave power and a receiving station, tuned to this frequency will be excited by it. If now the amplitude of this high-frequency wave is varied by some scheme, in accordance with voice waves, the envelope of the high-frequency radiation will resemble the sound waves of the voice. At the receiving station the ordinary crystal rectifier will give in the phones a sound corresponding to the envelope of the arriving radiation, and so will reproduce the voice actuating the transmitting station. Thus the only additional feature required by a radio-telephone transmitter over those required for a radio-telegraph transmitter, is a scheme which varies the radiated power according to voice sounds, instead of breaking it up into dots and dashes as does the ordinary sending key.

Microphone in Antenna Circuit. — The simplest scheme of sending out voice modulated waves is that shown in Fig. 30; the high-frequency generator

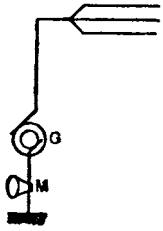


Fig. 30.

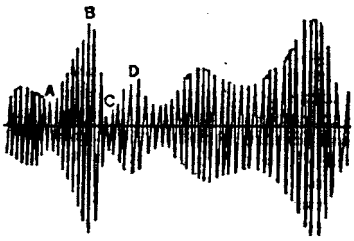


Fig. 31.

G excites the antenna in series with which is the microphone M. When spoken into the microphone varies its resistance above and below normal, and so varies the amplitude of current flowing in the antenna, the antenna current thus having a form as shown in Fig. 31. Such a wave arriving at a receiving circuit will give a noise in the phones corresponding to the envelope of the current amplitude, A–B–C–D, which represents the form of a voice sound wave. This method of modulation is far from perfect, is very inefficient (because of high microphone resistance), and is good for only small amounts of power, at most a few watts. If too much current is allowed to flow through the microphone it overheats and ceases to function.

Variable Induction Modulation. — A scheme used in a large radio-telephone station is shown conventionally in Fig. 32; it is due to Alexanderson.

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frequency generator G is shunted by a path in which there is included
ore inductance; wound on this core is an extra coil, the current from
obtained
he plate cir-
battery of
ered triodes
pliotrons).
circuit of
es is actu-
igh a trans-
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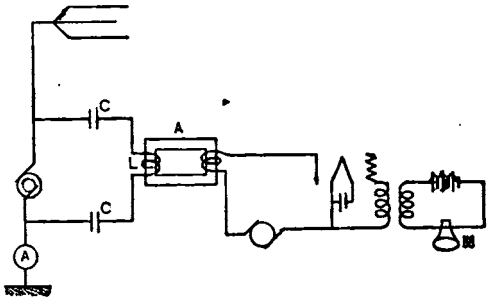


Fig. 32.

he generator C–L–C more or less short-circuits the generator, thus
he amount of power applied to the antenna more or less in accordance
voice sounds actuating the microphone. This scheme has been used
ate outputs of perhaps 50 kw. The actual circuit is more compli-
n the one shown, which is designed to give the elementary idea only.

ation by Triode Directly. — A scheme of modulation due to Heising
in Fig. 33. It is by far the best scheme so far used for low-powered

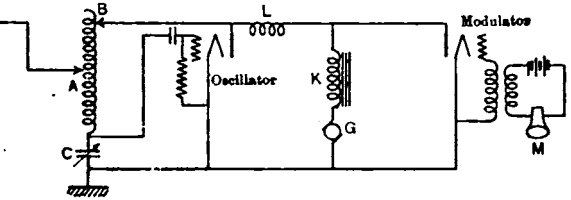


Fig. 33.

less than a few kw. The oscillator tube is connected to the antenna
, the plate current being supplied by generator G through the iron
l K and the high-frequency choke coil L. In small telephone outfits
tubes with an output of 3–5 watts) K is about 2 henries and L about
nries. The grid excitation for producing oscillation is controlled by
enser C which is about twice the antenna capacity, for tubes having an
tion factor of 4. The wave-length generated is affected somewhat
lue of C, but is controlled primarily by the position of tap A. To get
tion of the wave-length a small variable capacity condenser is usually
parallel with the antenna capacity. The position of tap B must be
chosen to get maximum current in the antenna circuit, this position
ith the resistance of the antenna.

odulator tube draws its plate current through the same iron-core choke
es the oscillator, and the amount of current taken by the modulator
led by the microphone M operating on the grid of the modulator tube.
f the high reactance of coil K the current furnished to the two plate

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circuits in parallel will be essentially constant, so that as the microphone makes the modulator take more or less current, the oscillator plate circuit is supplied with less or more. The amount of power supplied to the antenna by the oscillator depends upon the oscillator plate current, hence the action of the microphone modulates the antenna output. The choke coil L is to prevent the high-frequency output of the oscillator tube being partially absorbed by the plate circuit of the modulator.

The modulated high-frequency current in coil A-B may be used to excite a battery of high-powered tubes, instead of being itself the radiation current; in this case a condenser will replace the antenna in the oscillator circuit. This scheme of using a low-power triode to excite a battery of larger ones makes it possible to successfully modulate several kw. of power.

Elimination of Distortion of Speech. — To make the modulation follow closely the voice sounds great care must be used in properly proportioning the various parts of the circuit; the average grid potentials of the two tubes is one of the important factors affecting modulation; generally a suitable battery of small dry cells is inserted in series with the grid of each tube to maintain the average grid potential at its right value. The modulation with a well-designed Heising circuit is so perfect that the voice of the speaking operator is easily distinguishable at the receiving station, the articulation being much better than it is over the ordinary wire line.

Receiving Circuit for Radio Telephony. — At the receiving station a triode detector is used, connected as in Fig. 24. The coupling of L_1 and L_4 must not be adjusted as critically (for high amplication of signal) as is possible without having the tube oscillate, because the speech becomes drummy, the consonants being obliterated. As shown previously, the critical coupling of the coils L_1 and L_4 makes the effective resistance of the receiving circuit practically zero, which of course means a very low decrement of the receiving circuit.

The decrement of none of the circuits used in radio telephony can be too low without spoiling the quality of the speech. This statement holds for the transmitter as well as for the receiver. The modulated high-frequency current must be similar to the sound waves; this means that for certain voice sounds the amplitude of the current must change very rapidly, the consonants requiring the most rapid change. If the decrement of a circuit is very low, the current in the circuit cannot be changed in amplitude rapidly, and so cannot follow the voice modulation. Because of this fact the tuning of a good radio-telephone receiver is not as sharp as one designed for the reception of continuous-wave telegraph signals.

Two-Way Conversation. — Although the common small radio-telephone outfits require the operator to throw a switch to change from sending to receiving position, it is possible to have this done automatically by a sort of bridge scheme; it is also possible to have two separate antenna systems, one for sending and one for receiving, so interconnected that two-way conversation is obtained as in ordinary wire telephony.

ATMOSPHERIC DISTURBANCES AND THEIR ELIMINATION. — Space is continually agitated by electric disturbances, caused by ionization due to winds or the sun's rays, or by thunder storms with their electric discharges. Especially in the tropical regions are these "atmospherics" or "static" or "strays," as they are variously called, prevalent, probably because of the trade winds. Judging from the effect these electric disturbances have on an antenna it seems that they are radio pulses of very short duration, probably for the most part non-oscillatory. Due to their action all kinds of crackling and hissing noises are heard in the phones of a receiving set. These atmospheric disturb-

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ances are the present limit on the utility of radio communication; were it not or these extraneous undesired signals coming into the receiving set, it would be possible to carry on transoceanic communication with one kilowatt of power, or less, instead of several hundred kilowatts as must be used.

Many investigators have put forth solutions of the static problem, but it is still to be solved. Even the very high-powered stations with their wonderful transmitting and receiving circuits have to send their messages slowly, and repeat continually because of the static interference in the receiving station. The partial elimination of static is possible by using a coil antenna, properly combined with a ground antenna, or similar scheme in which it is endeavored to balance out the static picked by the two antennæ and still leave a little of the signal unbalanced; this is then amplified until it is intense enough to read.

DIRECTIONAL RADIO. — As radio waves are of exactly the same nature as light waves, and as light waves are directive, can be focussed, bent, etc., it would seem that radio waves could be sent out in one direction only, like the beam of a searchlight. Such is the case theoretically, but it must be remembered that a mirror, or lens, to be effective, must be of dimensions hundreds of times the wave-length to be reflected or focussed. With radio waves thousands of meters long the use of mirrors, etc., is evidently out of the question.

The form of antenna used does give a certain amount of directional effect, as was first pointed out by Marconi. The type of aerial shown in Fig. 6 sends out considerably more power in the direction of its length than it does sideways. The coil antenna is more directive than any other; it sends and receives no power at all in a direction perpendicular to its plane. The distribution of radiated power from an inverted L antenna is as shown in Fig. 34 and that of a

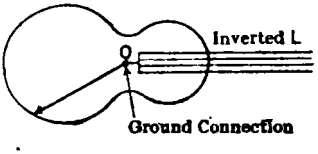


Fig. 34.

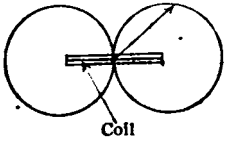


Fig. 35.

coil in Fig. 35; in each figure the radius to the locus gives a measure of the radiated power in that direction.

By suitable combinations of two or more antennæ it is possible to get somewhat more directive effects than those shown here. Practically all of the later attempts in this field follow very closely the original work of Bellini and Tosi, who were the pioneers in this branch of radio communication.

RADIO COMPASS. — It is now practicable for a ship at sea to get her bearings by radio, an especially useful operation for a ship approaching a harbor in a fog. Suppose the harbor is at *O*, Fig. 36, and the ship at *A*. The ship calls up station *O* and asks for bearings. *A* then sends out a standard signal of some sort for a short time, and by suitable coil antennæ the stations at *C*, *O*, and *B* get her direction simultaneously. The direction as obtained at *C* and *B* are sent in to the central station at *O*; the operator at *O* is thus able to plot accurately the ship's position on his chart, using one of

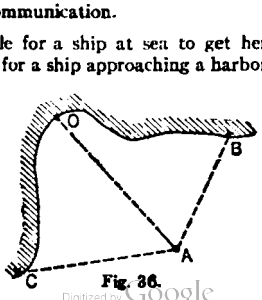


Fig. 36.

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the directions as a check on the other two. Operator at *O* then radios bac to the ship her exact position.

A scheme used by aeroplanes for getting their bearings at night or above th clouds utilizes the directive effect of a coil antenna, in this case the coil bein on board the plane. A series of land stations send out characteristic signal (each station a different one, of course) and the operator on the plane, b orienting his coil, gets his bearings from two of the stations and so can plo his position. To make the directive effect as sharp as possible, two coils at righ angles to each other are used, Fig. 37; they can be connected in series direct o reversed by the double-pole double-throw switch. When the plane of one of the coils is in the direction from which the signals are coming, reversing the switch will have no effect on the signal strength, as the other coil should be getting nothing. By this scheme a plane can get the direction of the waves to within one degree.

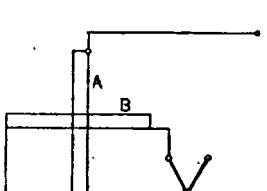


Fig. 37.

Inaccuracy of the Radio Compass. — Although the setting of such an antenna as that pictured in Fig. 37 can be carried out to such a wonderful degree of precision, the observation is not as valuable as the precision would seem to justify. Radio waves are subject to the same laws of refraction as light, and so may bend considerably, depending upon the condition of the atmosphere through which they are travelling. This effect has been noticed to a very great extent when the waves are travelling nearly parallel to a shore line, the deflection of the waves from such an obstruction being many degrees. Taylor states that a change of bearing, by wireless compass, of as much as 68 degrees takes place in only 14 minutes, this very large effect occurring during the setting of the sun.

SIMULTANEOUS TRANSMITTING AND RECEIVING. — It is not practicable to send and receive on the same antenna at the same time, although at present developments are taking place in that direction. It is however, practicable to send from one antenna and receive on another in the vicinity. This is generally accomplished by having at the receiving station two antennæ, one of them being used to balance out the intense signal induced in the real receiving antenna by the nearby transmitting antenna. The extra antenna is generally a directive one so oriented that it picks up a maximum signal from the transmitter. By suitably combining, in the coils of the detector set, the signals from this compensating antenna with those from the receiving antenna, the signal from the nearby transmitter may be completely neutralized, leaving the desired signal from the distant transmitter.

In most such stations the transmitter station is operated by remote control from the receiving station; all keys, etc., at the transmitter station being magnetically operated.

SPEED OF TRANSMITTING. — A good operator can read 25 to 30 words per minute, when there is not too much interference. This evidently limits the speed of transmission, unless some type of automatic receiver, such as the phonograph, be used at the receiving station. Up to the present none of the many schemes of mechanical reception has proved as efficient as an operator, and they are but infrequently used. Successful experiments have often been conducted, but the fact that practically all of the high-powered stations to-day are sending at slow speed shows that they are not dependable.

When high-speed sending does come into practice another effect, which cannot be analyzed in detail here, must be considered. It has been stated that the tuning of continuous waves is very sharp, so that interference between different stations is reduced to a minimum. This statement does not hold good if the transmitting is done at high speed, the higher the speed the more interference will different stations produce on one another. An antenna does not start to radiate full power the moment the transmitting key is closed, it taking an appreciable time for the antenna to build up to the steady state. With high-speed sending the time for the steady state to be set up becomes comparable with the time the key is closed, and under such conditions the conclusions one reaches from the steady state condition are of no value.

WAVEMETERS. — The wavemeter, although a very simple device, is the most important the radio engineer has at his command. It is essentially nothing but a coil and condenser in series, one or both of them variable, with means for telling when the current in the circuit is a maximum. As it is simpler to construct a variable condenser, of wide capacity range, than it is to do the same thing for an inductance, it is the condenser which is generally variable.

Evidently this circuit, coupled to another in which there is a high-frequency current, will have maximum current when it is in resonance with the e.m.f. induced by that circuit, and if the values of the capacity and inductance of the coil are known for all settings, the frequency of the impressed e.m.f. is obtained by adjusting the wavemeter for resonance, and then noting the natural frequency of the circuit for this setting. As the radio engineer generally thinks in terms of wave-length rather than frequency, the meter is calibrated, on the condenser scale, to give wave-length in meters.

As a variable condenser for this purpose is usable from its maximum value to about $\frac{1}{10}$ of its maximum value, the wave-length range of a meter with a single coil would be only about 3 to 1. To extend the range of the meter several coils, of different inductance, are generally furnished with it. In one type of wavemeter, for example, having a wave-length range from 100 meters to 6000 meters six coils are supplied.

The methods for detecting resonance differ according to the amount of power available. If the test is being made on a transmitting set (plenty of power), a hot-wire ammeter, which is permanently connected in series with the coil and condenser (*A* in Fig. 38) is used to show maximum current. Another scheme is to shunt the condenser with a small glass tube filled with neon (or other easily ionizable gas) at low pressure, as indicated in Fig. 38 by dotted lines; when the wavemeter is in resonance with the circuit being tested, there will be maximum voltage across the condenser and so maximum glow in the tube.

In still another scheme there is a small incandescent lamp connected in series with the coil and condenser, where the ammeter is in Fig. 38; this lamp is brought almost to incandescence by a dry cell in the wavemeter, the circuit to this cell having choke coils to keep out the high frequency. When the wavemeter is in resonance its current flows through the lamp in addition to that already flowing from the cell, and the lamp glows more brightly. This scheme is better than would seem likely, for only a slight increase in current is required to give a perceptible change in the color of the lamp, so that the resonance point can be located quite accurately.

When testing on a low-power set, such as a received signal, there is not enough power available to actuate either a hot-wire meter or a neon tube, so some more delicate means of detection must be used. For such a case the telephone and rectifier are shunted across the condenser as shown in Fig. 39. Sometimes the circuit is opened at the point indicated by *X* in the figure, and an additional

connection made as shown by the dotted line. Such a connection draws less power from the wavemeter, and so does not increase its decrement as much

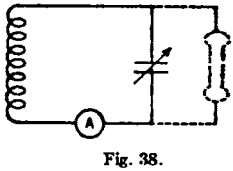


Fig. 38.

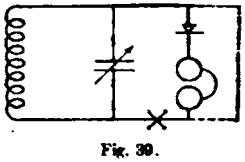


Fig. 39.

as does the other connection, thereby giving sharper resonance. This connection is often called a unilateral connection.

Uses of the Wavemeter. — The wavemeter is used principally to measure the wave-length radiated from a transmitter, as the name indicates. In doing this the coil of the wavemeter is held in proximity to the oscillating circuit, and the condenser varied until maximum indication is obtained in the hot-wire meter, phones, or other detector used. To get an accurate indication it is advisable to have the wavemeter coupled to the oscillating circuit as loosely as possible and still get a positive reading on the indicating device. This will make the indication sharp, and also, with loose coupling, there is no danger of the wavemeter changing the frequency of the oscillating circuit.

The wavemeter is also used to measure the decrement of a transmitting set. To do this the meter is brought in proximity to the antenna and adjusted for resonance as indicated by the hot-wire meter; the coupling of the meter to the antenna is then varied so as to get a reading well up on the scale of the ammeter and this reading is noted. The wavemeter is then detuned until the ammeter deflection indicates 0.707 of the current which flows at the resonance setting, and the wave-length for this reduced reading noted. Similarly the wavemeter is detuned on the other side of the resonance point until ammeter again indicates 0.707 of its resonance value and this wave-length noted. It frequently happens that the hot-wire meter used is calibrated in terms of current-squared; thus many German meters are calibrated in current-squared, and the scale values are marked off in watts used in the meter itself. Such meters are labelled "wattmeters," although evidently they are not wattmeters in the ordinary meaning of that term. In getting the two-detuned points with such an indicating instrument, the wavemeter setting is varied until the scale reading is just ½ of its value at resonance, this being the proper setting for 0.707 of the resonance current.

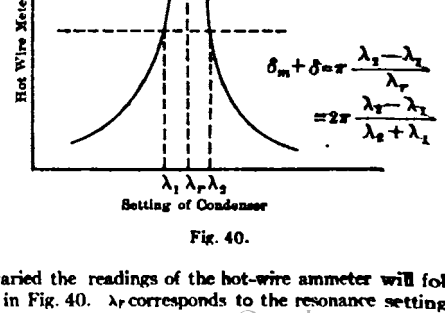


Fig. 40.

As the setting of the wavemeter condenser is varied the readings of the hot-wire ammeter will follow a curve as indicated in Fig. 40. λ_r corresponds to the resonance setting, λ_1 to the detuned condition above resonance, and λ_2 to the detuned condition

ce. The value of the decrement is then obtained from the rela-
pproximate),

$$\delta_m + \delta = 2\pi \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2} = \pi \frac{\lambda_1 - \lambda_2}{\lambda_r}.$$

on δ is the decrement desired, and δ_m is the decrement of the
nerally given with the meter. If this is not known, it may be
erforming the same test with a continuous-wave transmitter; as
of the set is in this case zero, the decrement obtained from the
is the decrement of the meter itself. An oscillating triode is a
ver source for making this test.

r. — Kolster has designed a wavemeter with a special scale attached
condenser with plates properly shaped so that it is possible to
the decrement of the set (plus that of the meter) from the setting
scale, after carrying out a simple operation; this wavemeter is
neter.

REQUIRED IN RADIO TRANSMISSION. — The trans-
io waves is an irregular phenomenon, as previously mentioned,
ghout the year as well as during the day. The strength of signal
e receiving station for successful transmission is not a constant,
atly with the amount of atmospheric disturbance present; this
obably 100 to 1. Thus it is evident that exact figures cannot
he values given in the table below are average values for a spark
a high musical note (1000 sparks per second). The power rating
nput to the primary of the power transformer.

supplied	0.3 kw.	1.0 kw.	5 kw.	30 kw.
es in day time..	50–100	125–250	250–500	500–1200

ious-wave transmitters the distances successfully covered are
than those given above, perhaps two to three times as great.
ations carrying on transoceanic communication all use between
00 kw. of power, in the antenna itself, the power supplied to the
being nearly twice this figure. Even with this amount of power
ation is not certain, as they transmit very slowly, often repeating
g the summer time. During the winter months the transmission
certain, and in many cases it is feasible to communicate half way
rld.

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RAILS, TRACK AND THIRD. — (*See also Bonds, Railway Track, Railways, Electric, Traction Systems for; Third-rail Systems; Trolley Systems.*) The A. E. R. A. Specification says that, unless otherwise specified, the lengths shall be 60 and 62 feet.

The American Electric Railway Association recommends that plain girder rails be used in paved streets except in large cities where the vehicular traffic is largely confined to the pavement area maintained by the railway. In the latter case, grooved rails should be used. The association has standardized the following rail sections which are described fully in its Engineering Manual.

Plain girder rails		Grooved rails	
Height, in.	Weight, lb. per yd.	Height, in.	Weight, lb. per yd.
5½	80	7	122
5¾	90	9	134
7	80 or 91		
6	100		

RESISTANCE AND CHEMICAL COMPOSITION. — The chemical composition of steel rails with respect to the impurities or elements other than iron (chiefly carbon, manganese, phosphorus, sulphur and silicon) varies over a considerable range, depending upon the process of manufacture. According to J. A. Capp, the specific resistance of an ordinary * steel rail may be taken as a rough indication of the total impurities present. Fig. 1 shows the results of tests on a number of samples of different makes, ranging in total impurities

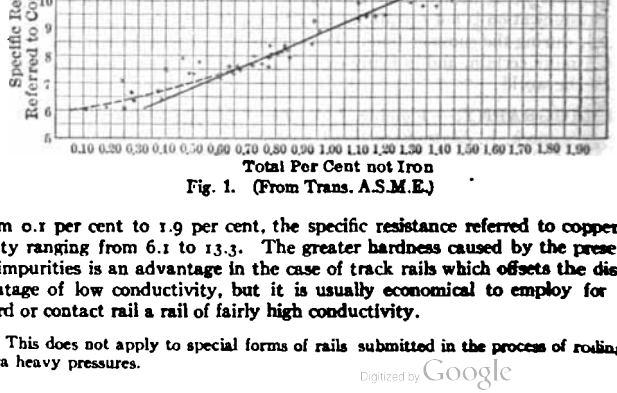


Fig. 1. (From Trans. A.S.M.E.)

from 0.1 per cent to 1.9 per cent, the specific resistance referred to copper as unity ranging from 6.1 to 13.3. The greater hardness caused by the presence of impurities is an advantage in the case of track rails which offsets the disadvantage of low conductivity, but it is usually economical to employ for the third or contact rail a rail of fairly high conductivity.

* This does not apply to special forms of rails submitted in the process of rolling to extra heavy pressures.

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The compositions given in the following tables are recommended by th authorities quoted.

PER CENT IMPURITIES AND SPECIFIC RESISTANCE OF STEEL RAILS

Item	Track rails			Third rails		
	Am. El. Ry. Assoc.			J. A. Capp		A. H. Armstrong
	Lower limit	Recommended	Upper limit	Recommended	Upper limit	Recommended
Carbon	0.60	0.68	0.75	0.15	0.20	0.12
Manganese	0.60	0.80	0.80	0.30	0.40	0.40
Phosphorus	....	....	0.04	0.06	0.06	0.10
Sulphur	....	....	....	0.06	0.06	....
Silicon	....	....	0.20	0.05	0.05	0.05
Approx. spec. res. referred to copper as unity	12.5			8.0		

PER CENT IMPURITIES AND SPECIFIC RESISTANCE OF SOME TYPICAL THIRD RAILS

Railroad	Per cent of impurities					Spec. res. referred to copper as unity
	Carbon	Manganese	Sulphur	Phosphorus	Silicon	
Long Island	0.080	0.022	0.029	0.074	0.074	7.55
District & Met.Ry., London.	0.05	0.19	0.06	0.05	0.03	6.4
Manhattan Ry.	0.098	0.485	0.158	0.085	0.022	8.98
I. R. T. Subway, N. Y.	0.161	0.561	0.055	0.091	trace	8.56
New York Central	0.10	0.40	<0.08	<0.10	<0.05	7.85
Detroit River Tunnel	0.10	0.40	<0.08	<0.10	<0.05	7.85

Allowance for Wear in Resistance Calculations. — Resistance calcula- ons should be made for rails worn down to the weight at which they will be rapped. It is usual to scrap rails when they have lost from 10 per cent to 20 er cent of the original weight, depending upon the importance of the line. The

resistances in the following table should therefore be increased from 10 per cent to 20 per cent.

RESISTANCE OF T-RAILS, A.S.C.E. STANDARD SECTION (1913)

(Full Cross section)

Weight, lb. per yard	Cross section, sq. in.	Area, millions of circular mils	Spec. res. 12.5 times that of copper		Spec. res. 8 times that of copper *	
			Ohms per 1000 ft.	Ohms per mile	Ohms per 1000 ft.	Ohms per mile
40	3.90	4.95	0.0261	0.138	0.0167	0.0882
45	4.40	5.60	0.0231	0.122	0.0148	0.0782
50	4.90	6.23	0.0208	0.110	0.0133	0.0702
55	5.40	6.86	0.0189	0.0996	0.0121	0.0637
60	5.90	7.50	0.0173	0.0911	0.0110	0.0583
65	6.40	8.14	0.0159	0.0840	0.0102	0.0538
70	6.90	8.77	0.0148	0.0779	0.00944	0.0499
75	7.437	9.45	0.0138	0.0729	0.00884	0.0467
80	7.80	9.9	0.0131	0.0689	0.00835	0.0441
85	8.34	10.5	0.0122	0.0645	0.00781	0.0413
90	8.83	11.2	0.0115	0.0609	0.00738	0.0390
95	9.30	11.8	0.0109	0.0570	0.00701	0.0370
100	9.82	12.5	0.0104	0.0547	0.00664	0.0350

* To find the resistance of rails of any specific resistance x referred to copper as unity multiply these resistances by x and divide by 8.

A-C. Resistance and Reactance. — See articles on *Trolley Systems, Overhead; Signaling, Railway.*

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RAILWAYS, ELECTRIC, TRACTION SYSTEMS FOR. — (*See also Automobiles, Electric; Bonds, Railway Track; Car Barns and Inspection Sheds; Cars, Electric; Conduits and Conduit Lines; Control Systems for Railway Motors; Depreciation; Electrolysis; Locomotives, Electric; Locomotives, Steam; Motors; Power Stations; Rails, Track and Third; Rectifiers; Signaling, Railway; Specifications; Substations, Railway; Third-rail Systems; Railways, Energy Requirements for; Railways, Location and Permanent Way for; Transmission Lines; Trolley Systems; Wires and Cables.*) The component parts of a railway system are the following: Generating station, usually three-phase alternating current; high-tension transmission line; substations with transformers and synchronous converters; low-tension distribution system, trolley and feeders; motive power or motor equipments; bonding and feeders for return circuit.

HISTORICAL DEVELOPMENT. — The history of electric traction is given briefly by a few salient epoch-making events.

1835. T. Davenport of Vermont built and exhibited a small model electric vehicle operating on a circular track.

1842. Davidson, Edinburgh, Scotland built a seven-ton car operated by primary batteries and electro-magnets.

1851. G. G. Page operated a small locomotive with primary batteries on the Baltimore and Ohio Railroad at Washington.

1877. S. D. Field in San Francisco operated a small car driven from a stationary remote generator.

1882. J. R. Finney first used the over-running trolley at Allegheny, Pa.

1883. Leo Daft equipped a full-sized passenger train running from Saratoga to Mt. McGregor, together with the over-running-trolley construction.

1886. Bently and Knight introduced the first conduit system in Cleveland, O.

1887–8. Several small installations.

1888. Frank Sprague equipped the Richmond Street Railway and demonstrated the practicability of the system. Bently and Knight equipped a road at Allegheny City. Thomson-Houston system installed at Washington, D. C. Van Depoele brought out the under-running trolley. The directors of the Boston West End System decided to adopt electric traction.

1896. Baltimore and Ohio tunnel at Baltimore electrified; the first electrification of a steam road.

For references to the original papers describing these early installations, see Burch, *Electric Traction for Railway Trains*, N. Y., 1911.

APPLICATIONS OF ELECTRIC TRACTION. — There are certain well defined fields in which electric traction is superior to other methods, the most important of which are the following:

1. Where the frequency of stops is so great as to require a high rate of acceleration in order to make a good schedule speed. If the service requires trains of several cars, any desired number of these cars can be made motor cars and thus a sufficient weight on the driving wheels can be economically secured to give the required adhesion and tractive effort.

2. Where local conditions prohibit the nuisance of the smoke, exhaust gases and noise of steam locomotives, as in cities and tunnels.

3. In heavy trunk-line service where the density of traffic is so great that a high load factor can be obtained with respect to both the power house and distribution system. The *operating* cost of an electric train is always less than the operating cost of a steam train but the *fixed* charges (Interest on investment and depreciation) of the electric system are high, for the first cost for the electric equipment, viz., locomotives, motor-car equipment, distribution

system and power house, is much greater than the first cost of steam locomotives, and their accessory equipment. If there are sufficient trains in a system so that the pro rata share of the fixed charges for each train is less than the difference between the operating cost of an equivalent steam equipment and the operating cost of the total electric equipment then electric traction is advantageous.

SYSTEMS OF ELECTRIC TRACTION. — Three different types of motors are in use for electric traction, the direct-current motor, the single-phase commutator motor, and the three-phase induction motor; see articles on *Motors*. The trolley or third-rail voltages (i.e., volts between trolley and track rails or between third rail and track rails) and the motor voltages employed are as follows:

Direct-current Systems. — Trolley or Third-Rail voltages of 600, 1200, 1500, 2400 and 3000 are in use. The motors for the 600-volt system are designed for operation at full trolley voltage. For all the other systems two motors are permanently connected in series electrically, each designed for half the trolley voltage.

Single-phase Systems. — Trolley voltages (third rails are not used) of from 3000 to 11,000 volts and frequencies of 15 and 25 cycles per second are in use. The trolley voltage is stepped down to from 200 to 500 volts, for which voltage the motors are designed.

Three-phase Systems. — Two trolley wires for each track are required, the two wires and the track forming the necessary three conductors for the three-phase distribution. The usual frequency is 25 cycles per second. The voltages used between the two trolleys and between each trolley and track range from 6000 to 11,000 volts. Transformers are employed to step this three-phase voltage down to from 400 to 600 volts between motor terminals.

Comparison of the Various Systems. — For ordinary street railway service the 600-volt d-c. system is almost universally employed, but for interurban and trunk-line service there is a great difference of opinion as to which of the various systems is the most economical when all the factors are taken into account. The factors which must be considered in comparing the three systems in any particular case are the following:

1. For a given weight and length of trolley or third rail the per cent power loss for a given amount of power transmitted varies inversely as the square of the trolley or third-rail voltage.

2. The higher the trolley or third-rail voltage the fewer are the number of substations required for the same efficiency of distribution and weight of conductor.

3. The higher the trolley or third-rail voltage the more costly is the insulation and supporting structure, and also the greater is the cost of maintenance of the distribution system.

4. Both the first cost and the annual expense of the substations are less for the a-c. systems than for the d-c. systems, since for the former static transformers only are required whereas for the latter rotary converters must be used.

5. The relatively low power factor of a-c. motors (80 to 90 per cent) as well as the relatively low power factor of the line (due to the reactance of the trolley wire and track return) gives rise to a greater power loss in the a-c. distribution system for the same power delivered than in the case of the d-c. system, and this great loss and lower power factor makes necessary the employment of generating apparatus of greater kv-a. capacity.

6. The 600-volt d-c motor, for the same horse-power rating and speed,

eighs less and occupies less space than either type of a-c. motor.
ltage d-c. motors cost more, weigh more and occupy more space
-volt type.
the a-c. motors transformers are required on the locomotive,
to the cost and weight of the locomotive equipment.
oo-volt d-c. motor costs less to maintain and is liable to fewer oper-
s than any of the other motors.
the commutating type of a-c. motor the power lost in the control
practically negligible, since the "potential" type of control can be
oth the d-c. motor and the induction motor a resistance control is
ith consequent loss in power (*see Control Systems for Railway Motors*).
nduction motor is inherently a constant-speed machine, and con-
e power input varies directly as the opposing resistance. The d-c.
he a-c. commutator motor are inherently variable-speed machines,
er input varies approximately as the square root of the opposing
ie speed at the same time falling off.
three-phase induction motor, when kept connected electrically to
f power, automatically operates as a generator when the train is
grade at a speed greater than the synchronous speed of the motor,
ius returning power to the line and at the same time acting as a
nting any considerable increase in speed. "Regeneration," as this
led, can also be obtained with the other types of motors but only
expense for the additional control equipment required.

s of the Use of the Various Systems. — In the following
sted (1) the most notable examples of high voltage d-c. interurban
U. S. A.; (2) the most notable examples of electrified steam railroads
A.; and (3) a complete list of single-phase railways in the U. S. A.

IS OF AN ELECTRIC RAILWAY PROJECT. — In the anal-
ticular problem the following general line of procedure is followed:
mine the number and capacity of cars to supply the service desired.
mine the power and energy required to propel these cars at the
ed desired; see *Railways, Energy Requirements for.*
the motors to correspond to the power determined in 2; see *Rail-
y Requirements for.*
ut distribution of cars, by train diagrams if necessary; see *Rail-
y Requirements for.*
late the capacity of the low-potential distribution system and of
ons; see *Substations, Railway; Railways, Energy Requirements for;
ystems; Trolley Systems.*
mine the capacity of the generating stations and transmission sys-
ower Stations; Railways, Energy Requirements for; Transmission

nate the first cost of the system; see articles on the various items

ate the cost of operation; see articles on the various items involved.
ate the earning power of the system.
case of a new road the earning power must exceed the sum of the
st and fixed charges by an amount sufficient to pay dividends.
case of the electrification of a steam road it must be poss ble to
(1) that the result of electrification has been to reduce the oper-
s by an amount more than sufficient to pay the fixed charges on
l apparatus, or, (2) that the result of electrification will increase
of the road or attract sufficient new business so that the increased

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THE MOST NOTABLE EXAMPLES OF HIGH-VO
INTERURBAN ROADS IN THE U. S. A.

Name of road	Date installed	Miles of single track	Trolley voltage
Indianapolis & Louisville	1907	42	1200
Central California Tr	1908	71	1200
Pittsburgh, Harmony & B	1908	82	1200
Milwaukee El. Ry	1910	135	1200
Washington, Baltimore & A	1910	103	1200
Ft. Dodge, Des Moines & S	1911	145	1200
So. Pacific, Oakland	1911	138	1200
Oregon El., Portland	1912	180	1200
Piedmont Ry	1912	125	1500
Kansas City, Clay & J	1913	74	1200
Oakland, Antioch & E	1913	118	1200
Texas El. Ry	1913	158	1200
Pacific El., Los Angeles.	1914	92	1200
Salt Lake & Utah	1914	77	1500
Utah-Idaho Central	1915	97	1500
Michigan Ry. Co. (G. R. to Kalamazoo & Battle Creek)	1915	95	1200
Michigan Ry., Grand Rapids	1915	77	1200

THE MOST NOTABLE EXAMPLES OF ELECTRIFIE
IN THE U. S. A. (1921)

Name of road	Date installed	Miles of single track	Main line, tunnel or terminal	Trolley or third rail	Trolley voltage
Baltimore & Ohio	1896	7.95	Tun.	3d R.	650
West Shore	1905	106	M. L.	3d R.	620
N. Y. Central	1906	268	Term.	3d R.	650
West Jersey & S. S.	1906	150	M. L.	3d R.	600
Grand Trunk	1908	12	Tun.	T.	3,300
N. Y., N. H. & H.	1907	552	Term.	T.	11,000
Great Northern	1909	6	Tun.	T.	6,600
Michigan Central	1910	26	Tun.	3d R.	600
Penn. & L. I. R. R	1910	316	Term.	3d R.	600
S. Pacific, Oakland	1911	138	M. L.	T.	1,200
Boston & Maine	1911	21.5	Tun.	T.	11,000
Butte, Anaconda & P.	1912	114	M. L.	T.	2,400
Spokane Inland	1912	130	M. L.	T.	6,600
S. Pacific, Portland	1914	162	M. L.	T.	1,500
C. M. & St. Paul	1915	650	M. L.	T.	3,000
Pa. R. R. Paoli & Chestnut Hill	1915	116	M. L.	T.	11,000
Norfolk & Western	1915	98	M. L.	T.	11,000

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E LIST OF THE SINGLE-PHASE RAILWAY INSTALLATIONS IN UNITED STATES AND CANADA. (1921)

Name of road	Year started	Route, miles	Trolley voltage	Manufacturer	Frequency
lis & Cincinnati	1904	107	3,300	West	25
orthern Railway	1905	15	2,200	West	25
action Company	1905	95	3,300	G. E.	25
d R. R., Sea Cliff Div.	1905	5	2,200	West	25
isco, Vallejo & Napa Valley	1905	34	3,300	West	25
Jamestown	1905	26	3,300	West	25
and Co. Traction Company	1905	7	1,200	West	25
Inland Empire R. R.	1906	162	6,600	West	25
Chicago Railway	1906	43	3,300	G. E.	25
Traction Company	1907	20	3,300	G. E.	25
oad—Rochester	1907	40	11,000	West	25
ne & Springfield	1907	22	6,600	West	25
Elec. Ry. & Lt. Co.	1907	68	3,300	G. E.	25
New Haven & Hartford R. R.	1907	500	11,000	West	25
& Butler	1907	39	6,600	West	25
& Chesapeake Bay	1907	16	6,600	G. E.	25
Essex & Lake Shore	1907	40	6,600	West	25
Elec. Rys. (Short Line)	1908	37	6,600	West	25
Lake Shore & South Bend	1908	90	6,600	West	25
Interurban R.R.	1908	54	11,000	West	25
ink Ry.—St. Clair Tunnel	1908	12	3,300	West	25
k York Railway	1908	21	6,600	West	25
n Ry.—Quebec	1908	1	6,600	G. E.	30 & 15
ec. Railway	1908	36	3,300	West	15
n, Baltimore & Annapolis	1908	87	6,600	G. E.	25
d Southern Railway	1910	52	11,000	West	25
, Westchester & Boston	1911	63	11,000	West	25
Maine Railroad (Tunnel)	1911	22	11,000	West	25
nia R. R.—Paoli Div.	1915	116	11,000	West	25
Western Railway	1915	90	11,000	West	25
Total, 30 roads			1926	miles	
Changed to D-C., 11 roads			473	miles	

* Changed to direct current.

† Single-phase trolley. Single, 3-phase locomotives.

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SELECTED EXAMPLES OF FOREIGN RAILROAD
TIONS HAVING SPECIALLY INTERESTING F
(1921)

Name of road	Date installed	Miles of single track	Main line, tunnel or terminal	Trolley or 3d rail	Voltage
Canadian Northern....	1915	30	Term.	T.	2,4
Hershey Ry., Cuba....	1920	80	M. L.	T.	1,2
Paulista Ry., Brazil....	1920	76	M. L.	T.	3,0
Bethlehem, Chili.....	1918	24	M. L.	T.	2,4
Central Argentine Ry.,	1915	100	Term.	3d R.	8
England:					
London, Brighton & S. C.....	1909	70	M. L.	T.	6,7
N. E. Ry., Middlesboro.....	1915	·50	M. L.	T.	1,2
Manchester & Bury...	1917	27	M. L.	3d R.	1,2
Rjukan Ry., Norway..	1918	286	M. L.	T.	15,0
Midi Ry., France.....	1911	75	M. L.	T.	12,0
Germany:					
Dessau-Bittersfeld....	1910	33	M. L.	T.	10,0
Magdeburg-Halle.....	1910	80	M. L	T.	10,0
Switzerland:					
Simplon	1907	26	Tun.	T.	3,0
St. Gotthard.....	1918	30	Tun.	T.	15,0
Lotschburg.....	1910	46	M. L.	T.	15,0
Italy:					
Valtelina.....	1904	70	M. L.	T.	3,0
Genoa-Giovi-Milan...	1904	26	M. L.	T.	3,0
Australia:					
Victorian Rys. Melbrn	1919	335	M. L.	T.	1,5
Imperial Rys., Japan ..	1915	40	M.L.	T.	1,2
S. Manchurian Ry., China.....	1914	43	M. L.	T.	1,2

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RAILWAYS, ENERGY REQUIREMENTS AND MOTOR EQUIPMENT FOR. — (*See also Locomotives, Electric; Motors; Power Stations; Railways, Electric, Traction Systems for; Railways, Location and Permanent Way for; Substations, Railway.*) From a consideration of the forces acting on a moving train it is possible to determine the motor capacity and energy required to operate it when the profile and contour of the road, the time table and the characteristics of the available motors are known. The various items are treated in the following sequence: -

Forces Acting on a Train	p. 1291
Train Resistance	1292
Acceleration and Braking	1295
Tractive Effort Required	1296
Gear Ratio and Speed	1296
Power Required at Given Speed	1298
Over-all Efficiency	1298
Speed-time and Distance-time Curves	1299
Energy Consumption from Tests	1302
Approximate Method of Calculating Energy Consumption	1303
Step-by-step Method of Plotting Speed-time Curves	1305
Motor Capacity; R. M. S. Current and Average Voltage	1313
Analytical Method for Predetermining Energy Consumption and Motor Capacity	1317
Train and Load Diagrams	1324
Power Required for Car Heating and Lighting	1325
Bibliography	1326

UNITS AND ABBREVIATIONS. — Throughout this article the various quantities employed will be expressed in the following units unless specifically stated otherwise: distances in feet, weights in tons of 2000 pounds, forces in pounds, speeds in miles per hour (abbreviated mph.), accelerations in miles per hour per second (abbreviated mphps.), mechanical power in horse power, energy in watt-hours.

FORCES ACTING ON A TRAIN. — The forces tending to accelerate a train are the tractive effort developed by the motors and the component of the weight along the track on down grades. The forces which retard the motion of the train are the various frictional forces and the component of the weight along the track on up-grades; also in braking, the frictional force due to the brakes. All the various frictional forces, except the braking resistance, such as track friction, journal friction, air friction, etc., which oppose the motion of a train on a straight track are usually considered together and are referred to as the "train resistance." The extra friction due to track curvature is usually considered as an equivalent up-grade.

Tractive Effort and Draw-bar Pull. — The tractive effort of a motor is the force exerted by the motor at the rim of the driving wheel to which the motor is geared. The tractive effort of a locomotive is the force exerted by the locomotive at the rim of the drivers. The draw-bar pull of a locomotive is the force transmitted through the draw-bar of the locomotive,* and is less than its tractive effort by an amount equal to the resistance due to the rolling friction of the locomotive wheels on the track and the air resistance of the locomotive.

Direct-current motors deliver a uniform tractive effort for a given current; the tractive effort of alternating-current motors pulsates to some extent with the alternations of the current; the tractive effort of a steam locomotive varies

* In the case of a steam locomotive, the draw-bar pull usually refers to the force transmitted through the coupling between the tender and train; i.e., the tender is considered as a part of the locomotive.

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from 28 to 50 per cent above and below its average value during each revolution of the drivers.

Train Resistance. — The total train resistance includes the following:

Rolling friction, which depends on the stiffness of the rail and the rigidity of the roadbed, and upon the speed and the weight of the train.

Journal friction, which depends on the speed, weight of the train, temperature and condition of lubrication.

Effect of oscillation and concussion, which depends upon the square of the speed, the weight of the train, and upon the condition of the track and roadbed.

Air resistance, which depends upon the square (approximately only) of the speed, the end area and length of train (number of cars), upon the shape of the end surface, and upon the kind of platforms or vestibules, but is independent of the weight of the train.

In view of the numerous factors which affect the train resistance, it is practically impossible to devise a formula for the resistance per ton of train weight which will be applicable to all types of cars and track construction. Numerous formulas have been suggested, most of which are of the form

$$r = A + Bv + Cv^2,$$

where r = the resistance in pounds per ton, v = speed in miles per hour and A, B and C are constants determined by experiment. The values of these constants naturally depend upon the type of cars, nature of roadbed, number of cars in the train, etc.; consequently the values of these constants as obtained from tests on various types of equipment and track construction differ considerably.

Burch (*Electric Traction for Railway Trains, New York, 1911*) gives the following values for these constants under normal conditions of track and weather. In winter the total train resistance may be as much as 60 per cent greater than the values calculated from the above formula, when these values of the constants are used. An electric locomotive is to be treated as a single car, its weight averaged with the weight of the cars. In the case of a steam locomotive and tender, the tender is to be treated as a car, but the locomotive resistance is to be added as a separate item (*see below*).

Value of A. — This constant depends chiefly upon the average total weight of car and load. Let w = this average total weight *per car* in tons; then for

w =	15	20	25–30	35	40–45	50	70
A =	6.0	5.5	5.0	4.5	4.0	3.5	3.0

Value of B. — This constant depends primarily upon the nature of the track and roadbed and also to some extent upon the weight and type of the car. Burch gives the following values:

Passenger cars on excellent track	0.06–0.11
Passenger cars on ordinary track	0.10–0.15
Freight cars on ordinary track	0.05–0.06

The heavier the car the higher the value of this coefficient.

Value of C. — This constant depends primarily upon the air resistance at the head and rear ends of the train and along the sides of the train. It may be expressed approximately by the formula

$$C = \frac{Ks\,(0.9 + 0.1N)}{Nw},$$

where s = the cross section of car in square feet, N = number of cars, w = average weight of car and load in tons, and K = 0.0010 for parabolic ends,

wedge-shaped ends, 0.0028 for vestibule cars, 0.0030 for open plat-
33 for freight cars and 0.0040 for flat fronts.
de on three-car trains in the Boston-Cambridge subway gave a value
nately 0.0050 for the constant K, the higher value being due to the
sistance in the tunnel. (*See Elec. Ry. Jour., 1912, Vol. 40, p. 280.*)

's Table of Train Resistance. — Using the above values of the
Burch has calculated the following table for train resistance.

TRAIN RESISTANCE FOR ELECTRIC TRAINS

ber of cars (including electric locomotive, if any);
age weight of car loaded, in tons (= total weight of train divided by N);
resistance in pounds per ton;
d in miles per hour;
s section of car in square feet;
constants in the formula; K taken as 0.0030 throughout.

$$r = A + Bv + \frac{Ka\,(0.9 + 0.1\,N)\,v^2}{Nw}. \qquad (1)$$

TABLE I. — VALUES OF TRAIN RESISTANCE

	w	A	B	a	Speed in miles per hour					
					10	20	30	40	50	60
	15	6.0	0.11	100	9.1	16.2	27.3	42.4	61.5	84.6
	20	5.5	0.12	100	8.2	13.9	22.6	34.3	49.0	66.7
	25	5.0	0.13	100	7.5	12.4	19.7	29.4	41.5	....
	35	4.5	0.13	100	6.7	10.5	16.1	23.4	32.4	....
	45	4.0	0.13	110	6.0	9.6	14.5	21.2	28.8	....
	15	6.0	0.11	100	8.2	12.6	19.2	28.0	39.0	52.2
	20	5.5	0.12	100	7.5	11.2	16.5	23.5	32.1	42.4
	25	5.0	0.13	100	7.0	10.2	14.8	20.8	28.0	36.5
	35	4.5	0.13	100	6.3	9.0	12.6	17.2	22.8	29.3
	45	4.0	0.13	110	5.7	8.2	11.5	15.6	20.5	26.3
	15	6.0	0.11	100	7.9	11.4	16.5	23.2	31.5	41.4
	20	5.5	0.12	100	7.3	10.3	14.5	19.9	26.5	34.3
	25	5.0	0.13	100	6.8	9.5	13.2	17.9	23.7	30.1
	30	4.5	0.13	100	6.2	8.7	12.0	16.1	21.0	26.7
	35	4.5	0.13	100	6.1	8.5	11.4	15.2	19.6	24.6
	45	4.0	0.13	110	5.6	7.8	10.5	13.9	17.8	22.4
	25	5.0	0.13	100	6.7	9.2	12.4	16.4	21.3	26.8
	30	4.5	0.13	100	6.1	8.4	11.3	14.9	19.1	24.0
	35	4.5	0.13	100	6.1	8.2	10.9	14.1	18.0	22.3
	45	4.0	0.13	110	5.5	7.6	10.0	13.0	16.5	20.4
	25	5.0	0.13	100	6.6	8.8	11.6	15.0	19.0	23.6
	35	4.5	0.13	100	6.0	8.0	10.3	13.1	16.4	20.0
	45	4.0	0.13	110	5.5	7.3	9.5	12.1	15.1	18.4
	35	4.5	0.13	100	6.0	7.8	10.0	12.5	15.5	....
	45	4.0	0.13	110	5.4	7.2	9.2	11.7	14.4	....
	45	4.0	0.13	110	5.4	7.0	9.0	11.2	13.7	16.4

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TABLE I.—VALUES OF TRAIN RESISTANCE—*Continued*

	N	w	A	B	a	Speed in miles per hour					
						10	20	30	40	50	60
Freight Trains	10	30	5.0	0.06	110	5.8	7.0	8.7	10.7	....	....
	20	30	5.0	0.06	110	5.7	6.8	8.2	9.9	....	....
	30	40	4.0	0.06	110	4.7	5.6	6.7	8.1	....	....
	50	40	4.0	0.06	110	4.7	5.6	6.7	8.0	....	....
	40	50	3.5	0.06	110	4.2	5.0	6.0	7.2	....	....

Other Formulas for Train Resistance. — Of the numerous other formulas which have been proposed for train resistance the two most commonly employed are Armstrong's formula

$$r = \frac{50}{\sqrt{Nw}} + 0.03\,v + \frac{0.002\,a\,(0.9 + 0.1N)\,v^2}{Nw}$$

and Mailloux's formula

$$r = 3.5 + 0.15\,v + \frac{(0.25 + 0.02N)\,v^2}{Nw}.$$

The symbols have the same meaning as above. Armstrong's formula gives considerably lower values than those given by Burch, except for heavy trains; Mailloux's formula gives lower values than those given by Burch except for heavy trains at low speeds, but the difference in most cases is not very great. For other formulas proposed from time to time see Burch, *Electric Traction for Railway Trains*. See also an excellent paper on the resistance of freight trains by E. C. Schmidt in Trans. A.S.M.E., May, 1910.

Resistance of Steam Locomotives. — The American Railway Engineering Association recommend the formula for the resistance of a steam locomotive

$$r_1 = 18.7 + \frac{80\,X}{w_1},$$

where r_1 is the resistance (between cylinder and rim of drivers) per ton weight on the drivers, X is the number of driving axles and w_1 the total weight in tons on all the drivers. Tests by the American Locomotive Company showed that the resistance per ton weight on the drivers is 22.2 pounds.

Train Resistance at Starting. — The formulas given above are not applicable to speeds below about 10 mph. The New York Central tests on electric trains show that the train resistance decreases with decrease in speed to 10 mph., but that as the speed still further decreases the resistance per ton increases. The resistance at starting may be from 6 to 18 pounds per ton, depending upon the condition of the bearings, track, etc., and upon the duration of the stop preceding the starting. These figures also apply to freight trains. Tests on the Rock Island system showed that in the case of a train which had stood overnight in cold weather (i.e., which had become "frozen up"), the starting resistance was 30 pounds per ton. The slack in the car couplings, however, renders it unnecessary for a locomotive to exert sufficient effort to start all the cars at once.

Grades and Curvature. — (*See Railways, Location and Permanent Way for.*) An actual up-grade of G per cent produces a retarding force of $20\,G$ pounds per

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wn-grade of G per cent produces an accelerating force of $20\,G$ pounds
curve gives rise to a retarding force which may be represented by

$$r = 0.058\,SC,$$

(excess) curve resistance in lb. per ton,
speed, m.p.h.,
degree of curvature.

midt and H. H. Dunn, Univ. of Illinois, Bulletin, No. 92.)
r angles of curvature up to 12 degrees the angle in degrees may be
o $5730 \div R$ where R is the radius of curvature in feet.

RATION AND BRAKING. — The permissible rate of accelera-
upon a number of factors.

ting of the motors; the larger the motors the higher the tractive
an develop and therefore the greater the acceleration.
eight on the driving wheels of the car or locomotive; the maximum
rt that a motor car can exert without slipping the wheels is from
cent of the weight on the drivers (*see below under Adhesion Coeffi-*

mfort of the passengers; the higher the acceleration rate the more
for a passenger to maintain his equilibrium. This also depends to
upon the uniformity of the acceleration.
ke a given schedule speed with the least amount of energy the
rate should be as high as possible. Very high rates of accelera-
r, are not in general justified on this score, as the increase in the
notors required may more than offset the saving of energy.
ving rates of acceleration represent common practice:

TABLE II. — ACCELERATION RATES

Service	Miles per hour per second
notive, freight service	0.1 to 0.2
notive, passenger service	0.2 to 0.5
omotive, passenger service	0.3 to 0.6
tor cars, interurban service	0.8 to 1.3
tor cars, city service	1.5 to 2.0
tor cars, rapid transit service	1.5 to 2.0
ctical rate	2.0 to 2.5

— The maximum retardation in braking is limited by the comfort
agers, and injury to equipment, a retardation of 1.5 miles per hour
eing the usual practical limit for electric or steam passenger trains,
; miles per hour per second is sometimes attained. For freight
raking retardation is from 0.7 to 0.8 miles per hour per second,
the rate of braking the less the energy consumption for a given
ed.

ration Constant." — The tractive effort required to give to one
ounds) a linear acceleration of one mphps. is 91.2 pounds. To
train of W tons requires a tractive effort of $91.2\,aW$ pounds to pro-
r acceleration of a mphps., but on account of the accompanying
leration of the rotating parts an additional force is required. This

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additional force is proportional to the linear acceleration a and also depends upon the radius of gyration (*see Mechanics, Principles of*) of all rotating parts, and upon the gear ratio of the motors (i.e., ratio of number of teeth in gear to number of teeth in pinion). The effect of the moment of inertia may be looked upon either as increasing the effective weight W or as increasing the acceleration constant, the acceleration constant being defined as the quotient of total accelerating force divided by the product of weight and linear acceleration.

The increase in effective weight (in tons) due to any rotating axle or wheel is $\frac{M}{2000}\left(\frac{K}{r}\right)^2$, where M is the weight in pounds of the part in question, K its radius of gyration (*see Inertia, Moment of*) and r its actual radius, both in feet. Each motor armature adds to the effective weight $\frac{M}{2000}\left(\frac{\rho K}{r}\right)^2$ tons, where M is the weight of the armature in pounds, K the radius of gyration of the armature in feet; r the radius in feet of the wheel to which it is geared and ρ is the gear ratio. The total additional weight W_r is the sum of the above items for all the rotating parts. The total force in pounds required to produce the acceleration of a mphps. is then CaW, where W is the actual weight of the train in tons and $C = 91.2\left(1+\frac{W_r}{W}\right)$. This quantity C is the corrected acceleration constant, and this corrected value should be used in all calculations.

The acceleration constant is raised by the flywheel effect discussed above by about 5 per cent (i.e., $W_r/W = 0.05$) for heavy cars and locomotives, and between 5 per cent and 10 per cent for light low-speed cars, 8 per cent being an average figure. However, C is usually taken as 100, corresponding to an increase in effective weight of about 10 per cent. A given linear acceleration of a mphps. then requires an accelerating force of $100a$ pounds per ton.

TRACTIVE EFFORT REQUIRED. — Let

F = tractive effort, in pounds per ton, exerted by motors,
G = per cent actual grade (+ for up-grade),
g = degrees of curvature,
r = train resistance, in pounds per ton,
a = acceleration in mphps (− for retardation).

Then the tractive effort required per ton of total train weight is

$$F = 100a + r + 20G + g. \qquad (1)$$

Example. — Given a train of three 45-ton cars moving with a speed of 20 mph. and accelerating at a rate of 1.5 mphps. up a 1 per cent grade on a straight track; what is the total tractive effort required?

Answer: $(100 \times 1.5 + 7.8 + 20 \times 1)\,3 \times 45 = 24{,}000$ pounds.

GEAR RATIO AND SPEED. — By gear ratio is meant the ratio of the number of teeth in the gear on the wheel axle to the number of teeth in the pinion on the motor shaft. A gear ratio greater than 6:1 is seldom used for railway motors. For a given torque developed by the driving motor, the tractive effort at the wheel rim and the linear speed for a given current depend upon the gear ratio and wheel diameter. Let D = the diameter of the wheel in inches, K = the gear ratio, F = the tractive effort for a given current input; then the tractive effort F_1 for this same current input but for a wheel diameter D_1 and gear ratio K_1 is

$$F_1 = \frac{DK_1}{D_1K}F.$$

If V is the speed corresponding to the tractive effort F for a given motor voltage,

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then the speed V_1 corresponding to the tractive effort F_1 for the same motor voltage and current is

$$V_1 = \frac{DK_1}{D_1K} V.$$

If the gear ratio is low, the maximum speed will be high and the rate of acceleration low; if the gear ratio is high, the maximum speed will be low and the rate of acceleration high.

For a given motor equipment, train weight, schedule, and profile the energy consumption and temperature rise of the motors depend upon the gear ratio selected, since this in turn determines the amount of coasting; see section below on *Importance of Coasting*. The proper gear ratio can be found only by trial calculation, plotting speed-time and distance-time curves from motor curves based upon different gear ratios, and calculating the energy consumption and temperature rise in the motors as described below.

MAXIMUM POSSIBLE TRACTIVE EFFORT — ADHESION COEFFICIENT. — The adhesion or "tractive" coefficient is the quotient (expressed usually as per cent) of the tractive effort in pounds which will slip the drivers, divided by the weight in pounds on the drivers. Burch gives the values in the following table. The maximum possible tractive effort is the product of the adhesion coefficient (as a decimal fraction) by the weight (in pounds) on the drivers.

TABLE III. — ADHESION COEFFICIENTS

Condition of track	Without sand	With sand
Most favorable condition	35	40
Clean, dry rail	28	30
Thoroughly wet rail	18	24
Greasy moist rail	15	25
Sleet-covered rail	15	20
Dry-snow-covered rail	11	15

Maximum Grade Train can Ascend. — Let

W = total weight of train in tons,
W_d = total weight on all drivers in tons,
p = adhesion coefficient in per cent,
r = train resistance in pounds per ton of total weight,
G = per cent grade,
g = degree of curvature,
a = acceleration in miles per hour per second.

Then the maximum tractive effort which the drivers can exert is $20\,pW_d$ pounds, and therefore $(r + 20\,G + g + 100\,a)\,W$ must be less than $20\,pW_d$, or the maximum per cent grade which the train can ascend is *

$$G = \frac{pW_d}{W} - \frac{(r + g + 100\,a)}{20}. \qquad (3)$$

* To be exact W_d should be multiplied by $\sqrt{1-(G/100)^2}$, but except for very heavy grades this correction is negligible.

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This grade is greater the less the acceleration, or the greater the retardation. The greater the speed before the train strikes the grade, the greater may the retardation be without bringing the train to rest on the grade, and therefore the steeper the grade it may ascend.

Example. — Assume no acceleration or retardation and no curvature, a train resistance of 8 pounds per ton, an adhesive coefficient of 15 per cent, and 25 per cent of total weight of train on drivers. Then the maximum grade the train can ascend is $G = 15 \times 0.25 - 8/20 = 3.35$ per cent.

The highest permissible grade is when all the weight is on the drivers, e.g., single cars or trains of motor cars with all axles equipped with motors. On steam freight roads the maximum grade seldom exceeds 2 per cent, and is usually considerably less, except in very mountainous country.

Weight of Locomotive. — The weight of locomotive required to accelerate a train weighing W tons at the rate of a miles per hour per second up a grade of G per cent on a g degree curve against a frictional resistance of r pounds per ton, when the q per cent of the weight is on the drivers and the coefficient of adhesion is p per cent, is given by the following formula:

$$\text{Weight of locomotive} = \frac{5W}{pq}(100\,a + r + 20\,G + g).$$

Example: What weight of locomotive is required to accelerate a 400-ton train at the rate of 0.5 mile per hour per second up a 0.1% grade against a frictional resistance of 8 lb. per ton, when 80% of the weight is on the drivers and the coefficient of adhesion is 20%?

$$\text{Weight of locomotive} = \frac{5 \times 400}{20 \times 80}(50 + 8 + 2) = 75 \text{ tons.}$$

POWER REQUIRED AT GIVEN SPEED. — Let

r = train resistance in pounds per ton of total train weight,
G = per cent grade,
g = degree of curvature,
a = acceleration in mphps.,
v = speed in mph.,
W = total weight of train in tons.

Then the power required *at the rims of the drivers* is $1.99\,v\,(r + 20\,G + g + 100\,a)$ watts per ton, or $p_0 = 2.67 \times 10^{-3}\,vW\,(r + 20\,G + g + 100\,a)$ horse power, total. (4)

The *power input* p_i to the car or locomotive is equal to the power at the rims of the drivers divided by the over-all efficiency ϵ of the controller, motors and gears, i.e.,

$$p_i = \frac{1.99\,Wv\,(r + 20\,G + g + 100\,a)}{1000\,\epsilon} \quad \text{kilowatts} \qquad (5)$$

Efficiency of Motors. — The over-all efficiency of the motors and gears when the motor is operating at full line voltage does not vary considerably for loads ranging from 50 to 150 per cent of rated load. The maximum efficiency is usually at about rated load, and has the values given in Table IV. At 50 and 150 per cent load, the efficiency may be from 3 to 10 per cent less, depending upon the design and the type of motor. The variation in efficiency with load is usually greater with alternating-current series than with direct-current motors.

Average Over-all Efficiency During Controller Period. — The over-all efficiency of the motors and controller depends upon the type of control employed and upon the resistance inserted or the connections made by the controller. Most modern controllers for interurban cars are provided with a

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TABLE IV. — MAXIMUM OVER-ALL EFFICIENCY OF MOTORS AND GEARS AT RATED VOLTAGE.

Horse power, 1-hour rating	Kind of motor	Max. eff., per cent
30–100	D.C. geared	83–88
100–250	D.C. geared	88–89
250–500	D.C. gearless	91–93
50–200	A.C. series geared	70–80*
200–500	3-phase induction geared	85–89

* Including step-down transformers.

current-limiting device which limits the current to a given value, usually the value of the current corresponding to the 1-hour rating of the motor. Under these conditions the *average* over-all efficiency of the motors and controller over the whole of the *controller period* (i.e., from time of starting until full line voltage is established across each motor or until all resistance is cut out) may be expressed as follows, on the assumption (which is very nearly exact) that the speed of the motor varies directly as the voltage impressed across its terminals:

Let ϵ = the over-all efficiency of the motors and gears at end of controller period. Then for straight resistance control with direct-current or induction motors the average efficiency during the controller period is $\epsilon/2$; for series-parallel control with 2 direct-current motors the average efficiency during the controller period is $2\epsilon/3$; with 4 direct-current motors first all in series, then 2 series sets in parallel, and then all 4 motors in parallel the average efficiency during the controller period is $8\epsilon/11$; for alternating-current series motors with voltage control the average efficiency during the controller period (including losses in step-down transformers) is about 0.90ϵ. Hence for a motor having an 85 per cent efficiency at the 1-hour rating and the starting current limited to the corresponding current rating, the average over-all efficiency of the controller, motors and gear during the controller period is

For straight resistance control	43 per cent
For series-parallel control, direct-current motors	57 per cent
For series-series-parallel control, direct-current motors	62 per cent

Example. — Given a train of three 45-ton cars each car equipped with two 200-horse-power direct-current motors. What is the input to each motor if the speed is 30 mph. and the train is accelerating at 1.0 mphps. up a 2-per-cent grade, the track being straight, and full line voltage being across each motor?

Answer: From Table I the train resistance is $r = 10.5$, and from equation (4) the total power output is

$$p_0 = 2.67 \times 10^{-3} \times 30 \times 135\,(10.5 + 20 \times 2 + 100 \times 1)$$
$$= 1627 \text{ horse-power},$$

or $1627/6 = 271$ horse power per motor. Assuming an efficiency of 87 per cent, the input to each motor is $271 \times 0.746/0.87 = 232$ kilowatts, and the total input to the train $6 \times 232 = 1392$ kilowatts.

If the train accelerates at this same rate from rest to a speed of 30 mph. at the end of the controller period (series multiple control) the grade being 2 per cent throughout, the average output of the motor would be the output corresponding to half speed or 15 mph., or 136 horse power per motor, requiring an

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average input of $136 \times 0.748/0.57 = 178$ kilowatts, and the average input to the train during the controller period would be $6 \times 178 = 1068$ kilowatts.

SPEED-TIME AND DISTANCE-TIME CURVES. — To determine the energy required to propel a car or train a given distance over a given track in a given time requires the consideration of a number of factors which can best be taken into account by the construction of various kinds of time curves. Such curves may be constructed with practically any degree of accuracy desired when the profile of the track, the weight of the train, the various resistances, schedule speed, time of stops, etc., are accurately known. Such data are, however, seldom known with any great precision, and consequently elaborate methods of plotting and calculation are seldom justified. Below will be given (1) some results of actual tests, (2) a rough but simple method of approximating the energy requirements, (3) a step-by-step method, which, though tedious in application, is susceptible of any degree of accuracy desired, provided the given data are accurately known, and (4) an analytical method by which the effect of changes in the time of coasting, rates of acceleration and braking, etc., may be predetermined.

The following terminology will be employed:

Speed-time Curve. — A curve showing the speed (in mph.) plotted as ordinates against elapsed time (in seconds) as abscissas; e.g., the curve *A BCEF* in Fig. 1. A speed-time curve may be conveniently divided into four parts, namely:

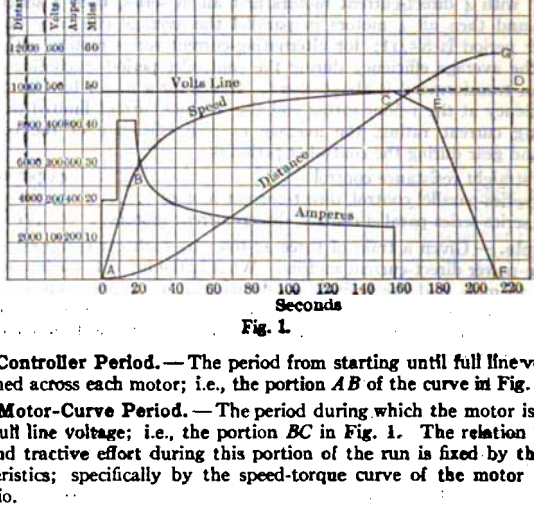


Fig. 1.

Controller Period. — The period from starting until full line voltage is established across each motor; i.e., the portion *AB* of the curve in Fig. 1.

Motor-Curve Period. — The period during which the motor is operating on full line voltage; i.e., the portion *BC* in Fig. 1. The relation between speed and tractive effort during this portion of the run is fixed by the motor characteristics; specifically by the speed-torque curve of the motor and the gear ratio.

Coasting Period. — The period during which the car or train is coasting; i.e., the portion *CE* in Fig. 1.

Braking Period. — The period during which the brakes are applied; i.e., the portion *EF* in Fig. 1.

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Distance-time Curve. — A curve showing the distance covered (in feet) plotted as ordinates against elapsed time (in seconds) as abscissas; e.g., the curve AG in Fig. 1.

Current-time Curve. — A curve showing the line current (in amperes) plotted as ordinates against elapsed time (in seconds) as abscissas; e.g., the curve marked "Amperes" in Fig. 1.

Voltage-time and Power-time Curves. — Curves showing respectively the voltage per motor (or the line voltage) and the power input to the motor (or train) plotted as ordinates against elapsed time (in seconds) as abscissas.

Average Speed and Schedule Speed. — The average speed V is the total distance run L' (in miles) divided by the time (in hours) the train is actually running. The schedule speed S is the total distance run (in miles) divided by the total time (in hours) of the run from one end of the road to the other, including time of all stops at intermediate stations. If the *total* time of all the *intermediate* stops is T_s' seconds, then

$$V = \frac{S}{1 - \frac{T_s' S}{3600\, L'}}, \tag{6}$$

where V and S are in miles per hour and L' is the *total* length of route in *miles*.

Duration and Frequency of Station Stops. — The duration of each stop for surface cars ranges from 5 to 10 seconds, for elevated and subway trains from 10 to 30 seconds, for interurban trains from 10 to 40 seconds. The stops per mile are the reciprocal of the average distance in miles between stops. For the six most important elevated and subway lines in Europe and America, the stops per mile average 2.5.

Average Equivalent Grade (G).—Grades may be taken into consideration by calculating the sum H_1 of all the rises on upgrades and the sum H_2 of all the drops on down grades, and taking for the average "equivalent" upgrade in per cent

$$G = \frac{100(H_1 - 0.5\, H_2)}{L}, \tag{7}$$

where H_1 and H_2 are in feet and L is the total length of the route in feet. On a round trip $H_1 = H_2$, and the "equivalent" grade in per cent is

$$G = \frac{50 H_1}{L}.$$

This method of dealing with grades is equivalent to assuming that half the kinetic energy stored in the train or down grades is utilized in taking the train up the following upgrade. The amount of energy thus rendered available of course will depend upon the amount of braking necessary on down grades to prevent excessive speeds and also upon the location of the stops with respect to the grades. The figure ½ is taken as an approximate average; this figure may be varied as seems reasonable in view of the actual profile.

Average Angle of Curvature (g). — Curves may be taken into account by finding the average curvature, i.e., finding for each curve the product of the degree of curvature by the length of the curve, adding all these products and dividing by the length of the route.

ENERGY CONSUMPTION FROM TESTS. — The table on p. 1302 gives the energy consumption, as found by tests, for a number of typical services. This table will be found useful as a rough check on any calculations made for a specific service. Methods of making such calculations are given below.

TABLE V.—WATT-HOURS PER TON-MILE AT CARS, FROM ACTUAL TESTS

	N.Y.N.H.& H.R.R.		N.Y.C.&H.R.R.		N.Y.N.H.& H.R.R.		N.Y.C.&H.R.R.		N.Y. N.H. &H. R.R.	Interborough Subway, N.Y.		Northern Texas Trac. Co.		Urban trolley lines.
										Express	Local			
Service	P	P	P	P	P	P	P	P	P	P	P	P	P	P
A. C. or D. C.	A. C.	A. C.	D. C.	D. C.	A. C.	A. C.	D. C.	D. C.	A. C.	D. C.	D. C.	D. C.	D. C.	D. C.
Locomotive or cars	*L.*	*L.*	*L.*	*L.*	*L.*	*L.*	L.	L.	L.	C.	C.	C.	C.	C.
Train weight, tons	316	285	266	250	477	493	432	434	1438	310.6	310.6	25.4	25.4	4–12
Length of run, miles	20.6	20.6	23.9	23.9	20.6	20.6	17.1	17.1	16.8	12.9	6.6	28.4	28.4	.....
Average grade, per cent	+0.053	−0.053	+0.129	−0.129	+0.053	−0.053	+0.129	−0.129	−0.52	0	0	0	0	.....
Schedule speed, mph	22.1	22.1	23.2	22.8	44.7	49.0	44.1	43.9	35.9	20.2	12.4	28.6	29.6	.....
Stops per mile	0.63	0.68	0.84	0.75	0.048	0.048	0.059	0.059	0.06	0.62	1.76	0.32	0.27	2–10
Watt-hours per ton-mile	85.4	74.2	81.6	59.4	35.0	30.0	20.2	17.6	25.9	58.2	78.6	75.5	72.5	100 to 160
Differences	1	1	2	2	1	1	2	2	1	3	3	4	4	

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APPROXIMATE METHOD OF CALCULATING ENERGY CONSUMPTION.—The following method is based upon simple kinetic principles, and, if certain characteristics of the run are known, gives the actual energy output at the wheel rims. This fact makes the method useful, not only for rough calculations, but also to check calculations made by the step-by-step method.

When the method is applied to checking purposes, the column of Table VI. headed "Actual energy output" should be used, and the input calculated from the known efficiencies. When applied to rough calculations, the column headed "Approximate electrical energy input" should be used. In the latter case the maximum speed and length of run with power on are not known, but it is possible to assume certain values, based upon experience, which will give a rough approximation to the energy required. Let

V = average running speed in miles per hour,
V_m = maximum speed in miles per hour,
L = length of run in miles,
L_p = distance traveled, with power on, in miles,
$n = 1/L$ = number of stops per mile including one terminus,
r = average train resistance, in lb. per ton (Say that corresponding to a speed from 10 to 20 per cent greater than the average speed),
G = average equivalent grade, in per cent,
g = average curvature in degrees,
$K = \frac{V_m}{V}$ = ratio of maximum to average speed; see Table VII,
$Q = \frac{L}{L_p}$ = ratio of length of run to distance traveled with power on; see Table VII.

TABLE VI.—OUTPUT AT WHEEL RIM AND INPUT TO CAR IN WATT-HOURS PER TON-MILE

Energy for	Actual energy output at wheel rims of cars	Approx. electrical energy input to cars
Acceleration	$\frac{V_m^2}{36.2L}$	$\frac{K^2nV^2}{25}$
Train resistance	$\frac{1.99\,rL_p}{L}$	$\frac{2.9\,r}{Q}$
Grades	$\frac{39.8\,GL_p}{L}$	$\frac{57\,G}{Q}$
Curves	$\frac{1.99\,gL_p}{L}$	$\frac{2.9\,g}{Q}$
Total	Sum	Sum

NOTE.—$25 = 36.2\,\epsilon$, $57 = 39.8 + \epsilon$, and $2.9 = 1.99 + \epsilon$, where ϵ is the efficiency, taken as 0.7. The formula for energy due to curves assumes each degree of curvature to be equivalent to a train resistance of one pound per ton, which is probably high.

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TABLE VII.—VALUES OF K AND Q

Stops per mile s	K		Q
	Locomotive Passenger Trains	Single cars, multiple-unit trains and freight trains	All trains
0	1.00	1.00	1.00
0.1	1.18	1.10	1.11
0.2	1.35	1.18	1.24
0.3	1.48	1.25	1.38
0.4	1.60	1.31	1.52
0.5	1.68	1.36	1.67
0.6	1.75	1.40	1.78
0.7	1.82	1.44	1.89
0.8	1.86	1.47	1.99
0.9	1.90	1.50	2.07
1.0	1.93	1.52	2.15
1.2	1.93	1.56	2.24
1.4	1.98	1.59	2.34
1.6	1.94	1.62	2.44
1.8	1.94	1.65	2.52
2.0	1.95	1.68	2.58
2.5	1.95	1.75	2.71
3.0	1.96	1.80	2.81
3.5	1.96	1.85	2.87
4.0	1.97	1.90	2.91
4.5	1.97	1.94	2.95
5.0	1.98	1.97	3.00
over 5.0	2.00	2.00	3.00

(The above method was worked out by D. C. Woodbury and W. A. Del Mar, the table being based upon a large number of actual and calculated runs.)

Example.—A multiple-unit train has a speed (excluding stops) of 25 miles per hour and makes 0.8 stops per mile. It ascends an average grade of 0.143 per cent. What will be its energy consumption in watt-hours per ton-mile?

From Table VII we find for $s = 0.8$, that $K = 1.47$ and $Q = 1.99$. Then using the formulas in Table VI, the results in the table on the next page are obtained, assuming 6.5 pounds per ton for friction.

Efficiency of Run.—The formulas given above enable one to judge the effect upon the energy consumption, of altering any of the principal physical elements upon which the run is based.

From the formulas for kinetic energy it is obvious that a low value of K means a low energy consumption. A low value of K, however, means a "square" speed-time curve; i.e, for low energy consumption the controller, acceleration and braking periods should be as short as possible, or in other words, the rate of acceleration and braking should be as great as practicable.

The quantitative effect of changing any of these variables may be estimated by the analytical method given further on.

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Energy for	Watt-hours per ton-mile
Acceleration	$\frac{1.47^2 \times 0.9 \times 25^2}{25} =$ 48.5
Train resistance	$\frac{2.9 \times 6.5}{1.99} =$ 9.5
Grades	$\frac{57 \times 0.143}{1.99} =$ 4.1
Total	62.1

This example worked out by the step-by-step method gave 60.5 watt-hours per ton-mile.

STEP-BY-STEP METHOD OF PLOTTING SPEED-TIME CURVES. — There is no way of exactly predetermining a speed-time curve except by a number of successive trials. That is to say, the time the current is kept on, the time of coasting and the time of braking must each be guessed and it is usually necessary to make a number of trials, by varying the proportion of motor run, coasting and braking, before the given distance is traversed in the desired time.

If the characteristics of the train and its equipment are expressed numerically, the principles of mechanics enable such trial runs to be plotted on paper and the proper proportion of motor run, coasting and braking, selected to make the train travel the desired distance in the given time. For a given motor equipment on a given route it is possible to plot by a step-by-step method these speed-time curves, and then from these curves and the characteristic curves of the motors the various characteristics, such as energy consumption, root-mean-square current, etc., may be determined. The accuracy of this method depends solely upon the accuracy with which the assumed data are known. The necessary data are:

Profile and alignment of road.
Characteristic curves of the motors.
W = total weight of train in tons,
T = the time of run in seconds between successive stops,
I_0 = the permissible starting current, or
a = the acceleration in miles per hour per second during the controller period,
b = the braking rate in miles per hour per second,
r = the train resistance in pounds per ton at any speed.

Determination of Acceleration and Retardation Rates. — From the motor characteristics, which are usually given in the form indicated in Fig. 2, determine the tractive effort and speed corresponding to the permissible starting current. This is usually taken as the current corresponding to the 1-hour rating; in the case of the motor whose characteristics are shown in Fig. 2, this current is 315 amperes, the speed 19.6 mph. and the tractive effort 4300 pounds. If each car is equipped with two motors, the weight corresponding to each motor is half the weight of the car. If the cars weigh 44 tons each, then the tractive effort per ton developed by the motors at this speed is $4300/22 = 195$ pounds per ton. At the point where the motors are changed from series to parallel the speed

will be approximately one-half the speed at rated voltage or 9.8 mph. If the average line voltage is less than the rated voltage, these speeds should be reduced in proportion to the ratio of the actual to the rated voltage. In the case selected the average line voltage is 571 volts; hence the speeds corresponding to the parallel and series points are 18.6 and 9.3 mph respectively. These speeds and the corresponding tractive efforts are entered into Table VIII.

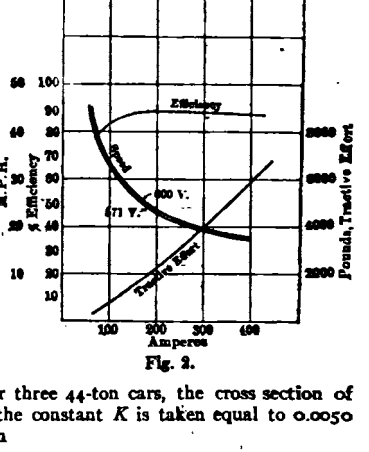


Fig. 2.

From the motor characteristics determine the tractive effort (f) in pounds per ton and the corresponding speeds (v), corrected for line voltage, up to the maximum permissible speed, and enter these in Table VIII. Also enter into this table the train resistance corresponding to the various speeds. In the table given, the train resistance is calculated from Burch's formula for three 44-ton cars, the cross section of each car being 120 square feet, and the constant K is taken equal to 0.0050 (subway service). The formula is then

$$r = 4.0 + 0.13\,v + 0.0055\,v^2,$$

where v is the speed in miles per hour.

The available tractive effort in pounds per ton for acceleration on any grade is then $f - r - 20\,G'$, and the acceleration rate is (assuming an acceleration constant of 100)

$$a = \frac{f - r - 20\,G'}{100},$$

where G' is the "equivalent" grade (including curvature, see above), in per cent. The value of a is calculated for grades of 0, 1, 2, 3, etc., per cent, both up and down, including the largest up and down grade. These values are entered into Table VIII. The maximum speeds are the speeds for which the acceleration becomes zero. These can be obtained by plotting the accelerations against speed, and finding the speed at which the curves cross the speed axis.

Similar calculations should also be made for the retardation on up-grades when the train strikes such a grade, with power on, at a higher speed than the free running speed on the grade, and also for the coasting period when no power is on. When power is on, the friction of the gears and motors is allowed for in the motor tractive effort curve, the tractive effort curve being the gross tractive effort less these losses. The friction of the gears and motors may be taken as approximately 5 per cent of the rated tractive effort, which, in the special case under consideration is $0.05 \times 195 = 10$ pounds per ton. The total train resistance in coasting is then the normal train resistance plus the resistance of gears and motors.

In the Tables a + acceleration signifies an actual increase in velocity, a − acceleration a retardation, or decrease in velocity.

The braking rate is assumed constant, usually $b = 1.5$ mphps.

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TABLE VIII. — ACCELERATION RATES

v	Motor tractive effort, pounds per ton f	Train resistance, pounds per ton r	Acceleration rates, mphps., = a: Per cent equivalent grade given in first line						
			+3	+2	+1	0	−1	−2	−3
3	195	6	1.29	1.49	1.69	1.89	2.09	2.29	2.49
6	195	8	1.27	1.47	1.67	1.87	2.07	2.27	2.47
	159	9	0.90	1.10	1.30	1.50	1.70	1.90	2.10
	112	10	0.42	0.62	0.82	1.02	1.22	1.42	1.62
	74	11	0.03	0.23	0.43	0.63	0.82	1.03	1.23
	45	13	.....	.....	0.12	0.32	0.52	0.72	0.92
	27	15	.....	.....	.....	0.12	0.32	0.52	0.72
	18	18	.....	.....	.....	0.00	0.20	0.40	0.60
	18	18	−0.60	−0.40	−0.20	.....	.....	.....	.....
	27	15	−0.48	−0.28	−0.08	.....	.....	.....	.....
	45	13	−0.28	−0.08	.....	.....	.....	.....	.....
	0	34	−0.94	−0.74	−0.54	−0.34	−0.14	+0.06	+0.26
	0	31	−0.91	−0.71	−0.51	−0.31	−0.11	+0.09	+0.29
	0	28	−0.88	−0.68	−0.48	−0.28	−0.08	+0.12	+0.32
	0	25	−0.85	−0.65	−0.45	−0.25	−0.05	+0.15	+0.35
	0	23	−0.83	−0.63	−0.43	−0.23	−0.03	+0.17	+0.37
	0	21	−0.81	−0.61	−0.41	−0.21	−0.01	+0.19	+0.39
	0	19	−0.79	−0.59	−0.39	−0.19	+0.01	+0.21	+0.41

The train resistance is assumed to be 6 lb. per ton from zero speed to 9.3 our.

uction of Acceleration and Retardation Time Curves. — The is to construct a set of acceleration speed-time and distance-time set of coasting speed-time and distance-time curves, and a braking and distance-time curve. The construction of these curves is based owing relations:

he speed in miles per hour at time t_1,
he speed in mph. at time t_2,
$\frac{v_1 + v_2}{2}$ = average speed during the interval $t_2 - t_1$,
he acceleration in miles per hour per second at time t_1,
he acceleration in miles per hour per second at time t_2,
$\frac{a_1 + a_2}{2}$ = average acceleration during the interval $t_2 - t_1$; (for the first speed corresponding to half the speed at end of controller period),
he distance in feet from the starting point at time t_1,
he distance in feet from the starting point at time t_2.
a small change in speed,

$$t_2 - t_1 = \frac{v_2 - v_1}{a} \quad \text{seconds} \qquad (8)$$

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and the distance covered in this interval is

$$x_2 - x_1 = 1.466\, v\, (t_2 - t_1)$$ fe

or, when the speed is plotted against time,

$$x_2 - x_1 = 1.466 \times$$ (Area of speed-time curve between

From equation (8), using the values of a given in Table which any speed is reached may be calculated. The re culations for the special case under consideration are given in plotted in Figs. 3, 4 and 5. The distance-time curves are tering the speed-time curves and multiplying by 1.466 (*see e* also plotted in Figs. 3, 4 and 5.

TABLE IX. — DATA FOR ACCELERATING, COAS RETARDING SPEED TIME CURVES

	Speed v	Total time in seconds to accelerate f Per cent equivalent grade				
		+3	+2	+1	0	
Accelerating, power on	0.0	0	0	0	0	
	9.3	7	6	6	5	
	18.6	14	12	11	10	
	20	17	13	12	11	1
	22	20	16	14	12	1
	25	33	23	19	16	1
	30	Max. speed =25.3	Max. speed =27.5	37	26	2
	35	..	..	Max. speed =32	49	3
	40	..	..	..	132	5
		Total time in seconds to retard from 40 m				
Retarding, power on	40	0	0	0	..	
	35	9	15	36	..	
	30	22	43	Min. speed =37	..	
	....	Min. speed =25.3	Min. speed =27.5	..	..	
		Time in seconds required for speed to decrease 5 mph. speed given in first column.				
Coasting, power off	45	5	7	10	15	4
	40	6	7	10	17	5
	35	6	8	11	19	7
	30	6	8	11	21	12
	25	6	8	12	23	25
	20	6	8	13	25	

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The speed during the braking period t seconds *before* the train stops is $v = bt$ and the distance to travel to come to rest is $x = \frac{1}{2} bt^2$.

In the special case of a braking rate of 1.5 mphps.,

$$v = 1.5\,t \text{ miles per hour,}$$

and the distance to travel to come to rest is

$$x = \frac{1.466 \times 1.5\,t^2}{2}.$$

The corresponding curves are given in Fig. 6.

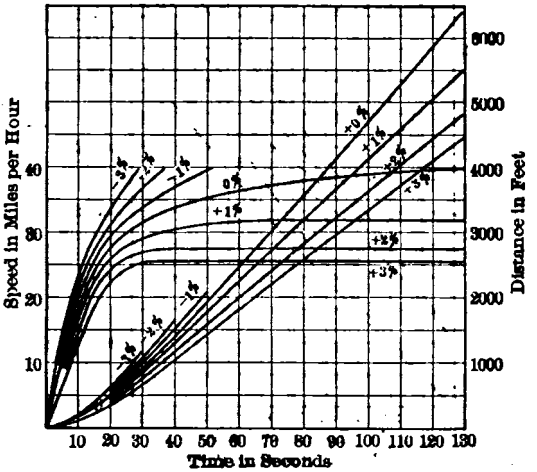


Fig. 3. Accelerating

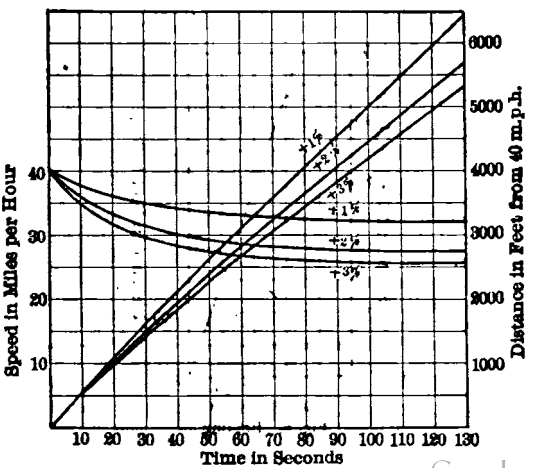


Fig. 4. Retarding, Power On

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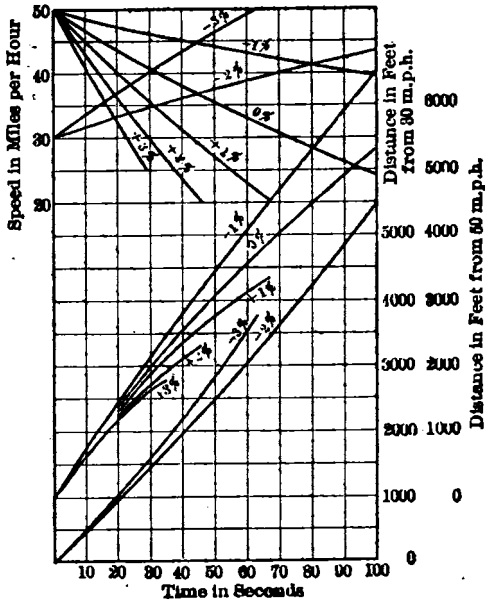


Fig. 5. Retarding, Power Off

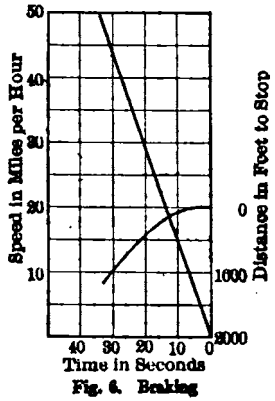


Fig. 6. Braking

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Time Curves for Given Profile and Alignment. — With these four sets of curves the speed-time curve for any given run with this particular equipment may be rapidly constructed. For intermediate grades interpolation may be readily made. In Fig. 7 is given a profile and alignment between two stops. The first step is to make up a table like Table X, dividing the route into sections such that the "equivalent" grade (= actual grade plus, say, 0.05 per cent for each degree of curvature, assuming a resistance of 1 pound per ton per degree of curvature) is the same throughout each section.

TABLE X. — "EQUIVALENT" GRADES

Stop	Distance between stops, feet	Length of section in feet	Per cent grade = G	Radius of curvature in feet	Degree of curvature = g	"Equivalent" grade $G' = G + 0.05\,g$
A	....	505	.....	....	...	.....
	....	145	.....	1130	5.0	+0.25
	....	908	+0.70	1130	5.0	+0.95
	....	77	+0.50	1130	5.0	+0.75
	....	633	+0.50	....	...	+0.50
	....	273	+3.00	....	...	+3.00
	....	273	+3.00	800	7.2	+3.36
	....	247	.....	800	7.2	+0.36
	....	94	.....	....	...	.....
	....	308	−2.95	....	...	−2.95
	....	800	+3.00	....	...	+3.00
	....	1862	−3.00	....	...	−3.00
	....	192	−3.00	5000	1.2	−2.94
	....	234	+0.12	5000	1.2	+0.18
	....	178	+0.12	....	...	+0.12
	....	69	+0.12	5000	1.2	+0.18
	....	358	.....	5000	1.2	+0.06
B	7321	165	.....	....	...	.....

For a complete round trip over the entire route the time curves must be plotted for the entire route in both directions. The run in one direction between two stations only will be considered in the numerical calculations given below.

Next lay off on a piece of tracing cloth, see upper part of Fig. 7, a distance equal to the time of run between the two stations (156 seconds in the example), to the same scale as Figs. 3 to 6. The braking speed-time curve can be laid off directly at the far end of the run by placing Fig. 6 under the tracing cloth and tracing the curve. Similarly, by placing Figs. 3 and 4 under the tracing cloth and tracing for the proper distance the curve corresponding to the proper grade, an acceleration curve can be built up until this curve intersects the braking curve. If the total distance, as read off from the corresponding distance-time curve, is greater than the actual distance, it will be necessary to introduce a coasting period of proper duration to make the total distance as read off from the distance-time curves equal to the actual distance. This can be done by placing Fig. 5 under the tracing cloth, and by cut and try finding the proper amount of coasting.

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In case there are curves or crossovers, requiring a reduction in speed at certain points, these reductions should be allowed for in plotting the speed-time

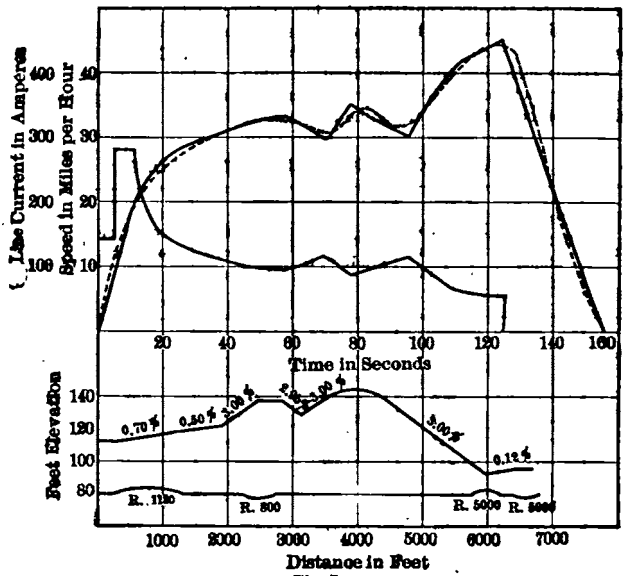


Fig. 7.

curve. A rough rule for the permissible speeds on properly constructed curves is that

$$\text{Speed on curve} = \sqrt{\text{Radius of Curve}},$$

where the radius is in feet and the speed in miles per hour.

The dotted curve in Fig. 7 was obtained from test.

Current-time Curve. — The motor current for any speed may be taken directly from the speed-time curve and motor characteristics. From the motor currents the line current is readily found by multiplying by *half* the number of motors during the *series* portion of the controller period and by the total number of motors during the rest of the time power is on. Current-time curves (line current) for the various grades may also be drawn once for all in the same manner as the speed-time curves in Fig. 3. The curve with the square shoulder in Fig. 7 is the current-time curve for the example considered.

Watt-hours per Ton-Mile. — During the first half of the controller period the input per motor is equal to the product of the current per motor by approximately one-half the line voltage (series-parallel control assumed); during the rest of the time that power is on, the input per motor is equal to the product of the motor current by the line voltage. Hence, calling A the area of the current-time curve from the start until power is shut off, and I_0 the starting current, E the average line voltage, T_1 the seconds duration of the controller period, L the length of the run in miles, M the number of motors and W the weight of the train in tons, then to a fair approximation,

$$\text{Watt-hours per ton-mile} = \frac{EM(A - 0.25I_0T_1)}{3600\,WL}.$$

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A more accurate, but tedious method, is to plot a power-time curve by multiplying the total current per train at successive intervals of time by the average line voltage during this interval, and then integrating this curve to find the total watt-seconds. This area, in watt-seconds, divided by $(3600\,WL)$ will give the watt-hours per ton-mile. In making such a calculation note that during the series part of the controller period the current per train is equal to the current per motor multiplied by *half* the number of motors.

Root-mean-square Current per Motor. — This may be found by squaring the ordinates of the current-time curve (current per *motor*), plotted as described above, and dividing by the time of run including stops and taking the square root of the quotient. Or, the current-time curve may be plotted in polar co-ordinates, taking time in seconds as the angle in degrees and current in amperes as the radius vector. See Fig. 8. Calling B the area of this curve, the unit of area being the square whose side has a length corresponding to 1 ampere, then the root-mean-square current is

$$I_e = 10.7\sqrt{\frac{B}{T+T_s}},$$

where T is the time that the train is moving and T_s the standing time, both in seconds.

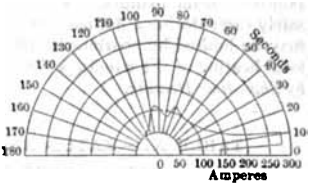


Fig. 8.

Average Motor Voltage. — For a simple run, such as shown in Fig. 1, average motor voltage during the controller period is equal to approximately 55 per cent of the line voltage, assuming 10 per cent of line voltage across the motors at the instant of starting. Let

E = average line voltage,
T_1 = time of controller period, from speed-time curve,
T_2 = time motor is running on full line voltage,
T = total time that the train is moving,
T_s = total standing time.

Then average motor voltage for the entire run is

$$E_m = \frac{0.55\,ET_1 + ET_2}{T+T_s}.$$

For a complex run, where the controller is shut off and put on again during the run, a voltage-time curve may be plotted and the average ordinate obtained by integration.

MOTOR CAPACITY. — A railway motor is usually rated in terms of the output in kilowatts or horse-power which it will give when run for 1 hour at rated voltage with a temperature rise above the surrounding air not exceeding 75° C. in any part of the motor, other than the commutator (*see Standards of the A. I. E. E.*).

The size of motor required for any particular service (i.e. for a given route, schedule, weight of car, line voltage and per cent coasting) depends upon two factors, (1) the motor must be of such a size that the maximum current required will not produce harmful sparking at the brushes or dangerous mechanical stresses in any part of the motor, and (2) the temperature must not rise to a value which will cause the insulation to deteriorate.

Size of Motor Limited by Commutation and Mechanical Stresses — The maximum current is usually that required at starting, and since the start-

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ing current remains practically constant up to the point where full line voltage is impressed across the motor, the corresponding maximum horse-power output of the motor can be calculated directly from equation (4), when v is taken as the speed at the end of the controller period and W as the weight of the train per motor, i.e., W is taken equal to the total weight of train divided by the number of motors. A safe rule for non-interpole motors in single-car or multiple-unit service is to limit the starting current to a value equal to the rated current. For interpole motors in like service the starting current may safely be 25 to 50 per cent in excess of the rated current.

In locomotive work a heavier starting current is sometimes demanded, and due to the low acceleration rate during the starting period the motor must carry this current for a longer interval than in the case of single-car or multiple-unit service. In selecting a motor for such service, information should be obtained from the manufacturer as to the maximum current which the motor can safely carry during a limited period, say for 5 minutes. This maximum current may be limited by sparking at the commutator, by mechanical stresses, or by local heating of the windings. See also section below on *Size of Motor Limited by Short-time Heating.*

TABLE XI.—RATED AND CONTINUOUS CAPACITY OF WESTINGHOUSE RAILWAY MOTORS

	Type, Westinghouse	Rated H.P.	Rated voltage	Rated amperes	Continuous current capacity		Weight in pounds
					At 300 volts	At 450 volts	
Self-ventilated	508A	25	600	37	32	35	1035
	514	40	600	60	35	36	1650
	532A	50	600	74	44	45	2300
	306CV4	65	600	94	58	60	2750
	548C8	100	600	145	90	93	3175
	333V8	125	600	180	110	115	3850
	557A8	140	600	202	130	135	4050
	577A6	190	600	268	175	180	5650
Non-ventilated	323A	32	500	58	28	26	1890
	307	50	600	73	37	35	2850
	306	50	500	87	44	40	2661
	310	60	500	107	50	46	3510
	305	60	500	107	50	46	3550
	304	75	500	130	60	55	3550
	303	100	550	158	70	65	3950
	302	125	550	195	95	85	4685
	301	160	550	246	120	110	5510
	300	200	550	310	150	130	6475

Size of Motor Limited by Heating.— The heat developed in a railway motor is carried partly by conduction through the several parts and partly by

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convection through the air to the motor frame, whence it is distributed to the outside air. As the temperature of the several parts is thus dependent not only upon their own internal losses, but also upon the temperature of the neighboring parts, it becomes necessary to determine the actual value and distribution of losses in a railway motor for a given service in order to determine with precision what the temperature rise will be; or, *vice versa*, to determine what size of motor will be required to avoid too great a temperature rise.

For ordinary electric railway calculations, however, in view of the other uncertain elements which enter, it is usually sufficiently accurate to assume that the *relative* temperatures in the different parts of the motor are independent of the *relative* values of the copper and core losses. The copper loss, i.e., the rate at which heat is developed in the windings, is proportional to the square of the current, and the core loss, i.e., the rate at which heat is developed in the core, due to hysteresis and eddy currents, may be taken as proportional to the first power of the voltage across the motor terminals (this latter relation being approximate only). When the motor reaches a constant temperature under a constant load, the temperature of any part will then be proportional (approximately) to the total power (kilowatts) lost in the windings and core. Similarly, under a fluctuating load continuing over a long period during which there are no excessively long breaks or excessive overloads, the temperature becomes fairly constant and the rise is proportional to the average power (kilowatts) lost during this period. There will be times at which the temperature rise will exceed this average and times at which it will be less, but on account of the heat storage capacity (or thermal capacity) of the materials of which the motor is made the fluctuations in temperature will be very much less than the fluctuations in the load.

Size of Motor Limited by Average Temperature Rise. — The manufacturers supply information as to the current which any motor will carry continuously (on stand test) without overheating, at various voltages from one-half to full voltage; see Table XI. From this information, making the assumptions noted in the preceding paragraph, it is possible to determine the approximate temperature of the motor for any given run or series of runs. The process is to calculate the root-mean-square current per motor and the average motor voltage for the particular service contemplated, using the methods given above in the paragraphs headed *Root-Mean-Square Current per Motor* and *Average Motor Voltage*. Call these values of the r.m.s. service current and average motor voltage I_s and E_m respectively. Let I_c be the continuous-current capacity at a given voltage E_c, as given by the manufacturer (see Table XI), and let T_c be temperature rise corresponding to this continuous rating. (Motors having ordinary fibrous insulation are rated on the basis of a 75° C. temperature rise on stand test, which corresponds to about 65° C. rise in actual service, due to better ventilation; see *Standardization Rules of the A.I.E.E.*; hence for ordinary motors T_c is 65° C.). Let J_c be the corresponding core loss and K_c the corresponding copper loss and $L_c = J_c + K_c$ be the corresponding total electrical losses. Then the total electrical losses corresponding to the average load are

$$L_a = \frac{E_m}{E_c} J_c + \left(\frac{I_s}{I_c}\right)^2 K_c,$$

and the average temperature attained by the motor in service will be approximately

$$T_a = \frac{L_a}{L_c} \cdot T_c.$$

For safe operation the average temperature rise T_a should never exceed the value T_c, which for motors with ordinary fibrous insulation is 65° C.

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Approximate Values of J_c and K_c. — When the core loss and copper loss are not given separately, a rough estimate of J_c and K_c may be made by assuming that at rated load (one-hour rating and line voltage) the core loss is, say, ¼th of the total electrical losses. The total electrical losses L_r in kw. at rated load may be found from the characteristic curves of the motor by using the formula

$$L_r = P\left(\frac{0.97}{\varepsilon} - 1\right),$$

where P is the one-hour rating in kilowatts, ε the efficiency of the motor with gears, and the 0.97 takes into account the frictional losses in the motor and the gears. Let I_r be the rated current and E_r the rated voltage; then

$$J_c = \frac{L_r}{4}\frac{E_c}{E_r} \qquad \text{and} \qquad K_c = \frac{3}{4}L_r\left(\frac{I_c}{I_r}\right)^2.$$

Size of Motor Limited by Short-time Temperature Rise. — When the service is such that the motor must take a heavy current for a comparatively long interval (e.g., a long starting period or a heavy grade for a considerable distance) followed by a like period of light load or no load, the average temperature for the run, as calculated above, may be within the required limits, but the short-time temperature rise may be excessive. This short-time temperature rise depends upon the heat-storage capacity of the motor, i.e., upon the *energy* loss (number of *kilowatt-hours* of heat developed in it) required to raise its temperature one degree, say, assuming no radiation of heat from its surface. The one-hour rating of a motor is an indirect measure of this heat-storage or thermal capacity.

The temperature-time curve during the first hour's application of a load is practically a straight line whose slope is proportional to the load. The rise in temperature of the motor due to a short-time load may then be assumed to be proportional to the *energy* (kilowatt-hour) input during this time, and the factor of proportionality may be obtained from the one-hour rating as follows: Let T_r = the temperature rise at the end of one hour due to a load equal to the one-hour rating of the motor (rated current and rated voltage), L_r = the total electrical losses in kilowatts corresponding to the rated load, L_a = the total electrical losses in kilowatts corresponding to the average load in service (L_r and L_a may be estimated by the method given in the preceding section), L_p = the total electrical losses in kilowatts corresponding to any given short-time or peak load, t_p = the number of minutes' duration of this peak load. Then during this interval t_p the rise of temperature above the average value T_a is

$$T_p - T_a = \frac{t_p\, T_r}{60\, L_r} \cdot (L_p - L_a).$$

T_p as calculated from this formula gives approximately the maximum temperature rise during the run. For safe operation this maximum temperature rise T_p should not exceed the safe limit stated by the manufacturer. For motors with ordinary fibrous insulation T_p should not exceed 75° C.

Final Choice of Motor. — No motor should be employed for a given service which does not meet the above requirements regarding the maximum current and heating limits. A larger motor than that fixed by these requirements may prove the cheaper in the long run, if by using such a motor the energy consumption can be materially reduced by increasing the amount of coasting during the run. In any event the motor should be of sufficient capacity to permit of a reasonable amount of coasting under normal conditions, so that there will be a sufficient margin in which to make up for lost time, due to unexpected slowdowns or extra stops.

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ANALYTICAL METHOD OF PREDETERMINING ENERGY AND MOTOR EQUIPMENT. — The following method was suggested by that developed by Cary T. Hutchinson, in two papers in the *A.I.E.E. Trans., Vol. 19, p. 129, 1902*, and *Vol. 22, p. 657, 1903*. In this method a speed-time curve similar in shape to the curve *ABCEF* in Fig. 1 is assumed. That is, the acceleration during the controller period, the train resistance and the braking retardation are all assumed constant, but a "motor-curve" period (*BC* in Fig. 1) is also taken into account, this latter constituting the essential difference between this method and the "straight-line" speed-time curve method frequently employed for approximate calculations. The introduction of this motor-curve period in the calculations enables one to approximate much more closely actual working conditions, and the results are much more accurate. In addition this method enables one to predetermine, without choosing any particular equipment, the effect of rate of acceleration, rate of braking, per cent of coasting, etc.

TABLE XII. — AVERAGE MOTOR CHARACTERISTICS

y = ratio of any given speed to speed at rated input	f = ratio of tractive effort at this speed to rated tractive effort	p = ratio of power input at this speed to rated input
0.80	2.06	1.82
0.85	1.67	1.54
0.90	1.38	1.30
0.95	1.19	1.14
1.00	1.00	1.00
1.05	0.83	0.87
1.10	0.71	0.78
1.15	0.61	0.70
1.20	0.53	0.625
1.25	0.46	0.57
1.30	0.41	0.525
1.35	0.365	0.48
1.40	0.32	0.45
1.45	0.295	0.425
1.50	0.27	0.395
1.55	0.23	0.375
1.60	0.215	0.35
1.65	0.20	0.33
1.70	0.18	0.315
1.75	0.17	0.30
1.80	0.16	0.29
1.85	0.14	0.28
1.90	0.13	0.265
1.95	0.125	0.26
2.00	0.12	0.25

Average Motor Characteristics. — To take into account the motor-curve portion of the speed-time curve it is necessary to consider the speed,

tractive effort and current input characteristics of the motors. However, instead of using the motor characteristics for any specific motor, the average characteristic curves of direct-current motors* given by Mr. Hutchinson are employed, see Table XII. These average characteristics were calculated by plotting the characteristic curves for the various sizes of direct-current motors manufactured by the General Electric and Westinghouse Companies, expressing the various quantities (current, speed, and tractive effort) as fractions of their values at rated load. Such curves are found to lie very close together, which justifies the use of a single set of curves representing the averages for the various motors. Mr. Hutchinson's curves were calculated from the characteristics of non-interpole motors, but have been found to check also quite closely with the curves for interpole motors. It is also found that these curves have practically the same shape irrespective of what point, between 75% and 125% of rated load, on the curves is taken as unity.

Method of Calculation. — The following symbols are employed:

n = number of stops per mile = total number of stops including one terminus divided by the distance between termini in miles,

V = average running speed in miles per hour,

$T = \frac{3600}{nV}$ = average running time between stops in seconds,

a = acceleration in miles per hour per second,†

b = braking rate in miles per hour per second,

r = train resistance in pounds per ton corresponding to a speed from 10 to 20% greater than the average speed V,

G = "equivalent" grade in per cent (*see above*),

g = average curvature, in degrees (*see above*),

$c = \frac{r + 20\,G + g}{100}$ = average "effective" coasting retardation in miles per hour per second,

e = over-all efficiency (expressed as a fraction) of motors and gears at rated load; e is about 0.85 for direct-current motors and about 0.75 for alternating-current motors, the latter figure including step-down transformer losses,

s = ratio of total standing time (including stops and lay overs) to total time that the train is moving,

W = total weight of train in tons,

M = total number of motors for the entire train,

E = average line voltage.

* The method is also applicable to alternating-current motors, but average characteristic curves for such motors are not available. They may, however, be readily constructed, or the characteristic curves given for direct-current motors may be used as an approximation.

† When the starting tractive effort is given, then a is to be calculated from the formula $a = (F - r) \div 100$, where F is the tractive effort in pounds per ton and r the train resistance corresponding to a speed from 10 to 20% greater than V. The actual starting acceleration will be greater than this, due to the lower train resistance at low speeds. Vice versa, if the starting acceleration is given, then the calculated tractive effort (and therefore the starting current and horse-power) at end of the controller period will produce a starting acceleration in excess of the assumed value. As far as the energy consumption and heating are concerned, however, these differences in the actual and assumed accelerations will be balanced by the higher train resistance at the higher speeds.

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Calculate

$$\beta = \frac{a}{c},$$

$$A = \frac{V}{T} = \frac{nV^2}{3600},$$

$$m = 2A\left(\frac{1}{c} - \frac{1}{b}\right),$$

$$q = \frac{a}{A}(1 + m).$$

Select a value of the ratio

$$x = \frac{\text{time power is applied}}{\text{time of controller period}}.$$

A run of specified distance can be made in a given time with various values of this ratio x, since this ratio depends upon the proportion of the time that the train coasts; i.e., the greater the coasting time the smaller the value of x, see Fig. 1. The less the value of this ratio, however, the greater will be the starting current required, and therefore the larger the motor capacity in order to avoid sparking. By carrying through the calculations for several values of x one can determine the relation between energy consumption, time of coasting and starting current, and, by plotting, find the minimum value of the energy consumption corresponding to the data assumed, see Fig. 9. In typical rapid-transit service (1 or more stops per mile) minimum energy consumption usually corresponds to a value of x between 2 and 5, i.e., for the controller period lasting from 50 to 20 per cent of the total time power is on.

From Tables *A* to *D*, pp. 1196 and 1197, find the values of y, λ, u and i* corresponding to the selected value of x and the ratio β. Using these values calculate

$$J = \frac{x + \beta y}{q}, \quad \text{and} \quad H = \frac{\lambda + \beta y^2}{2q}.$$

Then calculate the quantities listed in the following table.

---

* The analytical expressions for x, λ, u and i in terms of y, f and p (see column headings of Table XII for definitions) are

$$x = 1 + \int_1^y \frac{\beta\, dy}{(1+\beta)f - 1}$$

$$\lambda = 1 + 2\int_1^x y\, dx$$

$$u = \frac{1+\beta}{18.1\beta}\left[0.75 + \int_1^x p\, dx\right]$$

$$i = 199\left(1 + \frac{1}{\beta}\right)\sqrt{1 + \int_1^x p^2\, dx}.$$

In the expression for u the constant 0.75 is for series-parallel control. For straight resistance control change 0.75 to 1.00 and for series-series-parallel control change 0.75 to 0.69. For a-c. commutator motors change 0.75 to 0.56. Tables *A* to *D* were made up by calculating the value of the above expressions graphically, using for y, f and p the values given in Table XII. Similar tables may readily be calculated for a-c. commutator motors, or for any other type of motor whose "percentage" characteristics differ from Table XII.

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Speed at end of controller period in miles per hour....	$V_1 =$
Maximum speed in miles per hour.....	$V_m =$
Watt-hours per ton-mile	$U =$
Ratio of total running time to time on controller.....	$X =$
Ratio of coasting time to running time.....	$C =$
Horsepower output at end of controller period.....	$P_0 =$
Starting current per motor *.....	$I_0 =$
Root-mean-square current per motor (including stops) *.....	$I_e =$
Average voltage across motor terminals (including stops).....	$E_m =$

* For alternating-current series motors insert the power fact
denominator of the formula.

Example. — Consider the following example:

Number of stops per mile.....	
Average running speed.....	
Acceleration rate.....	
Braking rate.....	
Train resistance at 34.4 mph.....	
Average equivalent grade.....	
Average curvature.....	
Average effective coasting retardation.....	
Efficiency of motors and gears at rated load.....	
Ratio of standing to running time (20 sec. stops).	
Total weight of train in tons.....	
Total number of motors.....	
Average line voltage.....	

Then

$$\beta = \frac{1.84}{0.21} = 8.76,$$

$$A = \frac{0.938\,(28.7)^2}{3600} = 0.214,$$

$$m = 2 \times 0.214 \left(\frac{1}{0.21} - \frac{1}{1.60} \right) = 1.7$$

$$q = \frac{1.84\,(1 + 1.77)}{0.214} = 23.8.$$

Then (*see above for meaning of symbols*)

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$x =$		1	2	4	6	10
$y =$	.....	1.00	1.43	1.69	1.83	1.96
$\lambda =$	.....	1.00	3.52	9.88	17.0	32.1
$u =$	.....	0.0462	0.0822	0.126	0.162	0.228
$i =$	.....	222	260	281	301	321
$J =$	$\frac{x + 8.76\,y}{23.8}$	0.410	0.608	0.788	0.925	1.143
$H =$	$\frac{\lambda + 8.76\,y^2}{47.6}$	0.205	0.452	0.735	0.973	1.380
$V_1 =$	$\frac{28.7}{J + \sqrt{1.77\,(H - J^2)}}$	43.1	28.8	23.1	20 9	19.2
$U =$	$1.07\,u V_1^2$	92	73	72	76	90
$X =$	$\frac{247}{V_1}$	5.73	8.57	10.7	11.8	12.9
$C =$	$1.15\left(1 - \frac{x}{X}\right) - \frac{1.32\,y}{X}$	0.72	0.67	0.51	0.36	0.06
$P_0 =$	$12.07\,V_1$	520	348	279	253	232
$I_0 =$	$17.8\,V_1$	770	512	411	371	342
$I_e =$	$\frac{0.676\,i V_1}{\sqrt{X}}$	304	195	151	139	131
$E_m =$	$\frac{497\,(x - 0.45)}{X}$	47	90	165	233	367

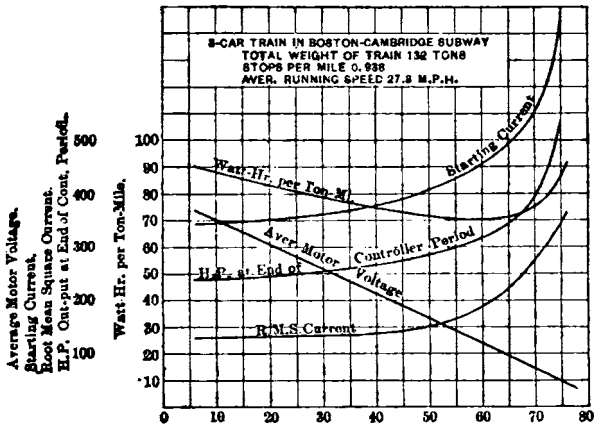


Fig. 9.

These results are plotted in Fig. 9. An actual test on this road was made, showing an average coasting time of 10 per cent. The table on p. 1320 gives the

TABLE A. — VALUES OF y IN TERMS OF x

x	Numbers in first line give values of $\beta = \frac{a}{c}$											
	1	2	3	4	5	6	7	8	9	10	15	20
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.17	1.22	1.24	1.26	1.27	1.28	1.28	1.28	1.29	1.29	1.29	1.29
2	1.20	1.30	1.35	1.38	1.40	1.42	1.42	1.43	1.43	1.43	1.45	1.45
2.5	1.22	1.34	1.41	1.45	1.47	1.49	1.51	1.51	1.52	1.53	1.55	1.56
3	1.23	1.37	1.44	1.49	1.53	1.56	1.58	1.59	1.60	1 61	1 63	1.64
4	1.24	1.37	1.48	1.55	1.60	1.63	1.66	1.68	1.70	1.72	1.76	1.79
5	1.24	1.38	1.50	1.58	1.65	1.70	1.73	1.76	1.79	1.81	1.86	1.89
6	1.24	1.38	1.51	1.60	1 67	1.73	1.77	1.81	1.84	1.87	1.94	1.98
7	1.24	1.38	1.52	1.61	1.68	1.75	1.81	1.85	1 88	1.92	2.00	2.05
8	1.24	1.39	1.52	1.62	1.70	1.77	1.83	1 88	1.91	1.95	2.05	2 11
9	1.24	1.39	1.53	1 63	1.71	1.78	1 84	1 90	1.94	1.98	2.10	2 16
10	1.24	1.39	1.53	1.63	1.72	1 80	1.86	1.92	1.97	2.00	2.13	2.20
12	1.24	1.39	1.53	1.64	1.73	1.81	1.88	1.95	2.00	2.05	2 20	2.28
14	1.24	1.39	1.53	1 64	1.74	1.83	1.90	1.97	2.02	2.07	2.24	2 35
16	1.24	1.39	1.53	1.64	1.75	1.84	1.92	1.98	2.05	2.10	2.27	2.40
18	1.24	1.39	1.53	1 65	1.75	1.85	1.93	2.00	2.07	2.12	2.31	2.44
20	1.24	1.39	1.53	1.65	1.76	1.86	1.94	2.02	2.09	2.15	2.34	2.48

Example. — For $x = 2$ and $\beta = 3$, $y = 1.35$.

TABLE B. — VALUES OF λ IN TERMS OF x

x	Numbers in first line give values of $\beta = \frac{a}{c}$											
	1	2	3	4	5	6	7	8	9	10	15	20
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.5	2.12	2.14	2.15	2.16	2.16	2.17	2.17	2.17	2.17	2.17	2.17	2 17
2	3.30	3.40	3.46	3.48	3.50	3.50	3.52	3.52	3.54	3.52	3.52	3.52
2.5	4.50	4.74	4.84	4.90	4.92	4.94	4.96	4.98	5.00	5.00	5.02	5.04
3	5.70	6.10	6.28	6.38	6.44	6.50	6.52	6.54	6.58	6.58	6.61	6.65
4	8.16	8.84	9.30	9.44	9.60	9.70	9.80	9.83	9.90	9.90	10.0	10.1
5	10.6	11.6	12.3	12.6	12.8	13.0	13.1	13.2	13.3	13.4	13.6	13.6
6	13.0	14.4	15.4	15.7	16 1	16.4	16.6	16.8	17.0	17.2	17.4	17.7
7	15.4	17.1	18.1	18.9	19.4	19.9	20.3	20.5	20.6	20.9	21.3	21.7
8	18.0	19.8	21.2	22.2	23.0	23.7	24.1	24.5	24.8	25.0	25.5	25 9
9	20.4	22.6	24.2	25.4	26.2	27.0	27.7	28.0	28.3	28.8	29.7	30.0
10	23.0	25.6	27.4	28.6	29.6	30.5	31.2	31 9	32.2	32.7	33.8	34.3
12	27.8	31.0	33.6	35.2	36.8	38.0	39.0	39.7	40.2	40.8	42.3	43 4
14	32.6	36.6	39.4	41.8	43.8	45.8	46.5	47.3	48.1	48.9	51.0	53.0
16	37.4	42.2	45.6	48.2	50.6	52.7	54.1	55.8	56.8	57.7	60.3	62 2
18	42.2	47.6	51.6	54.8	57.4	60.0	62.0	63.3	64.8	66.0	69.6	72.0
20	47.2	53.4	58.0	61 6	64.8	67.2	69 4	71.2	73.0	74.2	79.0	82 0

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TABLE C.—VALUES OF u IN TERMS OF x

x	Numbers in first line give values of $\beta = \frac{a}{c}$											
	1	2	3	4	5	6	7	8	9	10	15	20
1	0.082	0.0620	0.0550	0.0515	0.0495	0.0481	0.0472	0.0466	0.0460	0.0456	0.0445	0.0440
1.5	0.125	0.0922	0.0813	0.0760	0.0729	0.0709	0.0695	0.0685	0.0676	0.0670	0.0642	0.0627
2	0.161	0.115	0.100	0.0940	0.0895	0.0863	0.0843	0.0830	0.0819	0.0810	0.0780	0.0769
2.5	0.195	0.134	0.118	0.109	0.104	0.101	0.0980	0.0960	0.0948	0.0938	0.0902	0.0888
3	0.230	0.155	0.135	0.123	0.117	0.113	0.110	0.107	0.106	0.104	0.100	0.0975
4	0.298	0.193	0.162	0.149	0.140	0.135	0.131	0.128	0.126	0.124	0.118	0.115
5	0.362	0.232	0.194	0.175	0.163	0.156	0.150	0.146	0.143	0.141	0.135	0.133
6	0.431	0.270	0.222	0.199	0.185	0.176	0.170	0.165	0.162	0.159	0.151	0.147
7	0.500	0.310	0.252	0.223	0.207	0.196	0.188	0.182	0.179	0.176	0.166	0.161
8	0.565	0.347	0.279	0.247	0.227	0.215	0.207	0.200	0.195	0.191	0.179	0.174
9	0.634	0.386	0.309	0.270	0.249	0.233	0.223	0.216	0.210	0.206	0.192	0.188
10	0.705	0.425	0.338	0.293	0.270	0.252	0.241	0.232	0.227	0.221	0.204	0.199
12	0.833	0.500	0.390	0.339	0.307	0.287	0.273	0.263	0.255	0.249	0.230	0.220
14	0.965	0.580	0.450	0.381	0.349	0.324	0.309	0.296	0.286	0.278	0.251	0.239
16	1.11	0.653	0.504	0.430	0.388	0.360	0.342	0.327	0.314	0.305	0.273	0.259
18	1.24	0.738	0.580	0.475	0.427	0.395	0.373	0.356	0.342	0.331	0.293	0.278
20	1.38	0.809	0.620	0.521	0.468	0.430	0.406	0.387	0.371	0.359	0.314	0.290

TABLE D.—VALUES OF l IN TERMS OF x

x	Numbers in first line give values of $\beta = \frac{a}{c}$											
	1	2	3	4	5	6	7	8	9	10	15	20
1	398	300	267	249	239	232	228	224	221	220	213	209
1.5	452	334	297	278	267	260	253	250	248	245	238	233
2	488	355	312	292	280	272	267	262	259	257	249	243
2.5	518	369	322	301	289	280	274	270	267	263	257	250
3	546	383	337	311	298	289	281	277	273	270	261	254
4	599	411	352	327	310	300	292	287	282	279	270	263
5	647	432	369	338	321	309	301	295	290	288	277	270
6	688	455	382	350	331	318	310	303	299	295	283	275
7	730	475	397	360	340	326	317	310	303	300	289	280
8	770	497	409	369	347	331	321	315	310	305	292	284
9	806	513	421	379	355	340	329	321	315	310	297	288
10	845	531	431	387	361	344	333	327	320	315	301	291
12	911	565	454	403	377	358	345	337	329	323	307	295
14	975	600	479	422	391	370	356	347	338	331	313	300
16	1030	630	500	440	404	380	365	353	344	339	318	303
18	1085	656	518	451	414	390	372	360	350	343	320	307
20	1140	681	531	462	423	399	380	368	357	350	326	309

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actually observed values of the various quantities and the corre
taken from the calculated curves in Fig. 9 for a coasting time

	Observed
Watt-hours per ton-mile	91
Horse-power output at end of controller period	249
Starting current per motor	370
Root-mean-square current per motor	132
Average motor voltage	337

From Table XI the proper size of motor would be the inter
300, which is rated as 200 horse-power at 550 volts. The mot
was a Westinghouse motor, designated as 300 – *B*, and rated at
at 600 volts. The temperature rise from test, after 13 hours in

Armature
Commutator
Series field
Interpole field
Frame

Importance of Coasting and Selection of Gear Ratio. Fig. 9 shows that a much less energy consumption would be coasting period of 50 per cent instead of the actual coasting perio namely 72 watt-hours instead of 88 watt-hours. The starting in order to obtain this higher coasting time is 406 amperes instead or an increase in the starting current of 18 per cent. If no chan motor were made, this would require approximately the same crease in the gear ratio. The root-mean-square current would increase from 131 to 150, but the average motor voltage would drop from 350 to 170. The motor could therefore probably operate at this higher gear ratio without seriously overheating, but it would be safer to use a larger size motor, particularly as the starting current of 406 amperes is also close to the safe commutating limit.

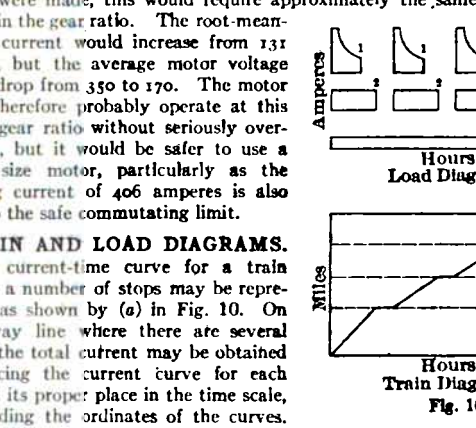


Fig. 1

TRAIN AND LOAD DIAGRAMS. —The current-time curve for a train making a number of stops may be represented as shown by (*a*) in Fig. 10. On a railway line where there are several trains, the total current may be obtained by placing the current curve for each train at its proper place in the time scale, and adding the ordinates of the curves. Such a process is very tedious and unnecessary where there is of trains. In such cases the high and low parts of the curves be with respect to one another more or less according to the law that each current curve may be replaced by a rectangle of the same base extending over the entire running time as shown by

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When this is done the kilowatts and amperes per train are derived from the watt-hours per ton-mile by the following formulas:

$$\text{kilowatts} = \frac{WV}{1000} \times (\text{watt-hours per ton-mile}),$$

$$\text{amperes} = \frac{WV}{E} \times (\text{watt-hours per ton-mile}),$$

where

W = weight of train in tons,

V = average running speed (excluding stops) in miles per hour,

E = line voltage.

The time when the current is cut off is indicated by 1, and that when the train stops, by 2, in Fig. 10.

Another approximation, which is even more often used, is to replace the series of rectangles shown at b, by a single rectangle as shown at c in Fig. 10. The area of this rectangle will be equal to the sum of the areas of the smaller rectangles or current curves. Using this approximation, kilowatts or amperes may be obtained from the above formulas, taking, however, V to be the schedule speed (i.e., speed including stops). The procedure is to plot a train diagram showing when each train comes on and off the line, neglecting intermediate stops, as shown for a simple case in Fig. 11. Each time a train comes on or off, the corresponding kilowatts or amperes are added to, or subtracted from, the load diagram.

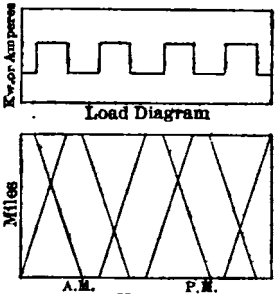


Fig. 11.

Power Required for Car Heating and Lighting. — In addition to the energy required for propelling the cars, a very appreciable amount is also required in the winter, for heating them, and a small amount at night for lighting. In making up a load diagram this energy should be included.

The average power for car heating varies, of course, with the climate and time of year. The following figures represent usual requirements in the northern parts of the United States:

TABLE XIII. — HEATING AND LIGHTING OF CARS

Length of car, feet	Average* kw. for lighting	Average† kilowatts for heating	
		Average conditions	Severe conditions
14–20	0.25	3.5	4
20–28	0.35	4.5	5.5
28–34	0.55	5.5	7.5
34–40	0.70	7.5	10.5

* During the hours lights are on, using Tungsten lamps.

† During the time car is in service.

Substation and Power-station Loads. — The load diagram obtained as described above gives the total load at the trains. To obtain the load at a sub-

station, the kilowatts or amperes must be increased by a
allow for the losses in the distribution system. The load di
station should allow for all transmission and distribution
power house and substation (*see Power Stations; Substations; Trolley Systems*), and also for all auxiliary power, such as th
tion lighting, shop machinery, etc.

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RAILWAYS, LOCATION AND PERMANENT WAY FOR. — (*See also Railways, Energy Requirements and Motor Capacity for; Railways, Electric, Traction Systems for; Third-rail Systems; Trolley Systems.*) There are four general steps in the determination of the location of a railway, (1) the reconnoissance, which is a personal examination by the locating engineer of the country through which the railway is to run, (2) a preliminary survey and investigation more particularly of the topographic features of the proposed road, (3) office study of the data obtained in (1) and (2), and (4) the field location and the preparation of final location plans.

RECONNOISSANCE. — First a careful examination of the country should be made, with a view not only of obtaining a line which will be reasonably straight and as free from grades as possible, but also with a view of selecting a line or lines which will earn a suitable revenue. An electric railway reconnoissance calls for a much more detailed study of the country than a steam railroad location and a very much more detailed study of the amount of population, its growth, and the likelihood of the population making use of the proposed line. The adapting of an electric line to take in the various intermediate centers of population is practically a necessity if the income of the line is to be sufficient to take care of the investment. The engineer should therefore realize fully that the commercial and financial matters relating to the road are more important than the engineering problems, and should always bear in mind that the road is constructed for the purpose of selling transportation.

Electric railway locations are divided in general into two classes: those which are operated on the public highways, and those which are operated upon their own private rights of way, where they are free to make the fastest practicable schedules. Speed and comfort must be considered. Both of them are, as a rule, better obtained on private locations. It is essential in this reconnoissance for the engineer to make a careful estimate of the probable gross income of the road, as well as to choose two or three lines which will later on be investigated by preliminary surveys.

PRELIMINARY SURVEY. — After the favorable lines have been determined by the locating engineer in his reconnoissance, a party is sent into the field to make a preliminary survey. This is usually a linear traverse run by transit and tape. After this a level party determines the profile of this line, this party being followed by a topographical party which sketches in the 5-foot contours, the locations of brooks, highway crossings, the number and kinds of industries located within say a mile or so of the line, the location of existing recreation points and picnic grounds, as well as the possible location and development of those which do not now exist. The engineer running the preliminary line should keep in mind that the railroad is built for the convenience of the public and that any inconvenient detail of the road will have a material effect upon its gross income.

The topographical party should note the character and property value of buildings or other structures which the line may affect, the character of soil (whether rock or gravel), the location of possible borrow pits, etc. In some locations the topographical features should extend a considerable distance from the transit line; in other locations, where, for example, the line is passing through a narrow valley, the topographical features need not be taken very far from the transit line. While the line should be as straight as possible, some curves are necessary. In locating curves consideration should be taken of the fact that electric traction permits of very rapid acceleration and retardation, and therefore sharper curves are permissible than in steam railroad practice because of the shorter time required to pass around it, even at the

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slower speed rendered necessary because of its greater curvature. The time lost in passing around the curve as well as the permissible speed are factors which should be taken into consideration. Roughly speaking, a safe rule is that the speed on curves in miles per hour can be equal to the square root of the radius in feet.

OFFICE STUDY. — On the preliminary map an accurate paper location is drawn and an estimate is made of the cost of the road and of the probable gross earnings, as well as of the fixed charges and the cost of operating and maintaining. This study is one of great importance and if the reconnoissance and preliminary survey are not thoroughly accomplished, errors in judgment may very easily creep into this part of the work. The office study shows the final alignment and the proposed grades of the road.

FIELD LOCATION. — After the completion of the office study the line is finally located in the field. Field location requires running out the line by straight lines and curves, using easement curves at the beginning and end of all changes in direction; the preparation of property maps showing the location required for the railway and all parcels of property affected by actual takings for slope easements; as well as studies of grade crossing eliminations where they are necessary. At this time soundings or borings are taken for bridges or other structures. Cross sections are made of the line, from which careful estimates are made. These cross sections are used in computing the final payment for the work of construction.

Locations in Existing Highways. — Such locations usually have the great advantage of easy grades which frequently cannot be so cheaply obtained upon private land. Locations in highways have the disadvantage of requiring much slower speed. Where such locations are made it is necessary to survey the highways as laid out by the proper officials, and not infrequently it is necessary to consider the widening of such highways by takings on either side. The electric road, for example, may be a 2-track road laid out in the center of the roadway, in which case the road would possibly occupy nearly the full width of the existing highway. In this case the electric road would be required to purchase additional property on either side and probably to build roadways for other vehicles in lieu of the portion which the electric line occupies. When this is done high speeds can sometimes be maintained. Where the electric road occupies one side of an existing highway, the speed often has to be reduced to a relatively low rate. This affects the amount of traffic which the road will attract and thereby reduces the gross earnings.

DEFINITIONS OF TERMS USED ON RAILWAY MAPS AND PROFILES. — Some of the more common terms are defined below.

Curves. — A curve is generally composed of successive arcs of circles joining two straight lines or tangents. When these arcs are of varying radii decreasing with the distance from the tangents the curve is said to be compounded or spiralled. To insure smooth riding the curve should begin with a large radius and gradually grow sharper until the circular part is reached. At the same time the outer rail should be gradually raised (see below) until it reaches its maximum elevation. A curve so built is called an easement curve. Curves, if properly eased, may be run at full speed. On high-speed lines curves sharper than 10 degrees should be avoided.

The following terms are in general use:

The point of curvature (P. C.) is the beginning of the curve, and the point of tangency (P. T.) is the end of the curve, going in the direction of the surveyor's stationing on the line.

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The point of intersection (P. I.) is the point where the two tangents through P. C. and P. T. intersect.

The tangent distance is the distance between the P. C. or P. T. and P. I.

The degree of curvature is the angle subtended at the center of a curve by a chord 100 ft. long. Up to a curvature of 12 degrees the radius of curvature may be found to a close approximation by dividing 5730 by the degree of curvature. The exact relation between the degree of curvature C and the radius R is

$$R = \frac{50}{\sin \frac{C}{2}}.$$

The middle ordinate is the perpendicular distance from the center of a chord to the curve.

Elevation of Outer Rail on Curves. — The outer rail on curves is raised above the inner an amount depending upon the velocity of cars and the degree of the curve. This elevation must be gradually attained. The amount of elevation required in order to make the weight of the car just balance the centrifugal force on the curve is

$$E = \frac{DV^2}{32.2\,R} \text{ feet},$$

where D is the distance between center lines of the two rails (not the track gage), V the speed of car in feet per second, and R the radius of curvature in feet. For standard track gage, viz., 4 feet 8½ inches from inside edge of the *head* of one rail to the inside head of the other rail, and taking $R = 5730/C$, where C is the curvature in degrees, the above expression for the elevation becomes

$$E = 0.000325\ V^2C \text{ inches}.$$

Grades. — A railroad grade is expressed in per cent, this per cent being the number of feet vertical rise in a horizontal distance of 100 feet; i. e., a 4 per cent grade means a rise of 4 feet in a horizontal distance of 100 feet. Calling L the distance in feet along the track and H the vertical rise in feet in this distance, the per cent grade may also be expressed as

$$G = \frac{100\,H}{\sqrt{L^2 - H^2}},$$

which for a grade less than 10 per cent is equal to $100\,H/L$ with an error of less than 1 part in 100.

Grades should be as small as financially practicable. It may be cheaper to operate over a grade than to pay interest on the sum needed to reduce it. Some steam road grades are as steep as 4 per cent, but such grades are extremely costly to operate. Two per cent is about the limit for steam roads and most roads try to keep grades down to about 0.5 per cent. On electric lines operating single trolley cars grades as steep as 10 per cent exist, but no grade over 6 per cent ought to be used unless it is absolutely unavoidable.

Virtual and Momentum Grades. — A driving force or tractive effort is required to accelerate a train, and a driving force or tractive effort is required to cause a train to ascend a grade at constant speed; hence an increase of the speed of the train may be considered, as far as the motive power is concerned, as equivalent to an up-grade. *Vice-versa*, a decrease of speed may be considered as equivalent to a down-grade. The energy required to give the train a speed of v miles per hour is the same as the energy required to raise it a height of $0.0334\ v^2$ feet. Hence, if to the actual elevation of the profile at each point is added a height of $0.0334\ v^2$ feet, where v is the velocity of the train at this

point, and a line is drawn showing the sum of the actual elevation and this velocity head at each point, this line may be looked upon as the "virtual profile" of the road, and the slope of this virtual profile, at any point, i.e., the change in its elevation per hundred feet, is called the "virtual grade" at this point.

The virtual grade at any point on an actual up-grade will be less than the actual grade, if the speed of the train is decreasing as it passes this point; the grade in this case is sometimes called a "momentum grade." That is, if the train has a high speed when it strikes an up-grade, and the operating requirements of the division will permit of a slowing down of the train as it ascends the grade, then the effective or virtual grade will be less than the actual grade. Under such circumstances a given locomotive can pull a given train up a short steep grade on which it could neither start this train nor pull it at constant velocity. A momentum grade must be comparatively short.

Ruling Grade. — The limiting or ruling grade on a division is that grade which limits the weight of the train which can be hauled over this division by the regular motive-power unit. Ordinarily, it is the maximum grade on the division, but if momentum grades are relied upon, the ruling grade might be the maximum virtual grade. Reliance upon momentum grades is not always considered good practice, since a heavy train which might get over this grade if it strikes the grade with sufficient momentum, cannot start on this grade if it should have to stop on the grade due to some emergency. When steep grades occur at only one or two places in a division it is sometimes economical to use helper engines on these steep grades, thus making possible the hauling of heavier trains, the weight of train then usually being limited by maximum grade on the remainder of the division.

Switches, Frogs, Cross-overs, Etc. — A switch is an arrangement of rails, which permits a car or train to pass from one track to another. A cross-over consists of a pair of switches connected by a short piece of track in such a way as to allow a car or train to pass or cross over from one track to another parallel one. A turn-out or siding is a short length of track parallel to the main track and connected thereto by a switch at each end; when used as a means of passing cars or trains it is usually called a turn-out, and when used primarily for storing cars or loading it is called a siding.

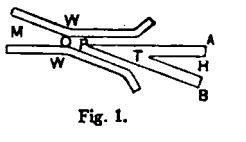


Fig. 1.

A frog, Fig. 1, is that part of the switch where the two inner rails cross each other, and is so designed as to allow the flange of the wheel to pass over without "riding up" on the rail. A guard rail is set close to the switch rail opposite the frog. The lead of a frog is the distance of a frog from the frog point P, see Fig. 1, to the point of the switch. The point of the switch is the tip end of the movable rail of the switch which is planed down to fit closely against the main rail. The number of a frog is equal to the quotient of the distance from P to the line AB divided by the length of the line AB.

Turn-outs. — Turn-outs are short sidings used on single-track roads to permit cars running in opposite directions to pass each other. The proper location of turn-outs is governed to a certain extent by topography. They can be readily located by drawing up a train diagram; see *Railways, Energy Requirements and Motor Capacity for*. To keep the number of turn-outs at a minimum the time intervals between cars (headway) should all be multiples of the shortest time interval. For accurate results the diagram should be carefully drawn to a scale large enough so that locations can be measured with an error not to exceed 200 feet for distance and one minute for time.

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CONSTRUCTION OF PERMANENT WAY.—In the preparation of the roadbed for ballast, ties and track, it should be noted that rails settle more or less and allowance must be made for this when grading is in progress. The surface of the roadbed should be flat, from 14 to 20 feet wide for a single-track road, and from 9 to 10 feet wider for a double-track road, with a ditch at each side for drainage. On this the ballast of broken stone, gravel or cinders is laid varying from 6 to 12 inches thick under the ties. The ballast should ultimately be brought up level with the tops of the ties.

Ballast. — Broken stone is best but most expensive in first cost and maintenance. It is clean and dustless. Gravel is cheaper and very satisfactory from a maintenance standpoint. It is apt to be very dusty. Cinders are fairly satisfactory but are very dirty.

Ties.—Ties are of the following materials in the order named: Oaks, southern pine, Douglas fir, cedar; chestnut, cypress, western pine, tamarack, hemlock, redwood, lodge-pole pine and white pine; see article on *Timber*. The average cost is about $1.00. Treated ties cost about $1.25. With the rapidly increasing cost of ties, preservative treatment is becoming important. Creosoting is best. Zinc chloride treatment is satisfactory in arid regions only. The average life of an untreated tie is 5 years for hemlock, 7 to 12 years for white oak, and 15 years for cedar ties. Treated ties may last 30 years, but must be protected from mechanical injury by rails and spikes. For this purpose tie-plates and screw spikes should be used. Ties are spaced about 2 feet between centers.

Rails.—See article on *Rails, Track and Third.*

Grade Crossings. — On high-speed lines grade crossings should be avoided wherever practicable. It costs less to avoid them in the beginning than to eliminate them afterwards. To eliminate an existing grade crossing costs from $40,000 up unless the topography is usually favorable.

COST OF PERMANENT WAY. — The following costs are based on pre-war prices. When tracks are laid in paved streets the railway usually has to pay for paving 18 inches of the street outside the rails. The total cost of such track, excluding overhead construction, and using 8- or 9-inch girder rails is about $5 per foot of single track. When the track is constructed with a light T-rail, as may be the case when laid on a private right of way or at the side of a street where there is no paving, the cost may be as low as $1 per foot, exclusive of ballast, bonding, and overhead construction. Ballast will cost from $1000 for cheap gravel to $3000 for thin rock, per mile of track. Thick rock ballasting as used on steam railroads may go as high as $5000 per mile.

Maintenance Costs. — Maintenance of way costs will depend largely on the character of the original construction and also upon the character and amount of traffic. On typical Massachusetts street and interurban railways maintenance of way expenses are reported as from $200 to over $500 per mile of track. $200 per mile is not sufficient to maintain the road and track in an adequate manner, but fom $350 to $380 is probably a fair figure.

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REACTANCE COILS OR REACTORS.—(*See also Alternating Currents; Inductance and Inductive Reactance.*) Coils designed particularly for the purpose of introducing reactance (*see Inductance and Inductive Reactance*) into a circuit, when connected therein, are called "reactance coils" or "reactors."

APPLICATIONS. — Reactance coils are used wherever (1) it is desired to produce a voltage drop in an a-c. circuit without producing a proportionate loss in power (*see Controllers*); (2) to introduce inductance into a circuit where a compounding effect is to be obtained by passing a leading current through the coils (*see Converters, Synchronous*); (3) in large power stations to limit the short-circuit current; and (4) as "choke coils" in connection with lightning arresters (*see Lightning Protectors*).

RATING OF REACTANCE COILS. — It is common practice to rate a reactance coil in terms of the kilo-volt-amperes absorbed by it when carrying such a current (of the given frequency) as will produce a temperature rise of 50° C., or 70° C., respectively, above the room temperature, depending upon the type or class of insulation used in accordance with the Standards of the A.I.E.E. on temperature limits. Usually the resistance is negligible compared with the reactance and under this condition the k-va. rating is I^2x.

Per cent Reactance. — A reactance coil having a reactance of x ohms is said to have a "per cent reactance" equal to $(100\,x\,I) \div V$, where I is the normal or full-load current through it and V the *total* normal voltage across the circuit in which it is placed; i.e., the percentage reactance is the percentage ratio of the reactance drop at normal current to the total voltage impressed on the circuit in which it is inserted. When the coil is to be inserted in one branch of a Y, the voltage V is the volts to neutral.

In the case of a three-phase generator, three-phase transformer or bank of transformers, or set of three single-phase reactance coils, the Y reactance, x, (*see Alternating Currents*) is related to the per cent reactance, p, by the formula

$$x = \frac{10\,pE^2}{(kv\text{-}a.)}, \qquad (1)$$

where E is the *kilovolts* between phases (i.e., between the terminals of the Y) and (*kv-a.*) stands for the total kilovolt-ampere rating of the three phases.

DESIGN OF IRON-CORE REACTANCES. — When a high inductance is required the coils are usually wound on an iron core, which usually contains an air gap, for the inductance of a coil on a completely closed iron core is by no means a constant, due to the variation of the permeability of the iron with the magnetizing current, and a straight-line relation between voltage and current does not hold. When a relatively low inductance is required the iron core may be omitted entirely. Reactance coils for use in connection with synchronous converters have an iron core.

In iron-core reactances the air gap is usually of such a length that practically all of the reluctance of the circuit is in the air gap. Hence in calculating the reactance of the coil the reluctance of the iron portion of the path may be neglected without materially affecting the results, provided normal magnetic densities exist in the iron (60,000 to 80,000 lines per square inch, maximum values). As the gap is made adjustable such errors as result from this approximation are allowed for by adjusting the gap afterwards.

The inductance L in henries and the reactance x in ohms are given approximately (neglecting effect of iron) by the equations

$$L = \frac{3.2\,S^2A}{10^8\,l} \quad \text{and} \quad x = 2\pi f L, \qquad (2)$$

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where S = number of turns in coil; A = cross section of path in gap, in square inches; l = length of gap, in inches; f = frequency in cycles per second. This must, however, be checked to see that the magnetic density B is not too great at the maximum current to be used, thus, $B = (3.2 \times \sqrt{2}\, SI) \div l$, where I = the effective value of current; B = maximum value of flux density = 60,000 to 80,000 lines per sq. in.

The losses in such a coil are the core-loss in the iron and the RI^2 in the copper. See article on *Magnetic Properties of Materials* for the method of calculating the core-loss. The procedure in proportioning the various parts is similar to that employed in the design of transformers (q.v.).

POWER-LIMITING REACTANCES.* — (*See also Power Stations.*) In order to avoid the prohibitive expense of high-voltage insulation, power-limiting reactances are always designed to be installed in the low-tension circuits. From the standpoint of economy, this requirement prohibits the use of a magnetic core. When power-limiting reactances are installed at a distance greater than one-half their diameter from any iron or steel structure, no appreciable eddy current or hysteresis losses will be produced in such structures.

The inductance and reactance of the coils can be calculated from the formula for a short solenoid given in the article on *Inductance and Inductive Reactance.*

It is desirable to reduce the size of reactance coils as much as possible, and they are therefore now usually designed for a temperature rise of 70° C. As to the dielectric test, the A.I.E.E. rules recommend 2¼ times the line voltage plus 2000 for one minute, from conductor to ground.

Location of Reactance Coils. — As noted above the reactance coils may be inserted in the leads from the generator, between sections of the low-tension bus-bars, or in the low-tension leads of the transformers. Which one of these locations or combinations is preferable depends on a number of conditions. Modern water-wheel-driven generators are now designed for a very high inherent reactance and external power-limiting reactances are usually inserted between the bus-bar sections or in the low-tension transformer leads.

Reactances in Generator Leads. — With reactances in the generator leads the current flowing in the armature winding is limited, and this method therefore affords an excellent protection for the generator itself. An objection to generator reactances is the fact that a short-circuit on or near the bus-bars will cause a voltage drop on all the feeder circuits connected thereto.

Reactances between Bus-bar Sections. — With reactance inserted between the bus-bar sections the trouble is confined to the particular section on which short-circuit takes place. Bus-section reactances afford no protection to the generators connected to the bus to which the faulty line is connected, but they give added protection to the generators on the other sections.

Reactances in Low-tension Leads of Transformers. — Reactances in the low-tension leads of the transformer banks are of considerable value for protecting against short-circuits in the lines, where they, of course, mostly take place. They are, however, not of value if the short-circuit should occur on the low-tension bus or in the generators or in their leads. There is also a constant loss of power in the reactance coils when they are inserted in the transformer leads, as is also the case when they are installed in the generator leads. For large systems this may reach a considerable value and must not be ignored when the selection of reactances is made.

Calculation of Short-circuit Kilovolt-amperes. — The short-circuit current for any arrangement of reactances and for a short at any point can be found

* By D. B. Rushmore.

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with sufficient accuracy by neglecting the resistances of the apparatus and connections and calculating the resultant reactance by applying successively the formulas for two reactances in series or in parallel, as the case may be. Note that the resultant reactance X_s of two reactances, x_1 and x_2 in series, and the resultant reactance X_p of two reactances, x_1 and x_2 in parallel, are respectively

$$X_s = x_1 + x_2, X_p = \frac{x_1 x_2}{x_1 + x_2} \quad (3)$$

provided the resistances of the circuits are negligible. The reactances, x_1, x_2, etc., of the various circuits can be calculated from the percentage reactance by formula (1). Let X_r be the resultant reactance of all the circuits feeding into the short circuit, and let E be the kilovolt rating of the generators, then

$$\text{Total short-circuit kv-a.} = \frac{1000\,E^2}{X_r} \quad (4)$$

For example, consider the case of four, 12,000 kv-a., three-phase, 11,000-volt generators feeding into a bus which is divided into two sections, *A* and *B*, with two generators feeding into each section, and one transmission line from each section, each line fed through a bank of transformers. A set of reactance coils, having 6 per cent reactance, connects the two bus sections. The inherent reactance of each transformer bank is 8 per cent, and the inherent reactance of each generator is 20 per cent. The reactance of each generator is then 2.0 ohms; of each transformer bank 0.4 ohm, and of each set of reactance coils 0.6 ohm. Let a short circuit occur between the three wires of the line connected to the bus section *B*. We then have $2.0/2 = 1.00$ ohm in series with 0.6 ohm, or a total of 1.6 ohms, which total is in parallel with the other two generators, i.e., in parallel with 1.0 ohm, giving a resultant reactance up to the transformer bank of 0.6 ohm; this is in series with the transformer bank, giving a final resultant reactance, $X_r = 0.6 + 0.4 = 1.0$ ohm. Hence the total kilovolt-amperes, from formula (4), is 121,000, or about 10 times the rating of each generator.

DIMENSIONS, WEIGHT AND COST. — Iron-core reactances with air gap occupy from 0.30 to 0.50 cubic foot per rated kv-a., weigh from 20 to 50 pounds per rated kv-a. and cost from $3 to $5 per rated kv-a., the first figure in each case applying to air-blast reactances and the latter figure to oil-cooled reactances. Power-limiting reactances occupy from 0.3 to 0.6 cubic foot per rated kv-a., weigh from 20 to 30 lbs. per rated kv-a. and cost from $4 to $12 per rated kv-a. The first figure in each case applies to reactances having a rating of approximately 500 kv-a. and the latter for ratings of approximately 50 kv-a. These figures apply to 60-cycle reactances and should be increased from 10 to 15 per cent for 25-cycle reactances. (1920 prices.)

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RECTIFIERS. — (*See also Arc, Electric; Converters; Motor-Generators.*) The term rectifier is applied to any stationary apparatus or rotating commutator for transforming alternating into direct current, or vice versa. Three types of rectifiers are in commercial use, viz., the mercury-arc rectifier, the electrolytic rectifier and the rotating commutator driven by a synchronous motor, but only the first type is at present of much importance commercially.

MERCURY-ARC OR MERCURY-VAPOR RECTIFIER. — The operation of this rectifier depends upon the fact that a tube containing mercury vapor under a low pressure and having one electrode of mercury, and the other of some other conductor, offers a very high resistance to a current tending to flow through the tube from the mercury to the other electrode, but has a very low resistance to a current flowing in the opposite direction, provided the current is once started by forming an arc in the tube, e.g., by tilting the tube so that the mercury touches for an instant the other electrode. See article on *Arc, Electric.*

Application. — Mercury-arc rectifiers find their chief application as a means of charging storage batteries and supplying a certain series type of d-c. arc lamp (*see Lamps, Electric*) from an a-c. supply. In the latter case the rectifier receives its current from a constant-current transformer and delivers a direct current of constant value. Mercury-arc rectifiers have also been tried out experimentally on electric cars and locomotives, power being supplied to the car or locomotive from a high-voltage a-c. trolley, stepped down to a lower voltage by transformers and converted into low-voltage direct current by means of the rectifiers. Although this scheme has not yet proved satisfactory commercially, it seems to be particularly promising when used in connection with high voltage (1200-volt) railway motors. The difficulty lies chiefly in producing a tube of rugged and lasting qualities.

Connections for Single-phase Operation. — The connections employed in practice are shown in Fig. 1. The complete equipment consists of a source of alternating current *HG*, the rectifier tube *AA'*, two reactances *E* and *F* and the load represented as a storage battery *J*. The rectifier tube is an exhausted glass vessel in which are two graphite electrodes (anodes *AA'*) and one mercury cathode *B*. Each anode is connected to a separate side of the a-c. supply, and also through one-half of the main reactance to the negative side of the load. The cathode *B* is connected to the positive side. There is also a small starting electrode *C* connected to one side of the a-c. circuit through a resistance and used for starting the arc. When the rectifier tube is rocked so as to form and break a bridge of mercury between the cathode *B* and starting anode *C* a small arc is formed. This produces mercury vapor in the tube and the arc immediately jumps to one or the other of the main anodes and alternates on these during regular operation.

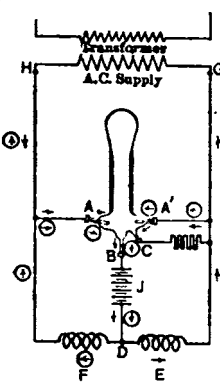


Fig. 1. Mercury-vapor Rectifier

Mode of Operation. — To analyze the operation, assume an instant when the terminal *G* is positive and *H* negative. The positive current will then flow from anode *A'* to cathode *B*, through the load *J* to *D* and through reactance *F* back to *H*. The current cannot jump from *A'* to *A* on account of the high

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counter electromotive force of the arc. The small arrows surrounded by circles show the path of the current during this half cycle. During the next half cycle the terminal *H* is positive and the current flows to *A* through the tube to *B*, through the load *J*, reactance *E* and back to *G*. The small arrows show the path of the current during this half cycle. Hence during a whole cycle the cathode *B* is continuously negative but first one anode is active and then the other. If the voltage and current should become zero coincidentally the arc would become extinguished and operation cease. Hence the reactances *E* and *F* are introduced. At the end of the first half cycle described, when the line voltage drops to zero, the inductance of *F* maintains the current and a local circuit is formed through *A*, *B* and *F*, which maintains the arc until the voltage at *G* has risen to a value which will maintain the arc.

The rectifier thus makes use of both half waves, or the entire alternating current, and the result is a uniform pulsating uni-directional current. On account of the reactance in the circuit, this current in the load never falls to zero and, in fact, with sufficient reactance, may be made very nearly constant. But this extreme is not always desirable, as it distorts the current wave in the a-c. supply circuit.

Arc Rectifiers on Polyphase Circuits. — Rectifiers may be arranged on two-phase and three-phase circuits, and in fact there is an advantage in the arrangement of the reactances in these cases.

Efficiency of Mercury-arc Rectifier. — The losses in the rectifier correspond to a constant counter e.m.f. of about 14 or 15 volts, thus the efficiency of the tube is constant at all loads and at high voltages is very high; the higher the voltage the higher the efficiency. In fact, for high voltages the losses in the transformer and reactance coils form the major part of the total losses. On account of the small losses in the tube itself, there is very little heat to be dissipated, and rectifier tubes of large capacity are very small in bulk.

Kilowatt Capacity of Mercury-arc Rectifier. — Rectifiers have been built for voltages up to 6000. The tubes may be of glass or steel. The glass tubes have a capacity of about 40 amperes and the steel tubes from 200 to 300 amperes. Several rectifiers may be operated in parallel for large currents. The power factor of the combination of tube and controlling devices is about 90 per cent. Rectifiers have been built of a capacity sufficient to operate motor cars and locomotives.

Dimensions, Weights and Costs of Mercury-arc Rectifier Outfits. — A standard outfit consisting of rectifier tube, transformer, reactance, switchboard panel, switches and instruments to supply a load of 30 amperes at 110 volts d.c. would occupy a floor space 16 × 19 in., have a height of about 64 in., and weigh complete about 600 pounds. The first cost of the outfit would be between $200 and $250 and the cost of renewing the tube about $20. The net efficiency would be about 78 per cent. Such an equipment is frequently used for charging the batteries of electric vehicles from a-c. supply circuits.

ELECTROLYTIC RECTIFIERS. — (*See also Condensers; Lightning Protectors.*) The operation of this type of rectifier is in a general way the same as that of the mercury-arc rectifier, being based on the fact that a certain electrolytic cell having electrodes of different metals (e.g., aluminum and steel electrodes in a solution of ammonium phosphate) have the property of allowing a current to pass in only one direction. By suitably combining two of these cells both the half waves of an alternating current may be rectified. Such rectifiers have a low efficiency and due to the large losses in them heat very rapidly. They are therefore applicable only to the rectification of small currents. Examples are the electrolytic rectifier of Nodon described at the International Electric Congress of 1904.

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TUNGAR RECTIFIER. — This rectifier acts on the principle of the Fleming valve (see *Radio Communication*), and consists of a heated tungsten filament for one electrode, and a tungsten plate for the other, both placed in a high vacuum in a glass bulb. If the plate is made positive to the filament a thermionic current will flow across the intervening space in the vacuum, but if the filament is positive to the plate no current will flow. By combining two tungar rectifiers with an auto-transformer, as is done with the two halves of the mercury-vapor rectifier, both half waves may be rectified. This rectifier is limited to small current (7.5 amp.) and is used chiefly for charging small groups of storage batteries at 15 volts or less.

MECHANICAL RECTIFIERS. — These usually consist of a commutator driven by a synchronous motor. Each commutator has as many live segments as there are poles on the synchronous motor. Alternate segments are connected to the source of alternating currents, and brushes properly spaced and bearing on the commutator collect the direct current. The objections to these devices are that if there is much inductance in the d-c. circuit (e.g., a motor) there will be a great deal of sparking, or if the load has a constant counter e.m.f. (e.g., a storage battery) there will be sparking. By alternating live and dead segments, this trouble can be obviated, provided the current to be rectified is not too large and the proportions of the live and dead segments are properly chosen. Commutator rectifiers of this type capable of rectifying currents up to 50 amperes at 200 volts have been constructed. The principal losses are in the driving motor; the efficiency is poor at light loads.

Many attempts have been made to produce a satisfactory rectifier by various schemes for interchanging the connections to the a-c. circuit at the end of every half wave, but none of them have as yet proved satisfactory for rectifying currents of any considerable magnitude. The difficulty lies chiefly in providing a means of preventing the formation of a spark when the circuit is interrupted or commutated.

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REGULATORS. — (*See also Batteries, Storage, Applications of; Controllers; Rheostats; Starters, Motor; Switchgear Equipment for Power Stations.*) Devices for adjusting and controlling the voltage in an electric circuit are called regulators. They may be divided into two classes, depending on whether they operate directly on the circuit or indirectly by means of the excitation of the generator.

FEEDER OR POTENTIAL REGULATORS, as the name implies, operate to raise or lower the feeder voltage. Where a feeder circuit is operated from a constant potential bus and it is desirable to compensate for the drop in the feeder, there is usually installed a regulator which adjusts the voltage impressed upon the feeder so as to maintain proper voltage at the point of distribution.

With d-c. circuits the only way to raise the voltage of the feeder above that of the bus is to connect a booster or a storage battery (q.v.) in series. The feeder voltage may be lowered by connecting in resistance. Owing to the inefficiency of resistance control and the complication of providing boosters or batteries, feeder control of d-c. circuits is used only in special cases, such as for the distribution system of a direct-current railway.

Feeder control for a-c. circuits is accomplished by transformer action. Feeder regulation for such circuits can be made in various ways, the most common being the "induction" type and the "step" type.

Induction Regulators, also called "induction potential regulators," are used on either single-phase or three-phase circuits and are arranged for hand operation, motor operation with distant control, or for full automatic operation by means of relays. An induction regulator is a special type of transformer, built like an induction motor (q.v.) with a coil-wound secondary. The primary is permanently connected across the feeder circuit, and the secondary which is connected in series with the feeder is normally stationary, but is movable at will for the purpose of adjusting the voltage. In comparison with the step-type regulator (*see below*) the induction regulator possesses the advantage of being operated without short-circuiting any transformer coils. It has the disadvantages of a large magnetic leakage and a high value of exciting current.

Single-phase Induction Regulator. — This regulator has a secondary induced voltage whose value depends on the relative angular position of the primary and secondary coils, but which is always in time phase with the primary voltage. This induced voltage is a maximum when the axes of the coils coincide and it is zero when the coils are at right angles to one another. The resultant feeder voltage is equal to the arithmetical sum (or difference) of the primary and secondary voltages.

Polyphase Induction Regulator. — This regulator has a rotating flux of constant value, set up by the primary current. Thus the secondary induced voltage is also constant in value but differs in phase from the normal line voltage depending on the angular relation between the primary and secondary windings. The resultant delivered voltage is the vector sum of the primary and secondary voltages, and its value varies with the position of the movable member.

Step-type Regulators, also called "contact-voltage regulators," consist essentially of a stationary transformer provided with a large number of secondary taps for cutting in and out sections of the transformer windings. The taps are connected with a dial or drum so that any pair of taps can be connected to the feeder circuit according to the voltage required.

The moving arm on the dial-type regulator is usually arranged so that in passing from the position of maximum boost the number of secondary turns in series with the circuit is reduced in equal steps until the turns are all cut out. Further rotation in the same direction throws over the reversing switch and

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then cuts in the same secondary turns in opposition to the main voltage until the position of maximum bucking is reached, when a stop prevents any further rotation in that direction. A similar stop prevents overtravel in the position of the maximum boost.

Automatic Operation of Feeder Regulators with either single- or three-phase circuits is obtained by the action of a voltage relay, which may or may not have a compensating device. This relay acts in conjunction with the motor on the regulator so that, as the load comes on or as the bus-voltage drops, the motor will turn the regulator in such a direction as to increase the voltage. By means of a compensator which can be set for a certain resistance and a certain inductive drop, the voltage at the point of distribution can be maintained constant independent of the amount and power factor of the load, provided the total drop is within the range of the regulator.

OUTDOOR INDUCTION REGULATORS.— During the last few years a number of induction regulators, both of the single-phase type and the polyphase type have been developed for outdoor service. The smaller regulators are arranged for mounting on a pole or pole platform while the larger ones, usually employed in connection with outdoor transforming stations, are located on the ground level. To secure satisfactory cooling the smaller size regulators are mounted in corrugated sheet-steel cases, while the larger ones are provided with radiators similar to the large outdoor self-cooling transformers.

Outdoor induction regulators have been built as large as 1750 kv-a., three-phase, 60 cycle, 13,600 volts, and larger regulators can be built whenever needed.

FIELD REGULATORS. — In order to maintain practically constant voltage on a-c. and d-c. generators, or to have these machines compound automatically to take care of feeder drop, field regulators of either non-automatic or automatic types are employed. The former are hand-controlled rheostats (see *Rheostats*), the latter are made in various forms of which the regulator originally known as the "Tirrill" type is the best known in America. These generator-voltage regulators are made in two forms, one using a d-c. magnet and the other using an a-c. vibrating magnet relay as the anti-hunting control device.

Either design of regulator depends for its operation on the rapid opening and closing of a circuit that shunts the field rheostats and thus changes the resistance in the field circuit of the generator to be regulated. For d-c. service the regulator usually works upon the main generator field and for a-c. service upon the field of the exciter. In both cases the rheostat is so adjusted that when in circuit it tends to lower the voltage considerably below normal, and when the rheostat is short circuited the generator voltage rises. The regulator automatically closes the shunt circuit and the voltage drops to a predetermined value and opens the shunt circuit when the voltage rises above that value.

The main features of the regulator with the d-c. vibrating magnet are: 1st, the method of control by shunting the rheostat; 2nd, that with the total range of regulation from no load to full load the maximum travel of the only moving part (the vibrating contact) is only $\frac{1}{16}$ inch; 3rd, the use of the exciter voltage as one of the main control circuits which prevents the generator voltage from overshooting. The vibrations are so rapid that the time factor is reduced to a minimum and there are no retarding effects due to dash pots or other damping devices.

Regulator for Direct-current Generator (Fig. 1). — This consists essentially of a main control magnet whose winding is connected across the generator terminals, and a differentially-wound relay magnet. When the effect of the potential winding increases, due to a rise in the generator voltage, the contact of the main control magnet is opened and in turn one winding of the relay

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magnet is deënergized. Thus the relay contact is opened and the short-circuit removed from the generator rheostat. When the generator voltage drops, the main contact is closed and the differentially-wound relay magnet acts to short-circuit the field rheostat. The relay contacts are shunted by a condenser to reduce sparking.

In case the generator is to overcompound for line drop a current winding is added to the main control magnet and is connected across a shunt in one of the local mains. The action of this current winding opposes the action of the potential winding in the control magnet end, and thus makes the generator overcompound for line drop. Regulators of this type can be adjusted for a line drop up to 15 per cent.

Where the generators are shunt wound a separate regulator is required for each machine which is operating at any time. Where several small compound machines are operating in parallel and all of the regulating is done by one machine, the others trailing after, provision is made for connecting any machine to the regulator. For field currents in excess of about 3 amperes at 250 volts, it is found that one relay contact is not sufficient, and for such cases regulators are built with as many as 10 relays, all being operated by a single main control magnet. For still larger d-c. generators whose field current could not be handled by a multiple-contact regulator, it is necessary to supply a separate exciter or exciters and the regulator then controls the field circuit of the exciter as described below for a-c. generators.

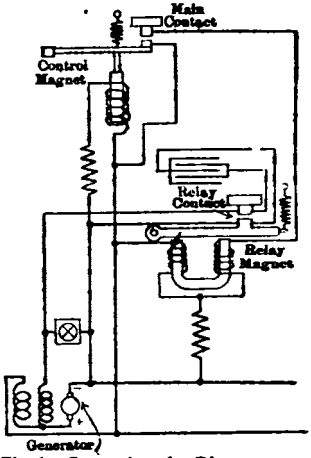


Fig. 1. Connections for Direct-current Tirrill Regulator

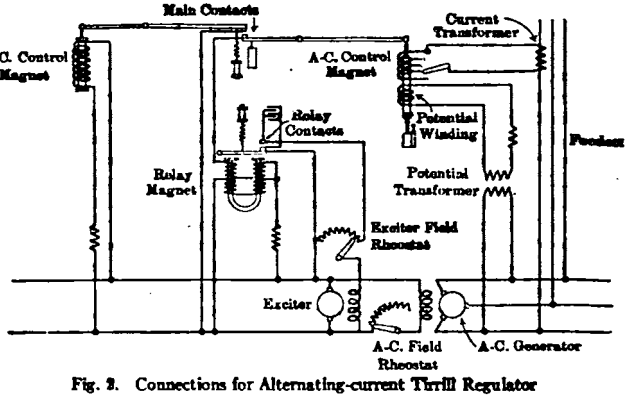


Fig. 2. Connections for Alternating-current Tirrill Regulator

Regulator with D-C. Vibrating Magnet (Fig. 2). — This works on the exciter field. The main contacts with this type of regulator are acted on by

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two sets of control magnets, one connected across the exciter bus and tending to move the main contacts farther apart as the exciter voltage rises, and the other acted upon by a-c. potential and current coils. Suitable springs and counterweights allow the proper adjustment to be made. When the main contact closes, it energizes the relay magnet, thus closing the relay contact, short-circuiting the exciter rheostat and raising the exciter voltage and consequently the generator voltage. The use of the exciter voltage as one of the main control circuits prevents the generator voltage "overshooting," for as the exciter voltage rises to bring up the a-c. voltage the d-c. control tends to keep the main contacts apart and so reduce the voltage again.

The compensating current winding of the a-c. solenoid is provided with a dial switch to give any amount of compensation required for the feeder circuit

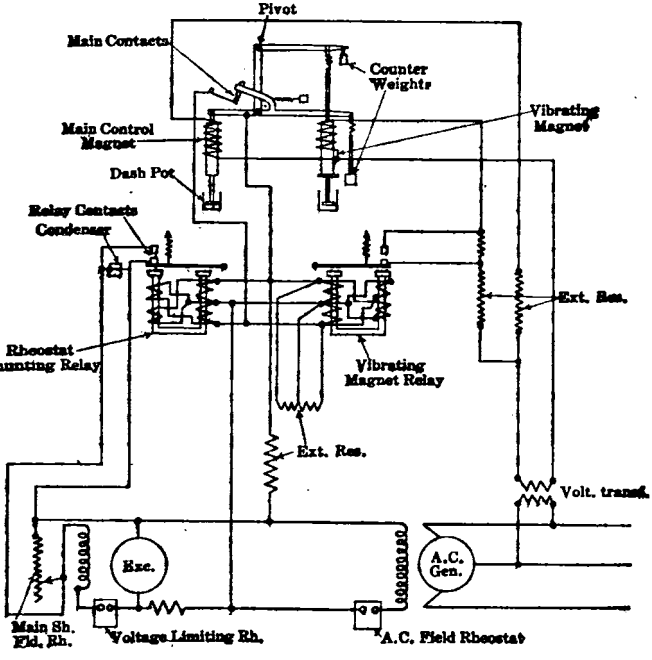


Fig. 3. Regulator with A-C. Vibrating Relay Control.

in which the current transformer is located. Where it is desired to compensate for both resistance and inductive drop under varying power factors a special compensator is provided. A modification of the regulator to take care of the large exciters has a number of relay contacts all operated at the same time from the one set of control contacts, the various relays being shunted by condensers to reduce the sparking. A single regulator may serve a number of alternators if they are operated in parallel and if all use the same exciter. If two or more exciters are operated in multiple, a single regulator will suffice; if not operated in multiple, a separate regulator is usually installed for each exciter.

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Regulator with A-C. Vibrating Magnet. — This type of generator voltage regulator does not employ any d-c. main control magnets, but uses an a-c. vibrating magnet relay and its general connections are indicated in Fig. 3. The main control magnet has its core attracted upwards and its core stem connected to the floating lever which is pivoted to the bell crank of the vibrating magnet. The two magnets are energized from the same voltage transformer and actuates the main contacts into and out of engagement with the fixed contact. The opening of the main contacts open all relay contacts and inserts the full resistance into the vibrating magnet circuit, weakening the pull and closing the main contacts again. This system comprising the main control magnet, the vibrating magnet, levers, rheostats, shunting and vibrating relays, constitutes a vibrating system when the circuits are properly energized and the control elements balanced. For a given line voltage there is a definite upward pull of the vibrating magnet core when the vibrating relay contacts are open, and a definite pull of greater value when the relay contacts are closed. When the regulator is connected to the system the rheostat shunting relays open and close the circuit across the shunt field or regulating rheostat of the exciter, and the effective resistance of this rheostat is determined by the time of contact engagement.

Regulators for d-c. service are built for pressures up to 550 volts and for a-c. service they can be made so that by means of master relays they may control as many as 60 rheostat shunting relays, each rheostat shunting relay being capable of handling between 2000 and 2500 watts where the total current of any exciter field winding does not exceed about 15 or 16 amperes. The regulator with the main d-c. control is usually intended for a 2 : 1 range with no load to full load excitation current. With the vibrating relay control a broad range system of regulator can be adopted securing a 10 : 1 or greater voltage range by energizing the relays from a separate source of direct current, such as a small motor generator set or storage battery.

REGULATOR APPLICATION. — The following conditions should be approached as nearly as possible in order to obtain satisfactory results:

(1) Prime movers must be provided with proper automatic governors that will respond instantly to changes in load and keep the speed reasonably constant, within 3 per cent to 4 per cent, from no load to full load.

(2) Alternating-current generators should have as nearly as possible the same percentage range of excitation from no load to full load.

(3) Exciters must be capable of delivering sufficient voltage to take care of the alternating-current generator field under the full load conditions, 80 per cent power factor plus a certain additional voltage. This additional voltage above the steady exciter voltage required to maintain constant bus voltage under full load conditions is necessary in order that the regulator will continue to vibrate and thereby have control of the exciter.

(4) Where more than one exciter are to be considered, they must be adjusted to operate in parallel under all loads, with any point on the saturation curve.

(5) Exciters for 125-volt service should be able to build voltage up or down between the limits of 30 and 125 volts in five seconds or less under load consisting of generator field circuits. The time constant should be the same for exciters of other rated voltages over proportional changes. Exciters with greater time constants than this may not permit the regulator to maintain constant voltage with rapidly fluctuating load.

(6) Interpole exciters for 125-volt service must be able to develop at least 135 volts with series windings disconnected and should be so operated. Series windings must be out of circuit in order to secure a satisfactory time constant. In general, the exciter must be capable of developing a voltage 10 to 15 per

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cent in excess of that required by the a-c. generator at full load, 80 per cent power factor, the a-c. generator field rheostat being adjusted so that with 60 volts on a 125-volt exciter, the a-c. generator develops normal voltage at no load.

Regulators can be arranged for satisfactory parallel control where generators are in parallel and the exciters operating independently.

EXCESS VOLTAGE PROTECTION. — Unless special devices are furnished with the generator voltage regulator, when a short circuit on the system is cleared away, a dangerous voltage rise is inevitable. On the occurrence of a short circuit on a system without some protective device, the main contacts of the regulators close, causing the exciter voltage to build up to the maximum value. When the short is cleared away, high voltage results from the high exciter voltage and the consequent high generator field current which lasts until the regulator has had time to again become operative. This condition of excessive voltage can, however, be prevented by means of excess-voltage protective devices arranged so that the exciter voltage can never rise above a predetermined point, which is usually a little above the no-load excitation value required by the a-c. generators. Different types of regulators require slightly different excess-voltage protective devices to accomplish this result.

COSTS. — The cost of regulators varies considerably due to the character of installation and varies between about $1200.00 for a one-relay regulator and $2715.00 for a ten-relay regulator.

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RELAYS. — (*See also Circuit Breakers; Telegraphy; Telephony; Regulators; Signaling, Railway.*) A relay is a device which opens or closes a local circuit under predetermined electrical conditions of the main circuit. There are three general classes of relays as determined by their respective functions of (1) protecting the main circuit, (2) regulating the current in the main circuit, or (3) signaling the condition of the main circuit.

PROTECTIVE RELAYS are auxiliary devices supplied for use with circuit breakers on systems that require protection more selective and flexible than that afforded by the usual control features of automatic circuit breakers (q.v.). The closing of a local circuit through the action of the relay causes in turn the tripping of the circuit breaker.

Types of Protective Relays. — The types which are most commonly employed are given in the following table, together with the apparatus with which each type is applied and the protection furnished by the operation of the relay.

Relays are built to furnish protection against overvoltage, no voltage, overload, no load, reverse power and reverse phase. They may operate either directly

TYPES OF RELAYS

Type of relay	Application	Operations	Approximate cost per relay*
D-C. overvoltage	Storage batteries d-c. apparatus	Prevents overcharging Prevents damage from excess voltage	$25 00
D-C. reverse current	Storage batteries rotary converters	Prevents discharging into charging source Protects against reversal of flow of energy	94.00
D-C. low-voltage release	D-C. motors	Operates if voltage falls below given value	25.00
D-C. underload	Storage batteries	Disconnects on completion of charge	25.00
A-C. overload	Feeders, motors, rotary converters, transformers	Protects against overload	33.80
A-C. reverse power	Feeders, generators	Protects against reversal of flow of energy	80.00
A-C. low-voltage	Induction motors	Protects against fall in line voltage	37.60
A-C. reverse phase	Synchronous apparatus, elevators and cranes	Protects against reversal of phase progression	42.25

* Costs do not include shunts for d-c. relays or current and potential transformers for a-c. relays, as the cost of these varies greatly with current and voltage. Costs are for 1921.

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or in connection with other relays, and may be made instantaneous or provided with a time limit either of definite duration (time-limit relay) or inversely proportional to the extent of overload (inverse-time-limit relay).

Definite Minimum Inverse Time-limit Overload Relays. — Where the time-limit relays are wanted for the protection of a-c. circuits, it is practically universal American practice to furnish relays that have an adjustable definite minimum time setting and an inverse time setting combined. With one type, there is a definite time setting of two seconds with the maximum adjustment so that, independent of the intensity of a short circuit, the breaker will not trip out until two seconds have elapsed. This definite time is, however, adjustable between practically any limits between 0.1 second and 2 seconds. Beyond the definite time there is an inverse time feature which gives selective action whereby the time of operation varies inversely with the load. With this type of relay the faulty line carrying the heavier load usually will have its breaker tripped out before the other breakers are affected.

Example of Use of Relays. — The various types of relays that may be used to advantage in a system are shown diagrammatically in Fig. 1, where

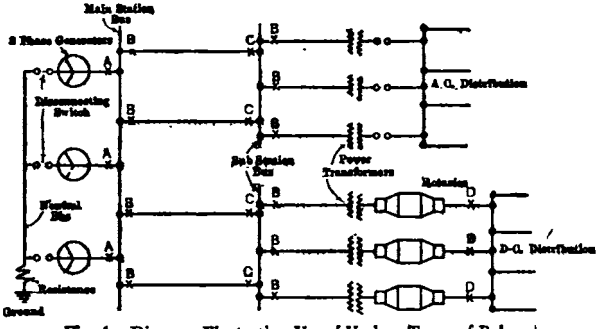


Fig. 1. Diagram Illustrating Use of Various Types of Relays.

three a-c. generators operate in parallel with their neutral points grounded through a resistance and feed a common bus supplying current to power transformers, rotaries, etc., for a-c. and d-c. distribution. Relays for the operation of circuit breakers are inserted as follows:

At A — a-c. overload and reverse power relays.
B — a-c. overload time-limit relays.
C — a-c. reverse power, time-limit relays.
D — d-c. reverse current, inverse time-limit relays.

The Principle of Operation of a protective relay depends somewhat on the duty to be performed. The actuating mechanism usually involves such a motive device as a solenoid and core, or a rotating motor. The mechanisms described below are those most frequently used for the respective types of service.

D-C. Overvoltage Relay. — One design consists of a permanent magnet which forms a base and two iron cores mounted parallel to the base and attached to it at one end with an eccentrically-pivoted armature carrying a suitable contact. With no current flowing the two cores exert an equal pull (due to the magnetic field of the permanent magnet) on the pivoted armature, which, due to its eccentric mounting, is pulled up against one core. When voltage is impressed on the coils wound on the iron cores the magnetism in one pole is strengthened and in the other weakened. At the predetermined over-

voltage the position of the armature is reversed, notwithstanding its eccentric mounting, and the contact is closed, tripping the breaker.

D-C. Reverse-current Relays for instantaneous operation are similar in construction to overvoltage relays (*see preceding paragraph*). The solenoids, however, are operated from a shunt in such a way that with the current in the normal direction the contact is held open, but when the current reverses in direction the contact is closed, thus tripping the breaker.

Reverse-current Time-limit Relays are built on the principle of a permanent-magnet d-c. ammeter operated from a shunt. In normal operation the armature of the relay tends to turn in one direction but is restrained by a stop; in the case of current reversal the armature turns in the opposite direction, its rate of movement being proportional to the strength of the current. The angle through which the armature has to turn to close the contacts is adjustable by moving the stationary contact.

A-C. Overload Relays are usually built in single pole units and are nearly always made to give a definite minimum inverse time element. These relays are of the induction type and have practically superseded the solenoid design. This definite minimum feature is obtained by the use of a torque compensator or a small current transformer that saturates at practically 5 amperes. The primary side of this torque compensator is connected to the current transformer in the main circuit while the secondary side goes to the relay operating coils. Independent of the severity of the short circuit and consequently the current furnished to the primary of the torque compensator, the current supplied by the torque compensator to the relay coils does not materially exceed 5 amperes so that the speed with which the contacts are moved is practically fixed. The damping is so arranged that normally two seconds are required for the contact arm to move through its entire length of travel. By shortening the distance through which the contact arm has to move, this definite minimum time can be adjusted down to approximately 0.1 second. Relays of this kind are usually operated from current transformers having a normal secondary current of 5 amperes.

A-C. Reverse Power Relays. — These are made in various types and one kind frequently employed practically combines the features of the definite minimum overload relay and a selective wattmeter element. The overload element closes its contacts on excess current in either direction but the selective wattmeter element does not allow it to complete the tripping circuit unless power is flowing in the reverse direction. A momentary surge which may reverse the power will cause the selective wattmeter element to close its contacts, but the relay will not operate to trip out the breaker unless the current in the reverse direction exceeds the relay setting and is maintained for two seconds or longer.

Relay Switch. — Where, as frequently happens, the tripping contacts of a relay will not carry enough current to trip the circuit breaker, a relay switch is employed. In this case the relay merely energizes the operating coil of the relay switch whose contacts can be made suitable for any reasonable amount of current.

Rating of Protective Relays for overload service is given usually in terms of maximum current in the main circuit (secondary of transformer with a-c.). For reverse-load relays the rating is expressed as the percentage of reverse load on which they will operate. For relays which are not instantaneous in their action a time rating in seconds is usually given.

REGULATING RELAYS. — See article on *Regulators*.

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LING RELAYS. — See articles on *Telegraphy; Telephony; Signal-*
y.

— See table above.

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RESISTANCE AND CONDUCTANCE, ELECTRIC. — (*See also Alternating Currents; Bridges for Electrical Measurements; Electricity and Magnetism, Principles of; Resistors, Standard; Skin Effect; Wires and Cables; Wires, Resistor.*) The general definition of the resistance R' of a substance between any two equipotential surfaces intersecting the path of a current I is

$$R' = \frac{P_h}{I^2}, \tag{1}$$

where P_h is the power dissipated as heat between the two equipotential surfaces and I is the *effective* value of the *total* current from one surface to the other. In the case of a varying current this dissipation of heat may occur in four different ways, viz., (1) as heat due to the conduction current through the substance, (2) as heat due to dielectric hysteresis accompanying the displacement current through the substance (when the latter is an insulator), (3) as heat due to magnetic hysteresis accompanying the varying magnetic flux produced by the current and (4) as heat due to eddy currents induced in neighboring conductors.

In the case of a continuous (non-varying) current the last three effects do not occur, and the heat is that due to the conduction current only. The resistance offered by a substance to a continuous current is called the "true," "ohmic," "continuous-current" or "direct-current" resistance, as distinguished from the "effective" resistance offered by the substance to a varying current. The effective resistance, even when there are no losses due to dielectric or magnetic hysteresis, is in general greater than the ohmic resistance, due to the skin effect; see *Skin Effect*.

Similarly, the general definition of conductance is

$$G' = \frac{P_h}{V^2}, \tag{2}$$

where P_h has the same meaning as above and V is the *effective* value of the potential difference between the two equipotential surfaces. When the voltage is non-varying the conductance is called the "true," "ohmic," "continuous-current" or "direct-current" conductance as distinguished from the "effective" conductance to a varying current.

In the case of a *continuous*, or constant current I, the above expressions for resistance and conductance reduce to

$$R = \frac{V}{I}, \qquad \text{and} \qquad G = \frac{I}{V}, \tag{3}$$

provided there is no source of e.m.f. between these two surfaces. The ohmic resistance and conductance, given by equations (3), are reciprocals of each other, but this is not true for the effective resistance and conductance.

RESISTIVITY AND CONDUCTIVITY. — When the current stream lines from one equipotential surface to the other are straight and parallel and uniformly distributed, and l is the distance between the two surfaces and A the area of each, the ohmic resistance and conductance of the prism or cylinder of the substance thus formed are respectively

$$R = \rho \frac{l}{A}, \text{ and } G = \gamma \frac{A}{l}, \tag{4}$$

where ρ and γ (which are reciprocals) are called the resistivity* and conductivity* of the substance respectively. For a given material at constant temperature throughout ρ and γ are constants.

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* Also called specific resistance and specific conductance.

Units of Resistivity and Conductivity. — From (4) it is evident that ρ is the resistance of a cube of the substance of unit length on each edge when the current stream lines are uniformly distributed and parallel to four of the edges of the cube; similarly, γ is the conductivity of such a unit cube. Resistivity is therefore frequently expressed as ohms or microhms per centimeter cube or per inch cube, and conductivity as mhos or mega-mhos per centimeter or inch cube. Note that a resistivity of x microhms per centimeter (or inch) cube is equivalent to a conductivity of $\frac{1}{x}$ mega-mhos per centimeter (or inch) cube.

Ohms per Mil-foot. — It is frequently convenient in dealing with wires to express lengths in feet and cross sections in circular mils. The corresponding value of the resistivity ρ is then expressed in ohms per mil foot.

Ohms per Meter-gram. — The cross section of a bar or wire of uniform cross-section is equal to the volume of the bar divided by its length, and the volume of the bar is in turn equal to its mass divided by the density of the material of which it is made. Hence, using the same symbols as above, and in addition calling m the mass of the conductor and δ its specific gravity,

$$R = \rho\delta\frac{l^2}{m}. \qquad (5)$$

For a given material at a given temperature $\rho\delta$ is also constant, hence

$$R = k\frac{l^2}{m}, \qquad (5a)$$

where k is a constant (equal to $\rho\delta$) for a given material at a given temperature; this factor k is then called the specific resistance of the conductor in "ohms per meter-gram" when l is in meters and m in grams.

Pounds per Mile-ohm. — In telephone and telegraph practice the specific resistance of a conductor is also expressed as the weight w, in pounds, of a wire one mile long having a resistance of one ohm. This weight w is sometimes called the "mile-ohm equivalent" of the wire.

"Annealed Copper Standard." — Matthiessen's Standard. — In 1862 Matthiessen published the results of a number of determinations of the resistivity of copper. Recent determinations of the conductivity of a number of samples of commercial annealed copper wire at the Bureau of Standards (*Bull. Bur. Stand., 1911, Vol. 7, p. 103*) gave a mean value of the resistivity very close to Matthiessen's value. A conductivity corresponding to 0.15328 ohm per meter-gram at 20° C. has been adopted (1912) by the Bureau and by the American Institute of Electrical Engineers (1914)* as the "standard" of conductivity, the name "Annealed Copper Standard" being suggested for it. (*See Standardization Rules of the A.I.E.E.*) Matthiessen's Standard, formerly used by the American Institute of Electrical Engineers as the basis for their wire tables corresponded to 0.141729 ohm per meter-gram at 0° C.

To reduce the value of the Annealed Copper Standard to resistivity and conductivity in volume units the value of 8.89 has been adopted as the density of copper in grams per cubic centimeter at 20° C. which corresponds to 8.90 grams per cubic centimeter at 0°C.

Per cent Conductivity. — The Bureau of Standards recommends that whenever the conductivity of a sample is expressed as a percentage, the measured resistivity or conductivity be corrected to reduce it to the value it would have

* Also adopted by the national electrical engineering societies in Germany and France.

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at 20° C.; see section on *Temperature Coefficient of Resistance*, below. A conductivity of P per cent is equivalent to

$15.328 + P$ ohms per meter-gram at 20° C.
$172.41 + P$ microhms per centimeter cube at 20° C.
$67.87 + P$ microhms per inch cube at 20° C.
$1037.1 + P$ ohms per mil-foot at 20° C.

For example, a conductivity of 60 per cent is equivalent to a resistance of 17.255 ohms per mil-foot.

CALCULATION OF THE OHMIC RESISTANCE OF A CONDUCTOR. — Values of the resistivity of various materials are given in the table below. Experiment shows that the resistance of a given length of wire of uniform cross section is independent of the shape into which the wire is bent, provided the diameter of the wire is small compared to the radius of curvature of the curve into which it may be bent. This condition is almost always realized in practice, and consequently formulas (4) and (5a) are in general directly applicable to the calculation of the resistance of a wire whether the wire be straight or curved or wound into a coil of any shape. These formulas are also applicable to the calculation of the resistance of a rod or bar, provided the rod or bar is not bent into a sharp curve, and the distance between its points of connection to the circuit is large compared to the linear dimensions of its cross section. Care should be taken, however, to express all quantities in the proper units; for example, the resistance in *ohms* of a wire which has a specific resistance of 1.6 microhms per centimeter cube, a length of 1000 feet and a cross section of ¼ square inch, is

$$R = 1.6 \times 10^{-6} \frac{1000 \times 12 \times 2.54}{0.25 \times (2.54)^2} = 0.0302 \text{ ohm.}$$

Resistance Formulas When the Stream Lines are Not Parallel and Uniformly Distributed. — When the stream lines of the current are not all of the same length, as, for example, when a current is established in a heavy short bar bent into a sharp curve, the resistance of the bar can be calculated only when the distribution of these stream lines is known. Again, when the stream lines of the current are not parallel, e.g., the leakage current through the insulation of a cable, these formulas are not applicable. However, when the formula for the capacity between any two conductors is known (*see Capacity and Charging Current*), the resistance of the insulation, if uniform throughout, may be found by multiplying the *reciprocal* of the capacity, viz., $\frac{1}{C}$, by $\frac{K\rho}{4\pi}$, where ρ is the resistivity of the insulation and K the specific inductive capacity in the capacity formula. See articles on *Rheostats* and *Wires and Cables, Insulated*.

TEMPERATURE COEFFICIENT OF ELECTRIC RESISTANCE. — The resistance temperature coefficient β_t of a substance *at* any temperature t is defined as the rate of change of the resistance at this temperature, viz. $\left(\frac{dR}{dt}\right)_t$, divided by the resistance R_t at this temperature, i.e.,

$$\beta_t = \frac{1}{R_t}\left(\frac{dR}{dt}\right)_t. \tag{6}$$

The *mean* temperature coefficient α_t between any two temperatures t and t_1 *referred to* the temperature t is defined as the *average* change in the resistance in this interval per degree change of temperature, divided by the resistance at the lower temperature, viz.,

$$\alpha_t = \frac{R_{t_1} - R_t}{R_t (t_1 - t)}. \tag{7}$$

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General Expression for Change of Resistance with Temperature. — In neral, the relation between the resistance R_t of a given mass of a substance at ıy temperature t may be expressed in terms of its resistance R_0 at zero de- ees as follows:

$$R_t = R_0 (1 + at + bt^2 + \ldots), \tag{8}$$

here a, b, etc., are constant coefficients.

Linear Relation Between Resistance and Temperature. — When all the oefficients except the first one, a, are of negligible magnitude, i.e., when the ılation between the resistance and temperature is a *linear* one, then, from the ɔove definitions, the *mean* temperature coefficient (α_t) referred to a given tem- erature t is equal to the temperature coefficient (β_t) *at* that temperature, and ıe zero degree temperature coefficient α_0 ($= \beta_0 = a$) and the t' degree tempera- ıre coefficient $\alpha_{t'}$ are related as follows:

$$\alpha_{t'} = \frac{\alpha_0}{1 + \alpha_0 t'}, \tag{9}$$

nd

$$R_t = R_0 (1 + \alpha_0 t) = R_{t'} [1 + \alpha_{t'} (t - t')], \tag{10}$$

here R_0 is the resistance at zero degrees, $R_{t'}$ the resistance at t' degrees and R_t ıe resistance at t degrees.

For most metals the simple linear relation expressed by equation (10) repre- ents the experimental facts within practical limits of accuracy and for ordinary emperature ranges; values of α_0 are given in the table below. For dielectrics, owever, the relation between the resistance and temperature is by no means near, and several terms in such an expression as equation (8) are needed to epresent the facts; see *Insulating Materials, Properties of*, particularly the sub- eadings *Cambric, Paper and Rubber*.

Calculation of Change in Resistance With Temperature. — Equation 10) may be conveniently expressed in the form

$$\frac{R_t'}{R_t} = \frac{T_0 + t'}{T_0 + t}, \tag{11}$$

here T_0 is written for the reciprocal of α_0, viz., $T_0 = \frac{1}{\alpha_0}$. (11a)

Equation (11) will be found very convenient for calculating the change of re- istance with temperature and the change of temperature corresponding to two measured resistances, particularly when a slide rule is used.

T_0 is approximately equal to the number expressing the absolute zero on the mercury thermometer scale (except for magnetic metals) and is sometimes called the "inferred absolute zero" for the particular metal in question.

MEASUREMENT OF RESISTANCE, RESISTIVITY AND TEMPERATURE COEFFICIENT. — The simplest method of measuring a resistance in ordinary engineering work is to send a direct current through the conductor and measure this current by means of an ammeter (q.v.) and measure the potential difference across it by means of a voltmeter (q.v.). For measuring very low resistances, however, and for high-precision measurements, a bridge method should be used; see *Bridges for Electrical Measurements*.

VALUES OF RESISTIVITY AND TEMPERATURE COEFFICIENT. — The resistivity and temperature coefficient of the more common metals and alloys are given in the tables below.

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RESISTIVITY AND TEMPERATURE COEFFIC

1 microhm per centimeter cube $= \frac{1}{2.5400}$ microhms
$= 6.0153$ ohms per
$= 0.01\ \delta$ ohms per
specific gravit
$= 57.08\ \delta$ pounds

ρ microhms per cm. cube at 20° C. $= \frac{172.4}{\rho}$ per cent c

The zero degree Fahrenheit temperature coefficie

$$\frac{5\alpha_0}{9 - 160\alpha_0}.$$

Substance (*Numbers refer to authorities, top of p. 1225*)	Remarks	Mi-crohm per ce timet cube at 0° ρ_0
Advance (3)	Copper-nickel	48.8
Aluminum (1)	Pure	2.62
Aluminum (7)	Wire, 61% cond.	2.60
Alum. bronze (1)	97 Cu+3 Al	8.85
Argentan (1)	61.6 Cu+15.8 Ni+22.6 Zn	28.5
Brass (1)	90.9 Cu+9.1 Zn	3.64
Brass (1)	65.8 Cu+34.2 Zn	6.29
Bronze (1)	88Cu+12Sn+0.94*P*..	17.8
Calido (8)	Ni+Cr+Fe	100.0
Carbon (1)	Graphite	400
		1150
Carbon (1)	Incand. lamp	4000
Climax (3)	Nickel-steel	87.1
Constantan (1)	60 Cu+40 Ni	49.0
Copper (7)	Annealed	1.589
	Standard	
Copper (1)	Electrolytic	1.56
Copper (1)	Hard-drawn	1.60
Copper-iron (2)	0.4% Fe	4.08
Excello (4)		91.4
Ferro-nickel (3)		27.1
German silver (3)	18% Ni with Cu and Zn	33.1
Gold (1)	99.9% Au	2.20

* See *Wires and Cables, Bare*, for the resistance of va
sistance, for additional data on resistance wires; and *Insu*
for the resistivity of dielectrics. See also the articles on

† For resistivities at *high temperatures* see pages 1354 a

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SISTIVITY AND TEMPERATURE COEFFICIENT OF RESISTANCE — *Continued*

stance *s refer to op of p. 1225)*	Remarks	Microhms per centimeter cube at °C. ρ_0	Mean temperature coefficient referred to 0° C. Temperature range °C. From	To	α_0
.....	Cu+Ni	49.0	.....	.....	0.0000±
4).....	Copper-nickel.....	47.1	.....	.....	0.000005
(4).....	Copper-nickel.....	50.2	.....	.....	−0.000011
.....	Very pure.....	8.85	0	100	0.00625
.....	soft steel	11.8	10	35	0.00423
.....	hard steel.....	45.6	10	35	0.00161
(2).....	soft	74.4	.....	.....	.....
(2).....	hard	97.8	.....	.....	.....
al (5).....	Nickel steel.....	85.0	.....	.....	0.00070
.....	Pure.....	19.8	0	100	0.00411
uth (1).....	42.3 Pb+57.7 Bi.....	63.3	.....	.....	.....
-copper (1)..	70 Cu+30 Mn.....	100	0	100	0.00004
(3).....	Cu+Mn+Ni	41.4	.....	.....	0.000011
		73.8	.....	.....	0.000039
1).....	.....	94.07	0	100	0.0008649†
um (6).....	Hard drawn	4.9	0	170	0.0050
um (6).....	Annealed	4.2	0	170	0.0050
al (3).....	Copper nickel.....	40.8	.....	.....	0.00206
(3).....	.....	98.7	.....	.....	0.00045
II (3).....	.....	109.2	.....	.....	0.00016
.....	Electrolytic.....	6.93	0	100	0.00618
.....	Commercial wire....	9.9	.....	.....	0.0039
el (1).....	4.35% Ni.....	29.4	.....	.....	.....
bronze (1)..	.....	7.75	.....	.....	.....
(1).....	Drawn.....	11.0	0	100	0.00367
iridium (1)..	80 Pt+20 Ir.....	31.6	−100	100	0.002±
rho-	90 Pt+10 Rh.....	21.1	15	.....	0.00143
1).....	.....	44.6	0	.....	0.0041
tal (1),....	48.9 Bi+23.5 Sn+27.6 Pb.....	64.5	0	94.3	0.0023
.....	Electrolytic.....	1.47	0	100	0.00400
*Iron)**					
4).....	Nickel-steel.....	87.1	.....	.....	0.00081
(1).....	Pure.....	14.6	0	100	0.0033
.....	Cu+Mn+Al.....	46.7	.....	.....	0.0000056
.....	.....	10.5	18	100	0.00465
(6).....	Hard drawn	5.42	0	170	0.0051
(6).....	Annealed	4.37			
etal (1)....	55.7 Bi+13.7 Sn+13.7Pb+16.2Cd	51.8	0	69.8	0.0023
lver (3).....	.....	33	.....	.....	0.000154
.....	Pure.....	5.38	18	100	0.00402

Rails, Track and Third. † To be used in equation (8) with $b = 0.00000112$.

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RESISTIVITIES AT HIGH TEMPERATURES. (*C. Hering, Met. & Ch. Eng.* 13, *pp.* 23 *and* 70, 1915)

At { 500° C. 932° F.	Ohms per cm.-cube	At { 1000° C. 1832° F.	Ohms per cm.-cube	At { 1500° C. 2732° F.	Ohms per cm.-cube
Graphite (b)	0.00080	Graphite (b)	0.00065	Graphite (b)	0.00058
Graphite (a)	0.0008.4	Graphite (a)	0.00086	Graphite (a)	0.00089
Carbon (a)	0.0027	Carbon (d)	0.0021	Carbon (d)	0.0016
Carbon (d)	0.0028	Carbon (a)	*0.0024*	Carbon (a)	*0.0022*
Carbon (c)	0.0033	Carbon (c)	0.0030	Carbon (b)	*0.0029*
Carbon (b)	0.0037	Carbon (b)	0.0034	Nernst filament, about	0.5
Carbon powder	0.22	Carbon powder	0.12	Refrax	*0.5*
Silicon	0.094 to 0.23	Silfrax B	0.84	Silfrax B	*0.7*
		Sodium chloride, fused	*0.90*	Carbon grains (b)	*0.85*
Lead chloride, fused, 520°	0.418	Glass, roughly, about	*1*	Graphite grains	*1.2*
Silver chloride, fused	0.547	Graphite grains	1.7	Kryptol	3.4
Lead chloride, solid	0.824	Carbon grains (b)	1.9	Alundum, about	750
Silfrax B	0.92	Carbon grains (a)	*2.8*		
Copper chloride, fused	2.50	Silicon powder	3.5		
Graphite grains	3.70	Refrax	3.7		

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RESISTIVITIES AT HIGH TEMPERATURES. (*C. Hering, Met. & Ch. Eng.* 13, *pp.* 23 *and* 70, 1915)

At { 500° C. 932° F.	Microhms per cm.-cube	At { 1000° C. 1832° F.	Microhms per cm.-cube	At { 1500° C. 2732° F.	Microhms per cm.-cube
Silver, solid	5.0	Copper, solid	9.42	Silver, fused	*23*
Copper, solid	5.1	Gold, solid	12.54	Copper, fused	*24.8*
Gold, solid	6.62	Silver, fused	17.01	Aluminium, fused	*29*
Aluminium, solid	10	Aluminium, fused	24	Gold, fused	*37*
Brass, 2–1, solid	12.5	Molybdenum, solid	*28.5*	Molybdenum, solid	*40.5*
Molybdenum, solid	*16.5*	Tungsten (a), solid	*30.5*	Tungsten, solid	*43*
Tungsten (a, b), solid	18	Tungsten (b), solid	33.4	Tungsten (b), solid	50
Platinum (b), solid	25.3	Platinum (b), solid	40.8	Platinum (b), solid	52.6
Cadmium, fused	34.12	Brass, 2–1, fused	41	Tantalum, solid (b)	74
Platinum (a), solid	34.4	Tantalum, solid	57	Tantalum, solid (a)	78
Tantalum, solid	36	Platinum (a), solid	*66*	Tin, fused	*80.5*
Zinc, fused	36.60	Tin, fused	*68*	Platinum (a), solid	*98*
Iron (a), solid, about	52	Lead-tin alloy, fused	98	Iron (a), solid, about	*131*
Tin, fused	54.62	Ferro, nickel, solid	105	Calido, solid	*136*
Lead-tin alloy, fused	81	Iron (a), solid, about	*111*	Lead, fused	*148*
Ferro, nickel, solid	94	Calido, solid	*122*	Iron (b), fused	166
Lead, fused	102.85	Lead, fused	*125*		
Calido, solid	109	Nichrome II	128		
Krupp metal, solid	115	Antimony (b), fused	136		
Nichrome II, solid	119	Bismuth, fused	*167.5*		
Bismuth, fused	139.9				
Antimony, solid	152				

Sources of Data in Tables on pages 1352 and 1353. — (1) Landolt and Börnsteins' Physical-Chemical Tables, 1912 Edition. (2) Smithsonian Physical Tables, (3) Driver Harris Wire Co. (4) Herman Boker and Co. (5) Thomas Prosser and Son. (6) Dr. Frink, Trans. Am. Electro-chem Soc., 1910, Vol. 17. (7) *Copper Wire Tables*, Circ. No. 31, Bureau of Standards, 1914. (8) Electrical Alloy Co.

Resistivity and Temperature Coefficient of Some Common Solutions. — (*See also Electrochemistry, Principles of.*) The table on p. 1357 is based on data given by Kohlrausch and Holborn (*Leitvermögen der Elektrolyte, Leipsig*, 1898). The temperature coefficient given is that corresponding to an increase of temperature from 18° C. to 19° C., and is a negative quantity, i.e., for an increase of temperature the resistance decreases. The resistivity temperature coefficient of aqueous solutions diminishes rapidly with increase of temperature, i.e., the higher the temperature the less is the decrease in resistance for each degree increase in temperature.

Resistivity and Temperature Coefficient of Ordinary Water. — The resistivity of ordinary tap or river water ranges from 1200 to 12,000 ohms per centimeter cube, ordinarily being between the limits 2000 and 5000 ohms per centimeter cube. The change of the resistance of such water with temperature between the limits 0° C. and 100° C. may be represented to a fair degree of approximation by the formula

$$R_t = \frac{40\,R_{20}}{20 + t},$$

where R_{20} is the resistance at 20° C. and t is any other temperature between 0° C. and 100° C. (*From Tests by Applequest and McKenny, Mass. Inst. of Tech.*, 1912.)

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ISTIVITY OF SOLUTIONS AND THEIR TEMPERATURE COEFFICIENT OF RESISTANCE

1 ohm per centimeter cube $= \frac{1}{2.540}$ ohm per inch cube.

ent solution is meant the weight of the dissolved salt or acid expressed as a of the weight of the solution.

lution less than 5% the resistivity is approximately inversely as the per cent l salt or acid, i.e., a 2 per cent solution of common salt has a resistivity of ely $14.9 \times 5/2 = 37$ ohms per centimeter cube. As noted above the resis- rdinary tap water ranges from 1200 to 12,000 ohms per centimeter cube; a ade from such water can not of course have a resistivity greater than that of

Per cent solution	Ohms per centimeter cube at 18° C.	18° C. temperature coefficient	Substance	Per cent solution	Ohms per centimeter cube at 18° C.	18° C. temperature coefficient
5	3.90	−0.015	$ZnSO_4$	5	52.3	−0.022
10	2.18	−0.014		10	31.2	−0.022
20	1.41	−0.014		20	21.4	−0.024
30	1.28	−0.014		30	22.5	−0.027
40	1.37	−0.015	$CuSO_4$	5	53.0	−0.021
50	1.59	−0.016		10	31.3	−0.022
60	1.96	−0.016		15	23.7	−0.023
5	2.53	−0.016	Na_2SO_4	5	24.4	−0.024
10	1.59	−0.016		10	14.6	−0.025
20	1.31	−0.015		15	11.3	−0.026
30	1.51	−0.015	Na_2CO_3	5	22.2	−0.025
40	1.94	−0.015		10	14.2	−0.027
5	4.80	−0.012		15	12.0	−0.029
10	2.55	−0.013	NaCl	5	14.9	−0.022
20	1.53	−0.014		10	8.25	−0.021
30	1.35	−0.016		15	6.09	−0.021
40	1.47	−0.018		20	5.10	−0.022
50	1.85	−0.019		25	4.68	−0.023
60	2.68	−0.021	NH_4Cl	5	10.9	−0.020
70	4.64	−0.026		10	5.63	−0.019
5	5.84	−0.019		15	3.86	−0.017
10	3.19	−0.019		20	2.97	−0.016
20	2.01	−0.020		25	2.48	−0.015
30	1.85	−0.022				
40	2.23	−0.027				

OGRAPHY. — See references in text.

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RESISTORS, STANDARD, AND RESISTANCE BOXES. — (*See also Bridges for Electrical Measurements; Resistance and Conductance; Wires, Resistance; Rheostats.*) The primary standard of resistance is a mercury column of certain specified dimensions (*see below*). Secondary or commercial standards are made in two forms, viz.: (1) resistance standards each consisting of a single coil, carefully calibrated, mounted in a metal case, and (2) the ordinary resistance box, which contains a group of coils of known resistance.

The ultimate or primary standard of resistance, when measured in the international units, is the resistance of a column of mercury at 0° C. having a length of 106.300 centimeters and having a mass of 14.4521 grams (*see Units, Practical Electrical*).

STANDARD MERCURY RESISTANCE. — For the practical realization of such a standard, the International Conference on Electrical Units held in London in 1908 adopted the following specifications:

The glass tubes used for mercury standards of resistance must be made of a glass such that the dimensions may remain as constant as possible. The tubes must be well annealed and straight. The bore must be as nearly as possible uniform and circular, and the area of cross-section of the bore must be approximately one square millimeter. The mercury must have a resistance of approximately one ohm.

Each of the tubes must be accurately calibrated. The correction to be applied, to allow for the area of the cross-section of the bore not being exactly the same at all parts of the tube, must not exceed 5 parts in 10,000.

The mercury filling the tube must be considered as bounded by plane surfaces placed in contact with the ends of the tube.

The length of the axis of the tube, the mass of mercury the tube contains and the electrical resistance of the mercury are to be determined at a temperature as near to 0° C. as possible. The measurements are to be corrected to 0° C.

For the purpose of the electrical measurements, end vessels carrying connections for the current and potential terminals are to be fitted on to the tube. These end vessels are to be spherical in shape (of a diameter of approximately four centimeters) and should have cylindrical pieces attached to make connections with the tubes. The outside edge of each end of the tube is to be coincident with the inner surface of the corresponding spherical end vessel. The leads which make contact with the mercury are to be of thin platinum wire fused into glass. The point of entry of the current lead and the end of the tube are to be at opposite ends of a diameter of the bulb; the potential lead is to be midway between these two points. All the leads must be so thin that no error in the resistance is introduced through conduction of heat to the mercury. The filling of the tube with mercury for the purpose of the resistance measurements must be carried out under the same conditions as the filling for the determination of the mass.

The resistance which has to be added to the resistance of the tube to allow for the effect of the end vessels is to be calculated by the formula

$$A = \frac{0.80}{1063\pi}\left(\frac{1}{r_1}+\frac{1}{r_2}\right)\text{ohm},$$

where r_1 and r_2 are the radii in millimeters of the end sections of the bore of the tube.

The mean of the calculated resistances of at least five tubes shall be taken to determine the value of the unit of resistance.

For the purpose of the comparison of resistances with a mercury tube, the measurements shall be made with at least three separate fillings of the tube.

STANDARD SINGLE-COIL RESISTANCES. — The mercury standard resistance is cumbersome to work with and must be kept at constant zero temperature. Secondary standards, made of wire having a low temperature coefficient, are therefore universally employed in ordinary testing laboratories. The unit is provided with suitable heavy copper terminals so arranged that it may be hung from mercury cups and dipped into an oil bath. The object of the oil bath is to keep the temperature constant. Very low-resistance units, designed to carry large currents, are kept cool by means of water circulating in a coil of pipe within the case itself. Low-resistance units are also provided with "potential terminals," see Fig. 1, the stated resistance being the resistance between these terminals.

Reichsanstalt and N.B.S. Types. — There are at present two recognized types of resistance standards, the Reichsanstalt type and the National Bureau of Standards (or N. B. S.) type. Fig. 1 shows a 0.1-ohm standard of the first type, and Fig. 2 a 1-ohm standard of the N. B. S. type.

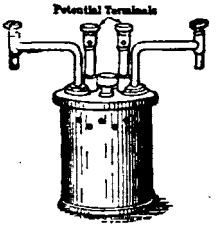


Fig. 1. Reichsanstalt Type Resistance Standard

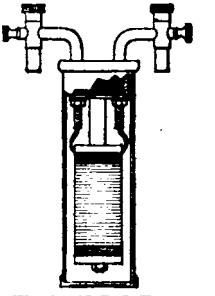


Fig. 2. N. B. S. Type Resistance Standard

The Reichsanstalt type and the N. B. S. type standards are insulated and baked in much the same manner as the coils in ordinary resistance boxes, though of course more carefully calibrated. The chief difference between the two types of standards is that the N. B. S. type is hermetically sealed in an oil-filled brass case, the oil having previously been freed from air by boiling. It is claimed that the N. B. S. units hold their calibration better than the Reichsanstalt units, the latter being subject to slight variations of resistance in climates where wide changes of humidity occur. (*See Bulletin Bureau of Standards, Vol. 5, p. 413.*)

Precision and Current-carrying Capacity of Standard Resistances. — The makers of standard units usually guarantee their accuracy as given below. The current-carrying capacity of the units is also given.

REICHSANSTALT TYPE, STANDARD RESISTANCE

Size of unit	Max. amp.	Error not greater than	Size of unit	Max. amp.	Error not greater than
0.0001	100	1/25 %	10	.3	1/100 %
0.001	30	1/25	100	.1	1/100
0.01	10	1/50	1,000	.03	1/100
0.1	3	1/50	10,000	.01	1/100
1	1	1/100	.....	.....	.....

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The National Bureau of Standards will calibrate any of these units and guarantee their accuracy of calibration to the above degree of precision, the charge being $4 to $6 per unit according to the value of the resistance.

RESISTANCE BOXES. — A brief description of the construction and arrangement of the coils in ordinary resistance boxes is given below.

Construction of Coils. — The coils are always wound non-inductively, that is, there are as many turns carrying the current in the right-handed direction as in the left-handed direction; this construction is illustrated in Fig. 3. Manganin wire (*see Wires, Resistor*) is usually employed. This wire is double-silk or enamel insulated, and is wound on wood or metal spools. Metal spools do not change in shape as wooden spools are liable to do, and since they more readily conduct the heat away, they may be safely used with larger currents.

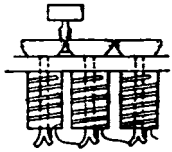


Fig. 3. Resistance Coil Construction

The wound spools are then dipped in shellac and baked from 10 to 15 hours at a temperature of 140° C. This baking removes the tension from the wire due to the winding and the resistance is rendered constant, whereas coils not treated in this manner will change their resistance to some extent long after being wound. The resistance coils are adjusted to the desired values by varying the length of the wire, and copper terminals are silver soldered to the ends of the resistance wire. The coils are then ready for soldering in place in resistance boxes.

Arrangement of Coils. — The principal arrangements employed at the present time in the construction of resistance boxes are the 1, 2, 3, 4 plan, the 1, 2, 2, 5 plan and the four-coil and five-coil decade plans. Nine- and ten-coil decades are also extensively used, particularly when a telephone receiver is used as a detector. With four- or five-coil decades there is a disagreeable sound in passing from step to step.

The 1, 2, 3, 4, and the 1, 2, 2, 5 Plans. — Resistance boxes built on the 1, 2, 3, 4 plan have coils of the following resistances: 1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, 400, 1000, 2000, 3000, 4000 ohms. These coils are all in series and each block on the top of the box is connected to a junction between successive coils. Inserting a plug therefore short-circuits a coil, see Fig. 3. In the 1, 2, 2, 5 plan the construction is similar, but the coils of any group have resistances in the ratio 1 : 2 : 2 : 5. Any resistance from 1 to 10,000 ohms can be obtained by either of these plans. On account of the large number of plugs to be manipulated, the large number of plug contacts and the necessity of making a mental summation of the values unplugged, these arrangements are being superseded in modern resistance boxes by the decade plan described below.

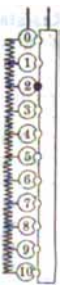


Fig. 4. 10-coil Decade

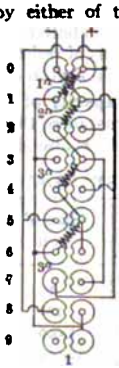


Fig. 5. 4-coil Decade

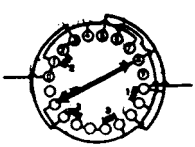


Fig. 6. 4-coil Dial Decade

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Decade Plan. — The name decade arises from the use of 10 plug holes or 10 sectors in a dial arrangement, for each group of coils, each hole or sector corresponding to a given number of units, tens, hundreds, etc.

There may be either 10, 9, 5 or 4 coils per set. The 10-coil arrangement is shown in Fig. 4, a 4-coil plug decade arrangement in Fig. 5, and a 4-coil dial decade arrangement in Fig. 6, and a 5-coil decade arrangement in Fig. 7. The 9-coil decade differs from the 10-coil decade only in the omission of the tenth coil.

The only gain in having the tenth coil is to make it possible to check the total resistance of the 10 coils of one decade against any one coil of the next higher decade. The 4-coil and 5-coil arrangement possesses all the advantages of the 9-coil decade, and has the added feature of fewer coils to get out of adjustment.

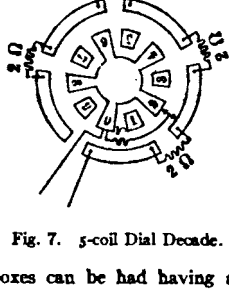


Fig. 7. 5-coil Dial Decade.

Precision of Resistance Boxes. — The precision to which the various coils in a resistance box are adjusted depends on the design and use to which the box is to be put. In the cheaper boxes the actual resistance of any coil may differ from the stated resistance by as much as ½ per cent, whereas higher grades of boxes can be had having an accuracy of $\frac{1}{10}$ per cent.

Precautions to be Taken. Care of Resistance Boxes. — The directions under these same headings given in the article on *Bridges for Electrical Measurements* also apply to the use and care of resistance boxes.

COSTS (Pre-war prices). — An ordinary 10,000-ohm resistance box (with coils for obtaining all resistances from 1 to 10,000 ohms) with the coils accurate to ½ per cent costs about $30. A high-grade 10,000-ohm resistance box with coils accurate to $\frac{1}{10}$ per cent costs about $90. The costs of Reichsanstalt standard resistances are approximately as follows:

0.0001 ohm	$40	1 to 1000 ohms	$20
0.001 ohm	30	10,000 ohms	25
0.01 and 0.1 ohm	30		

BIBLIOGRAPHY. — See *Bridges for Electrical Measurements.*

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RHEOSTATS AND RESISTORS. — (*See also Controllers; Control Systems for Railway Motors; Motors; Regulators; Resistors, Standard; Starters, Motor.*) A rheostat is a resistance device, usually adjustable, placed in a circuit for the purpose of regulating the current in that circuit. If used in connection with a machine, it may serve for regulating the speed, input, output, voltage or power factor. The name resistor is also used synonomously with rheostat, but is sometimes limited to mean a non-adjustable resistance device. This article treats primarily of the design of the resistance units, or resistors, used in the various controlling and starting devices employed commercially and in the laboratory; for their application, connections, etc., see the articles listed at the head of this article.

General Principles of Design. — Rheostats used for starting motors or for other intermittent work are usually designed on the assumption that no heat is radiated by them during the period (usually from 15 to 30 seconds) that they are carrying current. On this assumption the maximum allowable current I which a resistor can carry for t seconds without exceeding a temperature rise of T degrees is proportional to the square root of the ratio of T to t, the factor of proportionality depending upon the specific resistance and size of the current conductor, and the specific heats, weights and volumes of the materials heated, including the insulating material in which the resistors are embedded; see *Heat and Thermal Properties*. However, since there are so many variables entering into this factor K, the usual method employed in designing a rheostat is to determine experimentally the relations between current, temperature rise and time for a series of resistance units and to plot these relations in a set of curves. See also below under *Commercial Forms of Rheostats*.

The maximum temperature rise in the case of rheostats designed to carry a continuous load will occur when the heat radiated equals the heat generated. The proper resistance units for any service are determined from capacity curves for a variety of units subject to various conditions. Capacity curves are obtained by plotting as ordinates degrees of final rise of temperature against watts dissipated as abscissas. See also below under *Commercial Forms of Rheostats*. Natural draught is usually depended on for ventilation. For very large capacities forced ventilation is occasionally applied, if the space available is limited, but little is saved on the initial investment, and the maintenance expense is increased.

COMMERCIAL RHEOSTATS. — The term "commercial rheostat" is commonly meant to include besides the resistance elements the complete switching and control mechanism which serves to vary the resistance in the circuit for any particular kind of regulation.

Forms of Resistance Elements for Commercial Rheostats. — The more common forms of resistance elements are described below.

Standard "Unit" Type of Resistance Element. — Units of this type are made in either a flat or cylindrical form. One form of flat unit consists of a moulded flat core of vitreous material on which the resistance wire is wound; the surface is then coated with a special cement and baked. Thus the resistance material is protected from injury and made proof against moisture.

Standard cylindrical units usually have a core of asbestos tubing, or sometimes of metal tube coated with a suitable insulating material, such as enamel. A wire of low temperature coefficient is used; see *Wires, Resistance*. The tube with winding is covered with a suitable insulating compound, and porcelain bushings or metal rings (the latter for the clip type) are placed on the ends. The units are then thoroughly baked and mounted rigidly on a frame or in a suitable case. The coating protects the resistance material from mechanical injury,

l conductor of heat, and in case of a burn-out prevents appreciable unwinding of the wire. As a further protection, a sheet metal ometimes placed around the cement.

nd capacities of cylindrical units cover the following ranges approxi- er capacity, from 30 to 350 watts; current capacity, from 0.06 to resistance, from 0.1 to 10,000 ohms; length, from 4 to 22 inches; om 1 to 2.5 inches. The watt capacity for these resistance units approximately 1.5 to 3.5 watts per square inch of surface for con- ice, when assembled in frames affording good ventilation. This stat is rarely employed when currents of more than 50 amperes are l.

Type of Resistance Element. — In this type the resistance coils to a circular base of insulating material. The coils are either an insulating, heat-conducting cement and baked, or are enclosed ed iron case. Suitable contacts and a switch arm are provided. her than 60 amperes are rarely handled by this type of rheostat. sizes of plates range from 9 to 15 inches in diameter.

Type of Resistance Element. — This type of rheostat consists rids assembled on horizontal rods bolted to pressed steel end-plates. pe generally used for large currents. The rods are covered with a ng sleeve. If mounted on a frame affording good ventilation, the apacity of the standard grids is approximately 700 amperes per f cross-section for a maximum rise of 240° C.

and Control Mechanism for Rheostats. — (*See also Starters*, h those rheostats which contain distinct resistance elements, or rminals of the elements are brought out to metal contacts usually circle on an insulating, fireproof plate. The contact of the switch l currents up to 25 amperes per contact arm consists of an ordinary r contact brush;. for currents up to 350 amperes, solid sliding evenly-faced surfaces held by springs against the contact segments he switch-arms. For higher currents the laminated brush has been satisfactory because of the more uniform contact obtained. Most sed on the rule that for maximum current, 20° C. rise of temperature nding air should not be exceeded for contacts and face parts. operated rheostats cannot be mounted on the panel, chain and ve is usually employed. Gear control is also occasionally used. ats are frequently operated by solenoids or motors. Motor- ostats are usually employed for currents in excess of 350 amperes.

Forms of Commercial Rheostats. — For any particular class of nature of the regulation desired, and the kind of circuit to which the be connected will determine the arrangement, size and number of steps necessary as well as the proper type of switching mechanism See also *Motors, Industrial Application of.*

Rheostats. — The number of steps for a field rheostat depends ess with which adjustments of field current are to be made and on sired. For ordinary conditions a rheostat resistance equal to the the generator field is satisfactory. Machines which are regulated voltage regulators frequently require a rheostat resistance of from that of the generator field. Field rheostats for currents up to 60 usually in form of the plate type or unit type. For higher capacities e is employed. Field rheostats commonly have from 30 to 70 esistance. Double this number may be obtained in case of two or if the plates have the levers staggered. Field rheostats are either led or solenoid- or motor-operated.

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Field Discharge Resistors. — These resistances
field of motor or generator whenever the main-line swit
purpose of providing a gradual dissipation of the electrom
in the field, thus limiting the arc on opening and reducing t
force due to the inductance of the field circuit. They ar
for 15-second duty. In general, a resistance equivalent t
recommended. They are frequently included with the fiel

Starting Rheostats. — See *Starters, Motor.*

LABORATORY RHEOSTATS AND RESISTORS.
Standard.) On account of the extreme variety of the requi
in a laboratory, there are but few standard forms of rh
use on the market. Therefore, most laboratory rheostats

A good form of laboratory rheostat for moderately-larg
sisting of a thin metal tube, on which enameled resistance
sliders should carry two or more laminated brushes, bel
is scraped off. For fixed resistors the slider is omitt
capacity of this form of resistor of diameter from 1 inch to
4 to 6 watts per square inch of surface, if ventilation is go

Grooved porcelain tubes or rectangular slate slabs woun
wire will carry on an average from 2 to 4 watts per square

Resistance wire (*see Wires, Resistance*) wound on ope
frequently used for laboratory rheostats.

Data on Galvanized Iron Wire. — Iron wire, alt
lower resistance than the various forms of resistance wi
much cheaper and is therefore sometimes used. The fo
found useful in designing iron wire rheostats.

DATA ON GALVANIZED IRON W

B. & S. gage	Circular mils	Maximum* allowable current	Fee for
20	1,022	2.5	
19	1,288	2.9	
18	1,624	3.5	
17	2,048	4.2	
16	2,583	5.0	
15	3,257	6.0	
14	4,107	7.1	
13	5,178	8.5	
12	6,530	10.1	
11	8,234	12.0	
10	10,380	14.3	
9	13,090	17.1	
8	16,510	20.3	

* In air with free radiation.

Carbon Rheostats. — This type of rheostat consists
plates stacked in a suitable frame and provided with an
that the pressure between the plates may be varied. Al
different sizes are sometimes used in large rheostats to sec

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These rheostats are very useful when continuous variation of resist- relatively small ranges is desired; they are also very durable and cheap.

ata for the Design of Carbon Rheostats. — The following data rom an article by C. R. Moore in the *Elec. Rev. and West. Elec.*, 1912, . 672. Carbon plates, either circular or square, varying in thickness o ¼ inch are satisfactory, the sizes from ⅛ to 3/16 inch being preferable f the more uniform contact obtained between the plates. Since prac- l of the resistance is in the contacts between successive plates the aces must be ground very smooth. The current-carrying capacity for stats varies from 5 to 12 amperes per square inch with an average of s per square inch. For temperature rises ranging from 40 to 85° C. ing coefficient is from 0.002 to 0.005 watt per square inch of radiating r degree centigrade rise. For pressures ranging from 7.5 to 180 lb. per e variation in resistance per square inch per contact based on average shown in the following table:

RESISTANCE OF CARBON-PLATE RHEOSTATS

e,	Resistance, ohms per sq. in. per contact	Pressure, lb. per sq. inch	Resistance, ohms per sq. in. per contact	Pressure, lb. per sq. inch	Resistance, ohms per sq. in. per contact
	0.0230	35	0 0063	90	0.0029
	0.0185	40	0 0057	100	0.0027
	0.0145	45	0.0052	120	0.0024
	0.0125	50	0.0047	140	0.0021
	0.0100	60	0.0041	160	0.0018
	0.0082	70	0.0036	180	0.0015
	0.0071	80	0.0032		

ample for Design of Carbon Rheostats. — Given a circuit of sistance connected to constant potential mains of 110 volts, the current djusted between the limit of 17 and 21.5 amperes by means of a series Hence the corresponding voltage drops through the rheostat are .5 volts respectively, which calls for a resistance ranging from 1.47 0.116 ohm. For a current-carrying capacity of 7 amperes per square plates must have an area of 21.5 ÷ 7 = 3 sq. in. approximately; square 5 by 1.75 in. may therefore be used. A convenient thickness for plates e is ⅛ in. With 8 lb. per sq. in. as the minimum pressure, the resistance is 0.022 ÷ 3 = 0.0073 ohm (from table and area of plates as computed Hence the number of plates for 1.47 ohms resistance is 1.47 ÷ 0.0073 = s the length of the rheostat is approximately 200 × 0.125 = 25 in. mum resistance of 0.116 ohm requires 0.116 ÷ 200 = 0.00058 ohm , which is equivalent to 3 × 0.00058 = 0.00174 ohm per square inch ct. Hence, from the table the maximum pressure must be 165 lb. per hich is equivalent to a total pressure of 3 × 165 = 495 lb. acting on supporting the carbon blocks.

ing surface must be provided for a maximum of 25 × 17 = 425 watts. adiating constant of 0.004 watts per square inch per degree centigrade mperature, a maximum rise of temperature of 75° C. will require a of 0.004 × 75 = 0.30 watts per square inch. Hence a radiating sur- 5 ÷ 0.30 = 1420 sq. in. must be provided. Since the 200 plates rep- adiating surface (edges only) of only 200 × 4 × 0.125 × 1.75 = 175 sq.

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in., every other plate must be of a larger size. This may be secured by using 100 small plates 1¾ by 1¾ by ⅛ inch, having a total radiating surface (edges only) of 87.5 sq. in., and 100 plates 3 by 3 by ⅛ inch, having a total edge surface of $3 \times 0.125 \times 4 \times 100 = 150$ sq. in.; the total area of their projecting sides represents $(3 \times 3 - 3) \times 2 \times 100 = 1200$ sq. in. Thus the total radiating surface is $87.5 + 150 + 1200 = 1437.5$ sq. in.

SUBMERGED WIRE RHEOSTATS. — Steady loads for temporary work may be obtained from galvanized iron resistors placed in a river or tailrace or in a barrel continuously fed with supply water. The proper diameter and length of wire for any set of requirements may be calculated from the following formulas:

$$d = KI^{\frac{3}{4}}, \qquad l = \frac{d^2E}{112I},$$

in which d = diameter of wire in mils, I = the current in amperes, E = the impressed voltage, l = length of wire in feet, 112 = average value of ohms per mil-foot of galvanized iron wire. Values of K for barrels or tanks range from 3.25 to 2.75, for tailraces or rivers of moderate flow, 2.75 to 2.25, for conditions of rapid flow, 2.25 to 2.0. Wooden sticks with fairly-sharp edges will make reliable supports for the wire. For more careful work the wires may be held by porcelain cleats screwed to wooden frames. The heating of these wires in water is so great that there must be no obstructions to a free circulation of the cooling water, otherwise failure may occur due to the formation of gaseous envelopes surrounding the wire. The water used must be clean to prevent rapid destruction by electrolysis. When tanks or barrels are used, it is preferable to raise the container above the ground (on wooden blocks about two feet high) so as to avoid seriously grounding the circuit through the stream of cooling water.

DATA FOR SUBMERGED RHEOSTATS OF GALVANIZED IRON WIRE

From *Rheostats for Dynamo Load Tests*, Am. Elec., 1903, Vol. 15, p. 512.

Size of wire, B. & S. Gage	Safe carrying capacity, amperes	Minimum length in feet for safe carrying capacity at different voltages			Feet per ohm, *hot*
		110 volts	220 volts	500 volts	
4	584	66	131	298	348.0
5	489	62	124	282	276.0
6	412	59	117	266	219.0
7	347	55	110	250	173.5
8	293	52	103	235	137.5
9	245	47	94	214	109.1
10	205	45	90	205	86.5
11	173	42	84	191	68.6
12	145	40	80	182	54.3
13	122	38	76	173	43.2
14	103	36	72	164	34.2
15	88	34	68	155	27.2
16	71	32	64	145	21.5
17	60	30	60	136	17.1
18	50	29	58	132	13.5
19	42	27	54	123	10.4
20	36	25	50	114	8.5

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WATER RHEOSTATS. — A water rheostat serves as a simple, cheap and satisfactory means of dissipating large amounts of energy. It is extensively used in the commercial testing of apparatus and for other purposes where an adjustable, high-power-capacity resistance is required. Permanent installations are sometimes made in hydroelectric stations to improve hydraulic or electric regulation and to furnish an artificial load.

Resistivity of Water and Common Solutions. — The resistivity of ordinary water at 20° C. (= 68° F.), taken from streams, wells or reservoirs, usually ranges from about 800 to 2000 ohms per inch cube (2000 to 5000 ohms per centimeter cube) though extremes may be found as low as 500 and as high as 5000 ohms per inch cube (1200 and 12,000 ohms per centimeter cube respectively). In water rheostats designed for less than 1000 volts it is usually desirable to increase the conductivity of the water by adding a salt (common salt, copper sulphate or other cheap salt) or an acid (usually sulphuric). For example, the resistivity of a 5 per cent solution of common salt at 18° C. is 14.9 ohms per inch cube (38 ohms per centimeter cube). The resistivity of various solutions of different strengths is given in the article on *Resistance and Conductance*.

As noted in the article just referred to, the resistance of ordinary water and of salt and acid solutions diminishes rapidly with increase of temperature. To a close approximation the resistance of ordinary clean water between 0° C. and 100° C. may be calculated from the formulas

$$R_t = \frac{40\,R_{20}}{20+t}, \qquad \text{or} \qquad R_{t'} = \frac{72\,R_{68}}{4+t'}.$$

where R_{20} is the resistance at 20° C. = R_{68}, the resistance at 68° F., and t is any other temperature centigrade and t' any other temperature Fahrenheit.

Before designing a large high-voltage rheostat it is desirable to determine both the resistivity and temperature coefficient of a sample of the water which will be used. The sample should be tested in a miniature, low-voltage rheostat. If the large rheostat is to be operated on alternating current, the test with the miniature rheostat should also be made with alternating current, in order to avoid the effects of polarization. Determinations for a direct-current rheostat should be made with direct current, using a miniature rheostat of the same materials as are to be used in the large rheostat, and operated at the same current density and voltage. In designing a rheostat for permanent use data should also be obtained on the variations in the resistivity of the water throughout the year, for these variations are very marked in some cases.

Low-voltage Water Rheostats. — A simple form of water rheostat for direct-current or single-phase low-voltage work can be made of an oil barrel and two iron plates. One plate is placed on the bottom of the barrel. An insulated copper wire is connected to this plate and brought up along the side of the barrel and out through the top, or it may be attached to the underside of the barrel by means of a bolt passing through the plate and the bottom of the barrel. The other terminal is attached to a movable plate which is held by a window cord strung over two pulleys, the plate being held in position by a suitable counterweight at the free end of the cord. The barrel is filled with water, to which a relatively strong solution of common salt (NaCl), sal ammoniac (NH_4Cl) or washing soda (Na_2CO_3) is added in sufficient amount to give the required conductivity. It is essential that the substance should be dissolved before it is added to the water barrel and that the solution should be poured in very carefully, because a very small amount of a salt solution will add considerably to the conductivity of the water. A single-phase load of 100 amperes at 100 volts may be carried continuously in a 40-gallon barrel without causing the water to boil. The plates should have a surface (one side only) of at least 1 square inch per ampere.

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For low-voltage three-phase work a barrel with three pipes, suitably mounted and arranged to be raised or lowered by means of a cord and pulleys, is sometimes used. The pipes should have an immersed surface (outside surface only) of at least 1 square inch per ampere.

A serious objection to the use of a water rheostat containing a salt or acid is that the resistance for a given setting of the electrodes does not remain constant, due to the evaporation of the water, rendering the solution more concentrated. The increase in the temperature of the solution also causes very appreciable changes in resistance. When direct current is used the change in the concentration of the solution at the two electrodes (polarization) also causes a variation in the resistance with time.

High-voltage Water Rheostats. — For voltages above 1000 the conductivity of the tap or river water available is usually ample, without having recourse to the use of salts or acids. The use of ordinary water also makes it possible to keep a continuous flow of water through the rheostat and thus maintain a practically constant temperature. The discussion of such high-voltage rheostats given below is adapted from an excellent paper on this subject by E. A. Ekern in the *Stone and Webster Public Service Journal* for Nov., 1911.

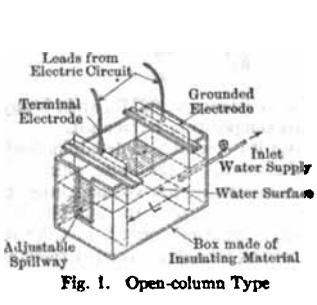


Fig. 1. Open-column Type

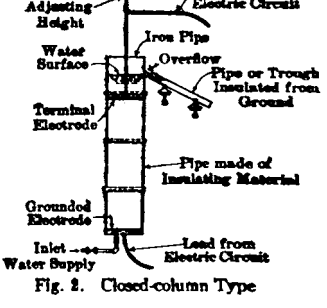


Fig. 2. Closed-column Type

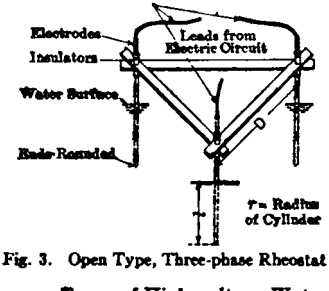


Fig. 3. Open Type, Three-phase Rheostat

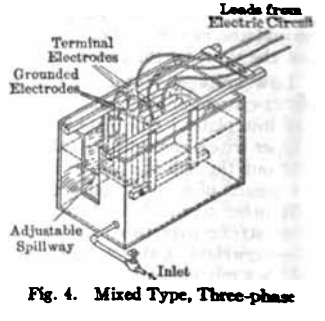


Fig. 4. Mixed Type, Three-phase

Types of High-voltage Water Rheostats. — Fig. 1 illustrates a simple form of such a rheostat, and will be referred to as the "open-column" type, and Fig. 2 illustrates another simple form which will be referred to as the "closed-column" type. The illustrations are for single-phase rheostats; three-phase rheostats are made by combining three single-phase elements with the neutral point grounded. Fig. 3 illustrates a three-phase type suitable for immersion

in an open body of water; this type will be referred to as the "open type." The type shown in Fig. 4, which is a combination of the column type and open type, will be referred to as the "mixed type;" the illustration shows a three-phase rheostat with three plates for terminal electrodes sandwiched between four neutral electrodes. The plates should preferably have rounded edges.

Calculation of Resistance. — The resistance of the column type of rheostat (Figs. 1 and 2) is computed by the formula

$$R = \rho \frac{L}{A}, \tag{1}$$

where ρ = the resistivity of the water in ohms per inch cube (as noted above ρ is usually between 800 and 2000 ohms per inch cube), L = the length of the column in inches, and A = the area of the cross section of the column in sq. in.

For the open type (Fig. 3) the resistance between any cylindrical electrode and the neutral is given by the formula

$$R = \frac{\rho}{2.73\, l} \log_{10} \left(\frac{2\,D}{d} \right), \tag{2}$$

where ρ = the resistivity of the water in ohms per inch cube, l = the wetted length of cylinder in inches, D = distance between cylinders in inches (center to center), and d = external diameter of each cylinder in inches. The equation is sufficiently accurate for all practical purposes when $2\,D + d$ is greater than 80 and may be used with but small error when this ratio is as low as 40. (*See also the article on Resistance and Conductance.*)

The resistance to neutral of the mixed type (Fig. 4) is computed by the formula

$$R = \frac{R_1 R_2}{R_1 + R_2}, \tag{3}$$

where

$$R_1 = \rho \frac{S}{2\,A} \quad \text{and} \quad R_2 = \frac{\rho}{2.37\,\lambda} \log_{10} \left(\frac{4\,S}{t} \right), \tag{4}$$

R_1 is the resistance between the face of any one terminal plate and the two neutral plates between which it is placed and R_2 is the resistance between the wetted edge (assumed rounded) of the terminal plate and the two plates between which it is placed. The letters in the expressions for R_1 and R_2 have the following meanings: ρ = resistivity of the water in ohms per inch cube, S = the distance between adjacent plates (terminal plate to neutral plate) in inches. A = area in square inches (one side only) of terminal plate, t = thickness of each terminal plate in inches, λ = total length in inches of wetted edge (perimeter) of one terminal plate. The expression for R_2 is a rough approximation, but as R_2 is small compared with R_1, the error in the resultant resistance R due to an error in R_2 is relatively small.

Allowable Current Density. — A current density at the electrodes in excess of 4 amperes per square inch is accompanied by a "spitting" or arcing and there is danger of short circuit. This limiting current density applies to clean water, but as there is always a likelihood of foreign materials getting into the water, it is not advisable to use a current density between flat plates in excess of 1 ampere per square inch, but at the edges of the plates or where there is a free and large circulation of water a current density as high as 3 amperes per square inch may be safely used.

Minimum Distance between Electrodes. — Calling σ the maximum allowable current density and v the voltage to neutral, then in terms of the notation defined above, the minimum spacing of the electrode is:

For column type (Figs. 1 and 2) $$L = \frac{v}{\rho \sigma}. \tag{5}$$

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For open type (Fig. 3) $$D = \frac{d}{2} \log^{-1}\left(\frac{0.869\, v}{\rho d \sigma}\right). \quad (6)$$

In the mixed type the limiting current density is usually at the edge of the plates, and the minimum spacing in this case is given by the relation:

For mixed type (Fig. 4) $$S = \frac{t}{4} \log^{-1}\left(\frac{0.869\, v}{\rho t \sigma}\right). \quad (7)$$

The logarithms are all common logarithms (i.e., to the base 10).

Minimum Size of Electrodes. — Using the same symbols as above, and in addition calling I the current per phase (terminal to neutral), the minimum area of each plate in the column type (Figs. 1 and 2) is $A = I \div \sigma$ square inches, and in the open type (Fig. 3) the minimum diameter of the electrodes is $d = I \div (\pi l \sigma)$ inches. In the mixed type the total area of the terminal plate (both sides and the edges) is approximately $(\rho S) \div R$, where R is the total required resistance. The area of the flat surface of the plate (one side only) may be taken from 10 to 15 per cent less than half of this total surface, to allow for the edges. The actual division of current between the edges and the flat surfaces will be inversely as the resistances R_1 and R_2 given by equations (4).

Example of Calculation of Dimensions. — The more complicated case of a mixed type of rheostat is chosen, to illustrate the use of both types of formulas. Power to be dissipated 3000 kw. at 2300 volts, three-phase. Then voltage to neutral is $V = 1328$ volts, current per phase $I = 753$ amperes, corresponding to a resistance of 1.762 ohms. Assume the plates to be ¼ inch thick, then $t = 0.25$. Allowing a maximum current density of 3 amperes per sq. in. at the edges, and taking $\rho = 800$, the minimum spacing is then, from equation (7), $S = 5.27$ inches.

The total surface (both sides and edges) of each terminal plate, assuming $\rho = 1200$, to allow for an increase in the assumed resistivity of the water, will be $(1200 \times 5.27) \div 1.762 = 3580$ sq. in., and the area of the plate should then be say 15 per cent less than $3580 \div 2$, or 1500 sq. in. approximately. A plate 60 by 25 inches will be a suitable size. The two resistances R_1 and R_2 are then from equation (4), $R_1 = 2.1$ ohms and $R_2 = 11.6$ ohms, and from equation (3) $R = 1.775$, which practically agrees with the required value of 1.762 ohms.

Supply of Water. — Due to the change in the resistivity of water with increase in temperature it is preferable to supply the rheostat with sufficient water to prevent much of an increase of temperature. At a hydroelectric station it is usually possible to use an open-type rheostat (Fig. 3) placed in a running stream or in a large body of water. When the water supply is limited it is sometimes necessary to allow the water to heat or even boil in extreme cases. Even in the case of limited water supply, however, a small steady overflow should be allowed, in order to prevent an accumulation in the rheostat of the salts contained in the water.

For an increase of $T°$ F. in temperature the water required to carry off P kilowatts, assuming no radiation or evaporation, is

$$\frac{0.91\, P}{T} \text{ cu. ft. per min.} = \frac{6.8\, P}{T} \text{ gallons per min.} \quad (8)$$

If only G gallons of water per minute are available and the water is allowed to boil, then calling T the difference between the boiling point and the temperature of the supply water in degrees Fahrenheit, the water evaporated when P kilowatts are supplied to the rheostat would be

$$G_e = \frac{P}{143} - \frac{GT}{970} \text{ gallons per min.} \quad (9)$$

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Example. — To dissipate 3000 kw. with a 10° F. rise in the temperature of the water would require $(6.8 \times 3000) \div 10 = 2040$ gallons per min. If only 60 gallons per minute are available at 62° F., $G_e = 3000 \div 143 - 60 \times (212 - 62) \div 970 = 11.7$ gallons per min. will be evaporated, leaving 48.3 gallons per minute for the overflow.

Notes on Design of Water Rheostats. — The column type of rheostat may be used for any capacity and voltage. For voltages up to 23,000, the mixed type is usually preferable for large loads. For higher voltages, the open type may then be employed to advantage. Common iron pipe or steel plates are satisfactory materials for electrodes. Rheostats designed for permanent use should have galvanized electrodes. For voltages of 2300 volts and less, well-oiled and shellacked wooden containing vessels for the water have been found satisfactory. Open-or mixed-types of rheostats may be put in any tank or body of water where the clearance to sides or bottom is greater than one-half the spacing of electrodes. Column type rheostats up to 44,000 volts having columns built of vitrified glazed tile cemented together with Portland cement shellacked over have been operated successfully. Open-type rheostats made of iron pipes insulated and held securely above the water surface are very satisfactory. Mixed-type rheostats having plates separated by common porcelain line insulators and all clamped into a wooden frame have been used very successfully. Plates or electrodes should always be so arranged and located as to obtain free circulation of water. Where insulating material may be partially or intermittently in and out of the water, material may be deposited from the water and sufficient leakage surface must be provided. Innumerable arrangements and contrivances for the operation of rheostats may be designed but the important considerations are sufficient insulation to protect the operator, and positive movements to obtain the required degree of adjustment. Water rheostats are practically non-inductive. A slightly-leading current is obtained due to electrostatic capacity, but it is often more than offset by the inductive reactance of the conductors.

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ROOTS AND POWERS. — The symbol a^n where n is a positive whole number means a multiplied by itself n times; n is called the exponent of a. The conception of an exponent is also extended to include negative and fractional exponents as follows: Let m be a positive whole number and let $n = -m$; then the expression $a^n = a^{-m}$ is defined as equivalent to $\frac{1}{a^m}$; that is, a^{-m} is taken as equivalent to the reciprocal of a^m. Again, let m be a whole number and let $n = \frac{1}{m}$; then the expression a^n is defined as equivalent to $a^{\frac{1}{m}} = \sqrt[m]{a}$; that is, $a^{\frac{1}{m}}$ is taken to represent the m root of a. In general, then, the properties of exponents are the following, where m and n may be positive or negative whole numbers or fractions:

$$a^{-m} = \frac{1}{a^m}. \qquad (a^m)^n = a^{mn}$$

$$a^{\frac{1}{m}} = \sqrt[m]{a} \qquad \sqrt[n]{a^m} = a^{\frac{m}{n}}$$

$$a^m a^n = a^{m+n} \qquad a^0 = 1$$

$$\frac{a^m}{a^n} = a^{m-n}$$

The calculation of roots and powers can be conveniently carried out by means of logarithms (q. v.); for the highest accuracy, a seven or nine place table should be used. Note that

$$\log a^n = n \log a$$

$$\log \sqrt[n]{a} = \frac{1}{n} \log a$$

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ROPES AND ROPE DRIVE. — (*See also Wires and Cables, Bare.*) The following terms relating to ropes and cordage are commonly employed:

Yarn. — Natural fibers twisted together.
Thread. — Two or more *small yarns* twisted together.
String. — Same as thread except of little larger yarns.
Strand. — Two or more *large yarns* twisted together.
Cord. — Several *threads* twisted together.
Rope. — Several *strands* twisted together.
Hawser. — A rope of three *strands*.
Shroud-laid rope. — A rope of four strands.
Cable. — Three *hawsers* twisted together.

In a strand the yarns are laid up left-handed; in a rope the strands are laid up right-handed; in a cable the hawsers are laid up left-handed.

WEIGHT AND STRENGTH OF ROPES. — The following tables give the weight per foot and breaking strength of hemp and steel ropes. Cotton ropes have approximately the same weight per foot as hemp ropes, but their breaking strength is only 60 per cent of that of hemp ropes. Iron ropes have the same weight per foot as steel ropes, but only 50 per cent of the breaking strength of cast-steel ropes.

APPROXIMATE BREAKING STRENGTH OF STEEL-WIRE ROPES

(*Trenton Iron Company*)

6 strands of 19 wires each					6 strands of 7 wires each				
Diam. rope, inches	Lb. per ft.	Approximate breaking stress, lb.			Diam. rope, inches	Lb. per ft.	Approximate breaking stress, lb.		
		Cast steel	Extra strong steel	Plow steel			Cast steel	Extra strong steel	Plow steel
2¼	8.00	312,000	364,000	416,000	¼	0.10	4,800	5,400	.....
2	6.30	248,000	288,000	330,000	1½	3.55	136,000	158,000	182,000
1¾	4.85	192,000	224,000	256,000	1⅜	3.00	116,000	136,000	156,000
1⅝	4.15	168,000	194,000	222,000	1¼	2.45	96,000	112,000	128,000
1½	3.55	144,000	168,000	192,000	1⅛	2.00	80,000	92,000	106,000
1⅜	3.00	124,000	144,000	164,000	1	1.58	64,000	74,000	84,000
1¼	2.45	100,000	116,000	134,000	⅞	1.20	48,000	56,000	64,000
1⅛	2.00	84,000	98,000	112,000	¾	0.89	37,200	42,000	48,000
1	1.58	68,000	78,000	88,000	11/16	0.75	31,600	36,800	42,000
⅞	1.20	52,000	60,000	68,000	⅝	0.62	26,400	30,800	34,000
¾	0.89	38,800	44,000	50,000	9/16	0.50	21,200	24,600	28,000
⅝	0.62	27,200	31,600	36,000	½	0.39	16,800	19,400	22,000
9/16	0.50	22,000	25,400	29,000	7/16	0.30	13,200	15,000	17,100
½	0.39	17,600	20,200	22,800	⅜	0.22	9,600	11,160	12,700
7/16	0.30	13,600	15,600	17,700	5/16	0.15	6,800	7,760	.....
⅜	0.22	10,000	11,500	13,100	9/32	0.125	5,600	6,440	.....
5/16	0.15	6,800	8,100	.....	....	.....	.....	.....	.....

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MANILA ROPE

(From Blue Book of Amer. Mfg. Co., N. Y.)

Diameter of rope, inches	Approx. pounds per foot	Breaking strength, pounds	Diameter of rope, inches	Approx. pounds per foot	Breaking strength, pounds
⅛	0.085	1,750	1⅝	0.65	13,200
⅝	0.13	2,730	1¾	0.77	15,700
¾	0.20	3,950	1⅞	0.90	18,500
⅞	0.26	5,400	1¾	1.04	21,400
1	0.34	7,000	2	1.36	28,000
1⅛	0.43	8,900	2¼	1.73	35,400
1¼	0.53	10,900	2½	2.13	43,700

Factor of Safety. — For ordinary purposes the maximum safe stress in wire ropes should be about one-third the ultimate, and for shafts and elevators about one-fourth the ultimate. In estimating the stress due to the load for shafts and elevators, allowance should be made for the additional stress due to acceleration in starting. For short inclined planes not used for passengers a factor of safety as low as 2½ is sometimes used, and for derricks in which large sheaves cannot be used and long life of the rope is not expected, the factor of safety may be as low as 2.

For power transmission by hemp ropes a factor of safety of 36 (referred to the nominal strength of the rope) is usually employed (*C. W. Hunt, Trans. A.S.M.E., Vol. 12, p. 230*).

Splicing and Knots. — See *Kent's Mechanical Engineers' Pocket-Book.*

ROPE DRIVING. — There are two methods of putting ropes on the pulleys, the multiple-rope and the single-rope systems. In the multiple-rope system several endless ropes are employed, and therefore there are as many splices as there are single ropes. In the single-rope system one endless rope is used, making several turns around the pulleys or sheaves, and therefore with but a single splice. In the first case the individual ropes are spliced in place, being made very taut at first, and less so as the rope lengthens, stretching until it slips, when it is respliced. In the second method tension pulley must be used to give the necessary adhesion and also to take up the wear.

Power Transmitted by a Rope. — The formulas given in the article on *Belts and Belting* are directly applicable to rope transmission, but may be put in a more convenient form as follows. Let

V = velocity of rope, in feet per minute,
d = diameter of rope, in inches,
m = weight, in pounds, of 1 foot of rope 1 inch in diameter,
T_1 = actual tension in driving side of rope, in pounds per circular inch (i.e., the tension in pounds in a rope 1 inch in diameter),
f = coefficient of friction between rope and pulley,
n = number of half-turns the rope makes around pulley,
$C = 1 - \epsilon^{-nf/\pi}$, where the value of $\epsilon^{-nf/\pi}$ is taken from the table of ϵ^{-x} in the article on *Exponential Functions*, putting $x = nf/\pi$.

Then horse-power transmitted by each taut rope from one pulley to the other is

$$P = \frac{CT_1 d^2 V}{33{,}000}\left(1 - \frac{mV^2}{116{,}000\,T_1}\right) \qquad (1)$$

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Power Transmitted by Hemp Rope. — A formula developed by C. W. Hunt (*Trans. A.S.M.E., Vol. 12, p. 230*) is frequently employed. This formula may be written

$$P = \frac{d^2V}{248}\left[1 - \left(\frac{V}{8500}\right)^2\right], \qquad (2)$$

which is the same as formula (1) when $n = 1$, $f = 0.35$, $C = 0.67$, $m = 0.32$ and $T_1 = 200$. The following table is calculated from Hunt's formula. For temporary work a rope of given diameter may be used with safety to transmit twice the horse power given in the table.

HORSE POWER TRANSMITTED BY HEMP ROPE AT VARIOUS SPEEDS

Computed from formula (2) given above

Diam. of ropes, inches	Speed of the rope in feet per minute									
	1500	2000	2500	3000	3500	4000	4500	5000	6000	7000
½	1.45	1.9	2.3	2.7	3.0	3.2	3.4	3.4	3.1	2.2
⅝	2.3	3.2	3.6	4.2	4.6	5.0	5.3	5.3	4.9	3.4
¾	3.3	4.3	5.2	5.8	6.7	7.2	7.7	7.7	7.1	4.9
⅞	4.5	5.9	7.0	8.2	9.1	9.8	10.8	10.8	9.3	6.9
1	5.8	7.7	9.2	10.7	11.9	12.8	13.6	13.7	12.5	8.8
1¼	9.2	12.1	14.3	16.8	18.6	20.0	21.2	21.4	19.5	13.8
1½	13.1	17.4	20.7	23.1	26.8	28.8	30.6	30.8	28.2	19.8
1¾	18.0	23.7	28.2	32.8	36.4	39.2	41.5	41.8	37.4	27.6
2	23.2	30.8	36.8	42.8	47.6	51.2	54.4	54.8	50.0	35.2

Power Transmitted by Iron and Steel Ropes. — Wm. Hewitt of the Trenton Iron Company gives the following formula for the power transmitted by a steel rope, excluding the losses due to journal friction of the sheaves,

$$P = Bd^2v, \qquad (3)$$

where v is the velocity of the rope in *feet per second* and B has the following values.

B for steel rope on	Number of half turns around sheave = n					
	1	2	3	4	5	6
Iron	5.61	8.81	10.62	11.65	12.16	12.56
Wood	6.70	9.93	11.51	12.26	12.66	12.83
Rubber or leather	9.29	11.95	12.70	12.91	12.97	13.00

For iron rope take for B one-half the figures given in the above table.

Hewitt's formula (3) is equivalent to (1) when the centrifugal force of the rope is neglected and T_1 and f are as follows:

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Kind of rope	Working tension T_1 in lbs. per circ. inch		Coeff. of friction $=f$
	Iron	Steel	
Iron	3600	7200	0.16
Wood	3600	7200	0.23
Rubber or leather	3600	7200	0.40

It should be noted that the coefficient of friction decreases rapidly with moisture or grease on the rope and sheaves, and consequently to transmit a given amount of power the tension must then be increased.

In the following table is given the horse-power that may be transmitted by a steel rope making a single half turn ($n = 1$) on wood-filled sheaves. This table agrees approximately with formula (3). The transmission of more than 250 h.p. by a single steel rope making a single half turn on filled sheaves is impracticable, as the filling would be rapidly cut out due to the increased tension (i.e., total tension $= T_1 d^2$) and high velocities required. If the rope makes several half turns around the sheave, however, a greater amount of power can be transmitted at a given speed and tension than when only a single half turn is used.

HORSE-POWER TRANSMITTED BY A STEEL ROPE ON WOOD-FILLED SHEAVES

Diameter of rope, in.	Velocity of rope in feet per second									
	10	20	30	40	50	60	70	80	90	100
¼	4	8	13	17	21	25	28	32	37	40
5/16	7	13	20	26	33	40	44	51	57	62
⅜	10	19	28	38	47	56	64	73	80	89
7/16	13	26	38	51	63	75	88	99	109	121
½	17	34	51	67	83	99	115	130	144	159
9/16	22	43	65	86	106	128	147	167	184	203
⅝	27	53	79	104	130	155	179	203	225	247
11/16	32	63	95	126	157	186	217	245	...	...
¾	38	76	103	150	186	223	...	...	...	...
7/8	52	104	156	206	...	...	...	...	...	...
1	68	135	202	...	...	...	...	...	...	...

The horse-power that may be transmitted by iron ropes is one-half of the above.

Power Lost Due to Friction of Sheaves and Shafts. — In the above formula no allowance is made for the friction of the sheaves and shafts. Wm. Hewitt of the Trenton Iron Company gives the following expression for the horse-power lost in friction

$$6 \times 10^{-6} (W + G_1 + G_2)\, v,$$

where W = total weight of rope, G_1 = total weight of terminal sheaths and shafts, G_2 = total weight of intermediate sheaves and shafts, all in pounds, and v = velocity of rope in feet per second.

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rs of Sheaves. — The following table gives the minimum diameter ecommended by Hunt for hemp ropes and by Hewitt for steel and iron e larger the diameter of the sheaves the greater the life of the rope.

MINIMUM DIAMETER OF SHEAVES

Hemp	Steel			Iron		
	7-wire	12-wire	19-wire	7-wire	12-wire	19-wire
..	20	15	12	40	30	24
..	25	19	15	50	38	30
..	30	22	18	60	45	36
..	35	26	21	70	53	42
20	40	30	24	80	60	48
..	45	33	27	90	68	54
24	50	37	30	100	75	60
..	55	41	32	110	83	66
30	60	44	35	120	90	72
36	70	52	41	140	105	84
42	80	59	47	160	120	96
54	..	..	..	...	...	..
60	..	..	..	...	...	..
72	..	..	..	...	...	..
84	..	..	..	...	...	..

Measured by Sag. — (*See also article on Transmission Lines.*) Let
t of rope per foot, in pounds,
ıce between centers of sheaves in feet,
feet midway between sheaves.
nsion at the sheaves, corresponding to the sag S, is approximately

$$T = \frac{wL^2}{8S} + wS \qquad \text{pounds}$$

e driving or the slack rope.

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RUBBER. — (*See also Gutta-Percha; Insulating Materials; Wires and Cables, Insulated.*) Rubber is derived from the milky secretion or latex of certain tropical trees, creepers and shrubs found chiefly in America, Africa, Ceylon and Malacca. When these plants are tapped, a thick milky-looking fluid or latex exudes from them. This latex is composed of very minute oil-like refractive globules, varying in size, which are in a state of rapid Brownian movement in a clear transparent liquid, called the serum. Besides these *caoutchouc* globules, or rubber-gum proper, the serum contains resins, protein, enzymes and various organic and inorganic compounds. Rubber or India rubber is the dried-up or coagulated latex. The best rubber is from a tree known as the *Hevea Brasiliensis*, and is known as *Heves* rubber. It grows wild in Brazil and is cultivated in Ceylon and the Malay Peninsula. In Brazil coagulation is effected principally by dry heat or smoking. A wooden paddle is dipped in the latex and held over a smoky fire until the latex has coagulated. This process is repeated until the caoutchouc layers have become sufficiently thick, when the lump of raw rubber is cut off, dried for several days and despatched usually as "fine Para biscuits" to a trading center. The plantation rubber is coagulated in sheets by means of acetic acid. If subsequently smoked it is known as "*smoked sheets.*" Para enterfine, Negro Heads and Sernamby are usually prepared from fine Para rubber which adheres to the tree during tapping or to the vessels containing the latex.

IMPURITIES IN COMMERCIAL RUBBER. — Commercial rubber contains, in addition to the caoutchouc, a number of foreign substances, such as sand, bark, etc., which can be removed by mechanical washing, followed by drying.

Acetone Extract. — In addition to the pure rubber gum, washed rubber contains resins and proteins which are soluble in acetone and are therefore often known as "acetone extract."

The accompanying table shows the loss in washing and the percentage of acetone extract in the best brands of raw rubber.

IMPURITIES IN COMMERCIAL RUBBER

(*Abstracted from a very comprehensive table in "Lectures on India Rubber," Edited by D. Spence.*)

Brazilian Rubber

Trade name	Geographical origin	Mean loss on washing, per cent	Acetone extract in washed dry rubber, per cent
Para, fine Island, soft cure	Brazil, the islands of the lower Amazon and its delta, and also other parts of the State of Para	17–20	1 9–2.1
Para entrefine, Islands entrefine		18–25	Varies
Negro Heads, or Islands Coarse Sernamby		35–40	2–6
Fine Para, upriver, hard cure	Amazon district. Also the districts drained by its large tributaries	15–20	1.9–2.9
Upriver entrefine, hard entrefine		18–25	Varies
Upriver coarse or Manaos Scrappy Negroheads		18–25	1.5–1.8
Cameta Negroheads	Southwestern Para	37–42	1.2–2.2

IMPURITIES IN COMMERCIAL RUBBER — *Continued*

Brazilian Rubber — *Continued*

Trade name	Geographical origin	Mean loss on washing, per cent	Acetone extract in washed dry rubber, per cent
Caucho Balls	Amazon district and its lower tributaries	25-35	3.6-4
Caucho Slabs and Strips		35-42	4-8
Ceará Scraps	Ceará, Piauhy and Rio del Note	29	2.1
Maniçoba			
Matto-Grosso, Virgin sheets, white Para	Matto-Grosso	15-30	2.5-3.5
Matto-Grosso, Negroheads	Matto-Grosso	25-35	2.5-6
Miscellaneous South and Central American Rubber			
Bolivian, fine medium	Bolivia	15	1.6
Virgin, coarse, entrefine	"		
Uncut Bolivian	"		
Molleado	South Bolivia, Peru	15-25	1.9-3
Peruvian, fine, medium and scrappy	Peru	15-22	1.9-3
Peruvian Balls (also Caucho)	"	20-35	3.6-4
Orinoco, also Angostura	Venezuela	18-22	1.9-2.9
Eastern Rubber			
Plantation Rubber, as fine biscuits, sheets, fine crepe, scraps and block	Malacca and Ceylon	2-7	2-3
African Rubber			
Upper Congo, black	Congo, Angola	10	3.1
Loando Niggers, red fine and fine black.	" "	10-20	3
Kassai, fine	" "	7-10	3.3

MANUFACTURE OF RUBBER INSULATION. — The washed, dried rubber is passed between heavy rollers and flattened into thin sheets. It is then cut into small pieces and again passed through the rollers with a large proportion of fine powder consisting usually of inert mineral substances, waxy hydrocarbons and sulphur. The mixture is thus masticated until all its constituents are thoroughly mixed and a smooth homogeneous paste obtained. This process is known as compounding.

Fillers Used in Compounding. — Experience has shown that 60 or 70 per cent of mineral filler, or even a greater proportion of rubber substitute, may be added to rubber gum, before the essential qualities of the rubber

cease to predominate. The majority of commercial 30 per cent insulating compounds have compositions which fall within the following limits.

Ingredient	Per cent
Rubber	30-32
Whiting	0-30
Zinc oxide	28-67
Litharge	1-12
Ozokerite or paraffin	2-4

In addition to the above fillers, from 2 per cent to 4 per cent of sulphur is added to the compound, the greater part of which combines with the rubber in the vulcanizing process (see below).

Barium sulphate, sublimed white lead, lead carbonate, lamp-black, talc, magnesium carbonate, red lead, barium carbonate and other substances are also used in small quantities. Talc is often objected to, as making the compound porous, and lampblack, as rendering analysis difficult.

Applying the Compound to Wires. — The rubber compound is applied to the wire by "tubing" machines, or is applied in strips, and the wire thus covered with the compound is coiled up ready for vulcanizing. See article on *Wires and Cables, Insulated.*

Vulcanizing. — If exposed for a long time to air and sunlight, rubber loses its elasticity and finally oxidizes completely into resinous matter soluble in acetone. By vulcanization, however, rubber is rendered more or less immune from deterioration by weathering. Vulcanization is the chemical union of rubber gum with sulphur. It takes place at a temperature of from 248° to 302° F.

The coils of wire, covered with the compound as above described, are placed in a suitable chamber to which steam at the proper temperature is admitted. The time required for vulcanization depends upon the thickness of the insulation, the nature of the compound, the temperature and pressure of the steam, etc., ranging from 2 to 8 hours.

Sulphur Required for Vulcanization. — The amount of sulphur required to produce vulcanization varies with the brand of rubber and the nature of the adulterants with which it is mixed. The ratio of the weight of combined sulphur to the weight of caoutchouc, which is insoluble in acetone, is called the vulcanization coefficient. The highest grades of 30 per cent hevea insulation usually have a coefficient between 5 per cent and 10 per cent.

The vulcanization of some brands of rubber cannot be accomplished without either an excess of sulphur or the presence of excessive quantities of some mineral accelerator, such as red lead. Such rubber is to be avoided where permanency is an important consideration. It does not follow from this that red lead is a detrimental ingredient.

SPECIFIC RESISTANCE. — The specific resistance of 30 per cent hevea rubber compounds is exceedingly variable, depending largely upon the success with which steam is prevented from condensing in the insulation during vulcanization. The megohm-miles are usualy computed from the following formula:

$$M = K \log_{10} \frac{D}{d},$$

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here
M = insulation resistance of a cable, megohm-miles,
d = diameter of cylindrical conductor,
D = diameter of cable over its insulation,
K = 5.8 × (millions of megohms per inch cube at 60° F.).

The value of K varies from 3000 to 7000, the usual specification value being 000 for 30% hevea compounds.

The specific resistance is not an indication of the quality of rubber insulation s it depends more upon the dryness, the proportion of mineral wax, and the egree of vulcanization, than upon the quality of the ingredients. When the negohms are low they can almost invariably be raised by drying the insulation n a desiccator. The specific resistance of very poor quality rubber compound s, however, sometimes so low that when a cable lies in damp earth, sufficient eakage current may flow to permit the passage of water by endosmose, when he conductor is negative to the ground (*see article on Endosmose*).

DIELECTRIC STRENGTH. — The disruptive strength of rubber insulation is generally given as between 350 and 450 kilovolts per inch or about 140 to 180 kilovolts per centimeter effective a-c. values. The pressures which should be used in commercial testing do not depend entirely upon the dielectric strength of the rubber, as air in the rubber or between the rubber and conductor or between the rubber and ground becomes ionized at a pressure of about 30 kilovolts per centimeter with consequent generation of ozone, which rapidly oxidizes and destroys the rubber. This does not occur with paper insulation because the impregnating oil precludes the possibility of air spaces; and no harm results in the case of varnished cambric because it is not seriously attacked by ozone. Hence test pressures for rubber insulation must be based upon experience rather than upon theory and if sufficiently high to permit ionization of the air, should not last long enough to permit the formation of an appreciable amount of ozone.

SPECIFIC INDUCTIVE CAPACITY. — The specific inductive capacity of pure rubber is about 2.3 (*Floy*), but the vulcanized compounds used for insulation have specific capacities ranging between 3 and 5, the latter value being nearer the average. The specific capacities of several compounds of stated composition are given by E. Jona (*St. Louis, 1904*), but they cannot be considered as representative of American practice.

SPECIFICATIONS. — Specifications for rubber insulation for wires and cables will be found under *Wires and Cables, Insulated*.

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SECOHMMETER. — (*See also Bridges for Electrical Measurements.*) The secohmmeter is an instrument used in connection with a Wheatstone bridge for changing the direct current from a battery to an alternating current, and commutating the portion of this current that flows in the galvanometer circuit to a direct current. The secohmmeter may be used in the measurement and comparison of self- and mutual inductances and in the measurement of the resistance of electrolytes.

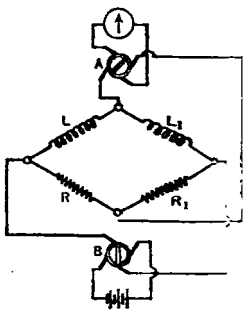


Fig. 1. Connections for Secohmmeter

Fig. 1 shows the relative position of the commutators and brushes of a secohmmeter when connected in a bridge circuit. *A* is the commutator to which the galvanometer is connected and *B* the one to which the battery is connected. They are on the same shaft and turn together.

The secohmmeter is not an altogether satisfactory instrument, due to the variation in the various contact resistances when used for any length of time. Whenever possible some other method of accomplishing the desired results should be employed, e.g., the use of alternating current with some sort of a-c. detector, such as a telephone receiver, electrodynamometer or a-c. galvanometer.

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M. — Selenium, an element of rare occurrence in nature, is found in as a selenide in combination with various metals. Vitreous selenium which has been fused, is dark brown in color and has a specific 28. Its melting and boiling points are 217° C. and 700° C. respecreous selenium is a very poor conductor of electricity, its resistance 60,000 ohms per centimeter-cube at room temperature. When nium is annealed it assumes a crystalline form sometimes called nium. As a result of the annealing process, the electrical resistance ly reduced (the amount depending upon the thoroughness of the nd becomes a function of the intensity of illumination, a property sessed to a lesser degree by tellurium and carbon.

itive selenium is said to be light-positive or light-negative depending r its resistance decreases or increases respectively when carried from t. Sensitive selenium is usually light-positive. The resistance of e selenium is usually less than that of light-positive selenium.

JM LIGHT-CELLS. — A selenium cell or unit is made by conral narrow strips of light-sensitive selenium in parallel between the brass plates. The higher the resistance the higher the sensibility l, that is, the greater the ratio of its conductivity in the light to its in the dark. The conductivity of a cell made of high-resistance y show a change in conductivity of 20,000 per cent (200 times) from direct sunlight to a dark room. Cells made of low-resistance ght-negative) show a much smaller change in conductivity, seldom cent for a change from direct sunlight to dark.

Intensity of Illumination. — The resistance of the cell when ight depends upon the time of exposure and the intensity of the . If a strong light is suddenly thrown upon a high-resistance cell lark room, the resistance of the cell decreases to its minimum value of a second and then begins slowly to increase again. If the inumination is not so great or the cell has a comparatively low resistne taken to reach a minimum resistance may be several minutes. y of experimenters on this subject agree that the change of resistas the square root of the intensity of illumination.

Wave Length of Light, Temperature, etc. — It is found that yellow rays are the most effective. The sensibility of most cells s the temperature increases. In certain selenium cells a large fference impressed across the terminals of the cell produces a variatance in the cell similar to that caused by an exposure to light.

Selenium Cells. — The light-sensitive property of selenium has l in the photophone and in connection with the electrical transmisures. In the photophone a beam of light reflected from a mirror the vibrating disk of a telephone transmitter is made to play across ell connected in series with a battery and a telephone receiver. In speech may be transmitted through space by means of light waves. nsmission of pictures a large number of selenium cells are usually roduce the light and shade of the picture. The light reflected from on the picture is then represented at the distant point by a corretensity of current, which may reproduce again electrochemically of the reflected light at each point.

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SEPARATORS, STEAM. — (*See also Boilers*
boilers, without superheaters, generally deliver steam
1.5 per cent of moisture. When the water level rises
the water contains substances which cause foaming
in the steam may be much higher. Condensation
also increases the moisture, and for this reason it i
pipe line near the engines one or more steam separa
by suddenly changing the direction of the flowing
of water are by their momentum carried out of th
jected against a baffle or bend in the pipe or separa
collected and removed through a trap. Separators
in the exhaust steam piping to eliminate the cylinder
steam.

Although absurdly high efficiencies are claimed
separators, efficiencies which cannot be realized in
separator should be retained in service that does
cent of the water carried by the steam approaching

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SERIES, MATHEMATICAL. — (*See also Equations, Differential; Wave Analysis.*) In calculating the numerical values of a function for given numerical values of the variable, it is frequently convenient to express the function as a sum of a series of terms each of which is a simple algebraic function of the variable. The simplest form of such a series is the

Binomial Theorem. —

$$(x+a)^n = x^n + nax^{n-1} + \frac{n(n-1)}{2!}a^2x^{n-2} + \frac{n(n-1)(n-2)}{3!}a^3x^{n-3} + \cdots a^n$$

Where 2! means 1×2, 3! means $1 \times 2 \times 3$, etc.

A particular case of this series is when $x = 1$, $a = \frac{1}{n}$ and n is taken infinitely large. The expression $\left(1 + \frac{1}{n}\right)^n$ is not unity, but has the value

$$e = 1 + 1 + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \cdots$$

This is the base of the natural system of logarithms and is numerically equal to 2.718282 +.

Taylor's Series. — Let $f(x)$ be any function of x, and for brevity write

$$f'(x) \text{ for } \frac{df(x)}{dx}, \quad f''(x) \text{ for } \frac{d^2f(x)}{dx^2}, \text{ etc.}$$

Then $$f(x+h) = f(x) + hf'(x) + \frac{h^2}{2!}f''(x) + \frac{h^3}{3!}f'''(x) +, \text{ etc.}$$

This expression is known as Taylor's series. Such a series is a useful expression for $f(x+h)$ only when the terms of the higher order are negligibly small, in which case the series is said to be convergent.

Maclaurin's Series is the special case of Taylor's Series when the x in the latter is taken equal to o and the h in the latter is put equal to x. In this case

$$f(x) = f(o) + xf'(o) + \frac{x^2}{2!}f''(o) + \frac{x^3}{3!}f'''(o) +, \text{ etc.}$$

Where by $f(o)$ is meant the value of $f(x)$ for $x = o$, by $f'(o)$ is meant the value of $f'(x)$ when $x = o$. etc.

The following are useful expressions derived from the above relations:

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \text{etc.}$$

$$\log(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \text{etc.}$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \text{etc.}$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \text{etc.}$$

$$\sinh x = x + \frac{x^3}{3!} + \frac{x^5}{5!} + \frac{x^7}{7!} + \text{etc.}$$

$$\cosh x = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \text{etc.}$$

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SHAFTING. — (*See also Bearings; Belts and Belting.*) Ordinary shafting for mill work is usually made of solid steel rods, although hollow shafting is sometimes used.

Diameter of Shaft. — The proper size of shafting to use to transmit a given amount of power may be expressed by the formula

$$d = \sqrt[3]{\frac{CP}{N}},$$

where d is the diameter in inches, P the horse-power transmitted, N the speed in revolutions per minute, and C a constant depending upon the desired factor of safety, the number and location of pulleys or gears, the weight of pulleys or gears and belting, etc. Various authorities assign different values to C, ranging from 40 to 125, the lower value for short shafts used simply for transmitting power, a higher value for line shafts (carrying several pulleys), and the highest value for head shafts carrying the main driving pulley.

Distance Between Bearings. — The distance between bearings may be expressed by the formula

$$L = \sqrt[3]{Bd^4},$$

where L is in feet, d in inches and B is a constant dependent upon the elasticity of the shaft, the load on the shaft and the allowable deflection. The latter is usually taken as $\frac{1}{100}$ of an inch per foot of length. The Pencoyd Iron Works take $B = 720$ for bare shafts, and $B = 140$ for shafts carrying pulleys.

Speed of Shafting. — The following represents average practice.

Machine shops	120–240 revolutions per minute.
Wood-working	250–300 revolutions per minute.
Cotton and woolen mills	300–400 revolutions per minute.

Efficiency of Shafting. — Experiments made by various engineers have shown losses between engine and machine in ordinary machine shops of from 50 to 60 per cent of the total power transmitted by the engine. This loss is greatest in shops where large machines are employed, located at some distance from each other, and it is here that other kinds of transmission can be used to advantage.

Cost of Shafting (Pre-war figures). — The cost of shafting, including the necessary hangers, couplings and pulleys will vary according to size between $2 and $6 per linear foot. A rough rule which may be used in preliminary work is to allow $1 per linear foot per inch of diameter.

BIBLIOGRAPHY. — See Kent's *Mechanical Engineers' Pocket-Book* and the various works on *Machine Design* listed in the Bibliography at the end of article on *Bearings*.

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LECTRIC PROPULSION OF.— The relative light weight, nd high steam economy of high-speed steam turbines, compared cating engines, naturally suggest the use of such turbines for the f ships. The most efficient speed of a ship's propeller, however, that of a steam turbine. Consequently, to obtain the best over-all ome means for speed reduction must be provided. At present o means available, namely, high-speed tooth-gearing and "electric ., high-speed generators direct-connected to the turbines and electri- ted to low-speed motors which in turn are direct-connected to the afts. By these two methods speed reductions as high as approxi- o 1 are being obtained. Ships equipped with electric gearing are eferred to as electrically propelled.

opment of the turbine and these two methods of speed reduction ne reciprocating engine relatively undesirable for ship propulsion, bly for quite small boats. The electric propulsion of ships is now e and more into favor. There are still, however, opponents to this ng ship owners and others. The more obvious application is for , such as warships and ocean liners. The many very great advan- tric propulsion for large warships is now fully recognized by the as all the many battleships and battle cruisers which are being ose which have been built during the last four years, are equipped thod of propulsion.

ago fire-boats, "Graeme Stewart" and "Joseph Medill" were h electric propulsion in 1908. The first large ship equipped with ulsion for the United States Navy was the collier "Jupiter," which continuous service since 1913. During the Great War the equip- nany times heavily overloaded. The Navy Department reports lly no expense has been caused by the electric equipment during riod.

l turbines, which in comparison with high-speed machines, are efficient, have been used for a number of years for driving ships. es are either directly connected to their propellers or are connected ngle reduction gearing. In some large ships a combination of steam engines and a low-pressure turbine have been installed.

versus Reciprocating Steam Engines. — Aside from questions d cost, the higher steam economy of high-speed turbines is of itself st cases to justify the adoption of the turbine for ship propulsion. ngine of the triple or quadruple-expansion type, due to the limi- ze of the low-pressure cylinder, cannot be made having a steam tio greater than about 16 to 1, or 20 to 1. The steam turbine has tation and is capable of using efficiently steam expanded to any xtent. Where turbines are used, a vacuum of 28.5 inches is quite 9.5 inches is being recorded in some central stations during winter e economy due to large expansions is indicated by a comparison ble energy of a pound of steam when expanded from boiler pressure grees of vacuum, viz.:

pounds pressure to 24-inch vacuum = 220,000 foot-pounds
pounds pressure to 26-inch vacuum = 238,000 foot-pounds
pounds pressure to 28-inch vacuum = 265,000 foot-pounds
pounds pressure to 29-inch vacuum = 289,000 foot-pounds

res give an indication of the saving that can be expected by the h can use efficiently steam expanded to a low degree. Little

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advantage, however, is gained with a reciprocating engine when the expansion is carried below 24 inches. This not only means a saving of fuel, but also in the size of boilers, auxiliaries, etc.

Application of Internal Combustion Engines to Ship Propulsion. — Electric gearing not only serves as a means whereby high-speed steam turbines may be effectively used for ship propulsion, but also makes possible the adaptation of relatively simple internal-combustion engines for this purpose. Some years ago two or three vessels in Europe were equipped with electric transmission gear between internal-combustion engines and propellers with partial success. Recently in America some low-powered boats have been equipped in a similar manner using direct current apparatus; for example, the trawler "Mariner," which has been in successful operation for about two years. The apparatus on this boat consists of two 165 kw.-125 volt generators, each direct-coupled to an eight-cylinder, four-cycle, 350 r.p.m. Diesel engine. These two self-excited generators are normally connected in series and supply current to a 440 horsepower, 250 volt, 200 r.p.m. motor which is direct coupled to the propeller shaft. For slow speeds of the ship, one engine can be shut down and the motor supplied with current at 125 volts. Two master controllers are provided, one in the pilot house and the other in the engine room. For emergency manual operation is also provided in the engine room.

FUNDAMENTAL REQUIREMENTS OF SHIP PROPELLING MACHINERY. — A ship may be equipped with 1, 2, 3, or 4 propellers. The most favorable propeller speed is generally from 75 to 200 r.p.m., depending upon the size and speed of vessel. Destroyers and similar vessels have higher speed propellers. The following are considered desirable turbine speeds (for the impulse type of turbine) for the corresponding output:

Horsepower	R.P.M.	Poles of generator	Cycles per second
7,000	3600	2 poles	60
10,000	3000	2 poles	50
16,000	2400	2 poles	40
29,000	1800	4 poles	60
65,000	1200	4 poles	40

To secure the most favorable speeds for both propellers and turbines, a high-speed reduction is required, the amount depending upon the size of the turbine and the design of the propeller. For example, for a twin-screw ship having a propeller speed of 100 r.p.m. and a total horsepower of 18,000 equipped with two main turbines, a speed reduction of 30 to 1 should be adopted.

Loss due to Incorrect Turbine and Propeller Speeds. — In many turbine-geared equipments it has been considered advisable to depart from the most desirable propeller and turbine speeds so as to reduce the speed ratio of turbine and propeller and thus obtain a simple gearing. This sacrifice of turbine and propeller efficiency in some cases has caused an increase of fuel consumption amounting to from 25 to 30 per cent. With electric propulsion the most favorable turbine and propeller speeds can be generally adopted and a speed ratio as high as 40 to 1 can be used if desired.

Reversing. — The propelling machinery of a ship must of course, be capable of backing the ship as well as driving it forward. With reciprocating steam

engines there is of course no difficulty in this respect. A steam turbine, however, cannot be reversed. Consequently, when a ship is equipped with turbines directly connected to the propeller shafts, or connected thereto through mechanical gearing, each shaft must be equipped not only with a forward-driving turbine, but also with a turbine whose normal direction of rotation is opposite to that of the forward driving turbine. Such turbines are called "reversing turbines" or "astern turbines." When the ship is driven forward the reversing turbine is driven backward, no steam being admitted to it. To reverse the direction of motion of the ship, the steam suply is cut off from the main turbine and admitted to the reversing turbine, the main turbine then being driven backward.

With electric gearing, reversing turbines are of course unnecessary, since the direction of rotation of the motors connected to the propeller shafts can be reversed merely by operating suitable switches. This is a decided advantage of electric propulsion over direct-connected or mechanically geared turbines.

Losses in Reversing Turbines. — Experiment has shown that a turbine forced in a direction opposite to its normal direction of rotation has about 10 times as much friction loss as when driven in its normal direction. This friction loss in a reversing turbine, which is always present when the ship is in motion, may amount to more than 1 per cent of the shaft horsepower of the propeller.

Two Efficient Speeds. — The propelling machinery of a war vessel should be capable of driving the ship efficiently not only at full speed, but also at cruising speeds, which are usually from 50 to 70 per cent of full speed. The same is also desirable in certain passenger ships. As the power required to propel a ship varies approximately as the cube of the speed, this means that at cruising speeds the propelling machinery will be running at less than one-third of its maximum load. Since a steam turbine is most efficient at or near maximum load and at full speed, it follows that when directly connected or mechanically geared turbines are employed, there must of necessity be a sacrifice in efficiency at cruising speed, which, in the case of a warship, is the speed at which the ship is driven by far the greater part of the time.

Cruising Turbines. — To avoid this difficulty, it is possible to provide, in addition to the main turbines, auxiliary high-speed turbines geared to the propeller shafts, the speed reduction being such as to give the desired cruising speed. Provision has to be made in this case for disconnecting the auxiliary turbines when the ship is driven at full speed by the main turbines. These auxiliary turbines are usually referred to as "cruising turbines." The two U. S. battleships "Idaho" and "Mississippi" are equipped in this manner. The full speed of these ships is 21 knots. The cruising turbines are used for speeds up to 17 knots for the "Idaho" and up to 15 knots for the "Mississippi."

With electric propulsion two efficient speeds are readily obtained without any such complication. All that is necessary is to change the ratio of the number of poles of the motors to the number of poles of the generators, which is readily accomplished by a simple switching operation. Since the propeller torque required at half speed is only about one-quarter that required at full speed, the voltage applied to the motors at cruising speed can also be reduced, thus keeping the motors operating at relatively high efficiency at reduced speed. The equipment of the U. S. battleship "New Mexico," which was the first electrically propelled battleship, being put into commission in 1918, is arranged in this manner. This ship is a sister ship to turbine-driven ships "Idaho" and "Mississippi."

Comparison of the "New Mexico" and the "Idaho" and "Mississippi." — During the period from 1918 to 1920 the relative maneuvering

qualities and the relative fuel economy of these three ships observed when operating together. The electrically propelled proven decidedly superior with regard to maneuvering quali superior in fuel economy. The fuel consumption of the "Ida "Mississippi" exceeds that of the "New Mexico" by the followi

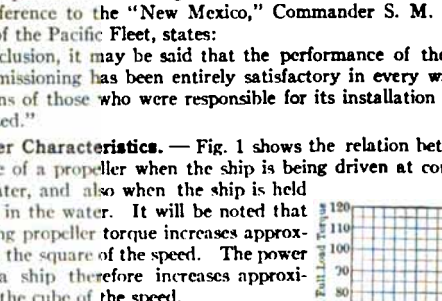
At 10 knots	20.0 per c
At 13 knots	42.7
At 16 knots	47.8
At 19 knots	40.1
At 21 knots (full speed)	32.2

At 19 knots, and also at full power, the "New Mexico" uses ab of oil per shaft horsepower per hour, and at 15 knots 1.1 pound horsepower per hour. These figures include the total oil used f

With reference to the "New Mexico," Commander S. M. Engineer of the Pacific Fleet, states:

"In conclusion, it may be said that the performance of the since commissioning has been entirely satisfactory in every w expectations of those who were responsible for its installation than realized."

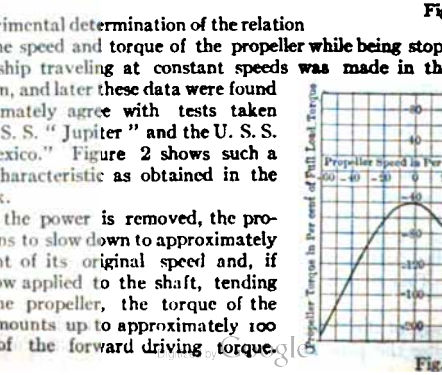
Propeller Characteristics. — Fig. 1 shows the relation bet and torque of a propeller when the ship is being driven at co smooth water, and also when the ship is held stationary in the water. It will be noted that the running propeller torque increases approximately as the square of the speed. The power to drive a ship therefore increases approximately as the cube of the speed.



Fi

Torque Required to Stop and Reverse. — When the driving power is removed from a propeller with the ship traveling at a high speed, the propeller will continue to revolve in the same direction, being driven by the water. In order to stop the ship in the shortest time, or to maneuver quickly, it is necessary, not only to stop the propeller against the action of the water, but also to drive it in the reverse direction.

An experimental determination of the relation between the speed and torque of the propeller while being stop with the ship traveling at constant speeds was made in th Washington, and later these data were found to approximately agree with tests taken on the U. S. S. "Jupiter" and the U. S. S. "New Mexico." Figure 2 shows such a propeller characteristic as obtained in the model tank.



Directly the power is removed, the propeller begins to slow down to approximately 73 per cent of its original speed and, if power is now applied to the shaft, tending to stop the propeller, the torque of the propeller mounts up to approximately 100 per cent of the forward driving torque.

Fig

This maximum torque is attained at between 35 per cent and 40 per cent of normal propeller speed.

From this point on less torque is needed to bring the propeller to rest. If the propeller is now reversed, with the ship at full speed, 100 per cent torque is attained at a speed of about 30 per cent of normal. From this curve, therefore, it will be noted that it takes approximately 100 per cent torque to break the propeller away from the water, but only requires about 40 per cent torque to hold the propeller stationary after being stopped.

From experience obtained to date, it would seem that machinery for high-speed ships, having two or more propellers, should give 100 per cent reversing torque to quickly bring the propellers to rest when reversing from full speed. On lower speed ships, indications are that the maximum stopping torque is considerably less than 100 per cent. On single screw cargo boats, the stopping torque is probably quite low.

Variation of Propeller Torque with Pitching of Ship. — The General Electric Company has taken a number of elaborate tests with reliable apparatus to determine the variation of the propeller torque when the ship is in a sea-way. An illustration of the variation which may be expected in moderately rough sea is shown on Fig. 3. Although the ship was only pitching 4°, the increase in torque varied from no load to 175 per cent of normal load.

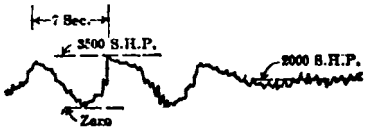


Fig. 3.

These results were obtained on a cargo ship equipped with double reduction gearing. This turbine equipment did not have a governor and the variation in torque may, in part, be due to the variation in speed of the propelling machinery, but was mostly due to the different conditions of wake at different depths below the surface of the water.

Under worse conditions of sea, it may be expected that this variation in torque would be considerably increased.

It was observed that, when the propeller approached the surface of the water, the load was quickly released and was again gradually increased as the propeller went deeper into the water. The record was taken with the ship in ballast and it was observed that the propeller did not break water. This variable condition of torque has been confirmed on electrically driven ships by observing the variation of load by electrical instruments.

The electric motor is an ideal piece of machinery for absorbing these shocks without deterioration. As there is no mechanical connection between the turbine and the propeller, this shock is absorbed in the air gap of the motor; it being necessary only to give the electrical machinery a sufficiently strong magnetic bond to hold the generator and motor together. This bond is increased by simply increasing the degree of excitation. If the motors drop out of step with the generators, then to bring them in step again it is necessary only to reduce the turbine speed and increase the excitation. Then the turbine speed can again be increased to normal. No harm is done if these motors are left out of step for short periods as the generator is so proportioned that the increase in current cannot greatly exceed the normal.

EQUIPMENT FOR ELECTRIC DRIVE. — The essential elements required for electric transmission between the turbines and the propellers of a ship are the generators, the motors, the cables connecting these two, and the switching and control devices.

Relative Weights of Electric Drive and Gear Drive. — When properly designed, the weight of the machinery required for electric drive is but little,

if any, in excess of the weight required for gear drive, except high-speed boats as destroyers, scout cruisers and pleasure y tain cases the weight of the electric drive may be actually less t gear drive. For example, in the case of a 3000 horsepower sing having a propeller speed of 100 r.p.m., assuming that the bo center of the ship and, in both cases, the turbine is installed n and in the case of the electric drive the motor is installed in boat, the electric propelling machinery, including the propeller 10 per cent less than the geared propelling machinery.

Alternating versus Direct Current. — Alternating-curren usually adopted for ship propulsion in preference to direct c are, however, a few cases where direct current is used when sp involved, and also when Diesel engines are used as prime movers

Alternating current has many advantages over direct curre which may be stated as follows:

1. The combined transmission losses of the generator and mot nating-current apparatus is used, is from 5 to 8 per cent less tha apparatus.

2. High-speed prime movers and generators can be used w current, whereas with direct current, when a high-speed steam t it is necessary to have a reduction gear between this and the l current generator. High-speed apparatus is cheaper and lighter

3. Alternating-current apparatus is, generally speaking, mor direct current. As the distance between the generator and s board is short, there is no advantage in using high-voltage tra the case on land. Lower voltages, therefore, are usually adopte of voltage on cargo boats is from 1100 to 2300. The General pany's records, over long periods of years and covering such ratus as is used on cargo ships, show that only about $\frac{1}{10}$ of 1 per c of such voltage give any electrical trouble in a period of ten ye trical apparatus includes all motors and generators installed in a vice.

In warships, machines designed for 5000 volts are being used.

Types of Motors Suitable for Electric Drive. — Five types current motors have been used for ship propulsion:

1. Induction motors equipped with slip rings and external resi

2. Induction motors without slip rings, but with two squi windings. A high-resistance rotor winding is placed in the slot n ery of the rotor and beneath this a low-resistance winding. running, when the current alternates slowly in the rotor, the winding carries the current. When, however, there is a high- rent flowing in the rotor, as is the case during reversals of the self-induction of the low-resistance winding forces current resistance winding, and this produces a high torque.

3. Induction motors without slip rings but with one squi winding, consisting of deep, narrow bars. The action of this reversal is similar to the double squirrel-cage motor.

4. Induction motors equipped with slip rings but no ext The rotor is wound with a low-resistance winding near the pe rotor and beneath this a high-resistance squirrel cage windi resistance winding is connected to the slip rings. To make t ance winding carry the current during reversal of propeller, ance rotor winding is opened by means of contactor switc across the slip rings. If this motor is wound to give two di

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the slip rings can be made neutral for high-speed running, and thus need not carry heavy current. All reversals are accomplished with low-speed connection.

5. Synchronous motors, the periphery of the poles being equipped with a low-resistance bar winding. With this type of motor the propeller is brought to rest during reversal by reversing the phases with the circuit "dead," and then applying a strong field on the motor, leaving the field off the generator. The propeller thus drives the synchronous motor as a generator, being loaded on the turbine generator. Sufficient torque is developed to bring the propeller approximately to rest. Field is now applied to the main generator and removed from the synchronous motor. If the turbine governor has previously been set for a slow speed, the synchronous motor will now reverse and quickly reach approximate synchronous speed at which time the field is again applied. A small and simple air cooled resistor can be switched in multiple with the generator during the stopping period. If this is done a higher torque can be developed with less excitation and with lower current flowing between the machines.

The following advantages are claimed for the synchronous motor over the induction motor:

1. A higher transmission efficiency due to operating at unity power factor.
2. Larger air gaps can be provided.
3. The generator and motor are lighter and cheaper.

The induction motor is more suited to cases where two different numbers of poles are desired for running at different speeds, such as is desired for warships.

Efficiency of Electric Transmission. — Opponents of electric propulsion have made claims that the transmission efficiency of this type of drive is low compared to other forms of speed-reducing machinery. However, when all the losses incident to the transmission by mechanical gearing are taken into account, the difference in efficiency of the two types of drive is by no means so great as is frequently stated, the advantage in favor of the mechanical gearing being less than 2 per cent. The following comparison for a low-powered cargo ship of 2500 shaft horsepower, driven by a single screw running at 100 r.p.m., is quoted from a paper by Mr. W. L. R. Emmet. (Read as a paper before the *Society of Naval Architects and Marine Engineers*, New York City, Nov. 13, 1919; also published by the *General Electric Review*, Jan., 1920).

"The selection for comparison of a ship of low power is unfavorable to electric drive in the matter of transmission efficiency, the conditions being better for this method in ships of higher power. The generator designed for this case has an efficiency of 95.6 per cent and the motor 95.9 per cent, making the transmission efficiency, including cable loss, etc., 91.6 per cent. In machinery designed for certain high-power ships, the efficiency is as high as 94 per cent.

"To determine the efficiency of gear transmission as compared with the figures just given, very careful tests have been made at Schenectady. A 2400-horsepower ship turbine was connected through two sets of double-reduction gearing to a generator, and the steam consumption was tested at various degrees of load and speed; then the same turbine was connected to the same generator without gearing, and tests were run with the same conditions and the same degree of steam flow. All this was done on a testing stand where conditions are uniform and accurate, the gears ran with perfect smoothness and all conditions were favorable. Since the comparison gives the loss of two gears, the differences are considerable and the determination should be very close to the correct value. This test showed that the performance of a single gear is as follows:

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Shaft horsepower	R.P.M.	Loss of gearing, horsepower	Efficiency of gears, per cent
2400	87	125	95.0
1420	77	80	94.7

"In addition to these gear losses, we must also consider the loss in friction of the reversing turbine, which is estimated from reliable data to be 28 horsepower, and we must also consider the bearing losses on about 100 feet of shaft, which in perfect alignment will be 8.5 horsepower. These additional losses reduce the transmission efficiency to 93.5 per cent, leaving only 1.9 per cent advantage to the gearing. With the shaft more or less out of line and the gears operating under sea conditions, it is probable that the losses given would be greatly increased. Noise is an indication of loss, and most marine gears are at times noisy, while the gears in this test were almost silent. The gears tested in this case were of the General Electric Alquist type, and it might be claimed that other kinds of gears would be more efficient but it is obvious that, under fixed load and with similar gear speeds and diameters, there could be no advantage in any other type even if it ran with equal smoothness."

Gain in Efficiency at Low Speeds by Operating at Reduced Voltage. — Electric motors for shore purposes usually operate at approximately constant voltage regardless of the load carried. At light loads, therefore, they are relatively inefficient due to the iron losses remaining approximately constant. Motors, however, used for propelling ships usually obtain their power from a generator whose voltage can be varied to suit the motor's load. At reduced speeds, therefore, in an electrically driven ship, the voltage can be reduced; this reduction has the effect of materially reducing the losses in the iron laminations of both motor and generator. Thus, at reduced loads, the percentage of power lost is nearly the same as at full load. Whereas with gear, the transmission loss remains quite high at reduced speeds. Also the percentage loss of power in the gears increases when the gears have become worn.

Location of Propelling Machinery. — When vessels are equipped with turbine electric propulsion, the driving motors can be placed as far aft as convenient, thus shortening the propeller shafting. This also gives a larger and better disposition of cargo space and eliminates the long shaft tunnels. The turbine-generator units can be placed near the boilers at any desired level, reducing to a minimum the length of steam piping and other piping systems. The controlling mechanism, as in an electric locomotive, can be placed at one or more convenient positions.

Ventilation of Electrical Apparatus. — It is very important to ventilate the electrical apparatus in such a way that it will not collect moisture when shut down or running under light loads. To prevent this the temperature of the apparatus must not be lower than that of the surrounding air. The ventilating air should, therefore, be taken from the same room in which the apparatus is placed. This air, after passing through the machines, can be used under the boilers. Suitable dampers can be provided to prevent the engine room from becoming uncomfortably cold during the winter weather.

In some cases the air after leaving the generator and motors is passed between cooling tubes through which water is circulated. After passing between the tubes, the air enters the room in which the apparatus is placed and again cir-

ulates through the generators or motors. Thus the same air is used continually.

This method eliminates the large ducts leading from the upper decks of the hip and also ensures clean air being always used. These coolers can be made uite small for this purpose.

Electric Drive for Auxiliaries. — A source of considerable loss in the operaon of many ships is due to the use of steam driven auxiliaries. With electric rive it is necessary to maintain a direct current electrical supply independent f the main generators for purposes of excitation and lighting. This same source an be used for driving electrical auxiliaries. If turbine units are chosen for his auxiliary power, the steam from these units can be exhausted into a suitble stage of the main turbine and, by automatic means, exhausted into the ain condenser when the load is removed from the main turbine. A more imple method is to design the auxiliary turbines as condensing units and conect their exhaust directly into the main condenser. An auxiliary condenser hould, however, be provided for use in port. In certain cases it may be desirble to use a few steam-driven auxiliaries, such as boiler-feed pumps and the xhaust from these can be utilized for feed heating. If necessary, this steam an be supplemented by either "bleeding" the main turbine or using part of he exhaust from the auxiliary units.

In some cases these d-c. auxiliaries can be equipped with slip rings from which lternating current could be taken for driving the main motor in cases of emergncy at reduced speed.

Some European cargo ships are equipped with auxiliaries driven by alterating-current motors from the main generating unit. In such cases reduced peeds of the ship are obtained by running the turbine generator at approximately full speed and reducing the motor speed by means of an external resistnce. The fuel consumption during these reduced speeds is greater with this nethod than when the turbine speed can be reduced as there is a large loss of ower in the external resistance.

Operating Force. — The following is quoted from a paper by Mr. W. L. R. Emmet. (Read as a paper before the *Society of Naval Architects and Marine Engineers*, New York City, Nov. 13, 1919; also published by the *General Electric Review*, Jan., 1920.)

"The history of the electrical industry has repeatedly shown that persons who have not used electrical apparatus assume that its operation requires a high order of skill and expert knowledge, and of this assumption we have already heard much in connection with electric drive for ships. A vast amount of experience has repeatedly shown that this assumption is the direct reverse of the truth, and a little thought as to the conditions in electrical apparatus should make the reason obvious. Conductor circuits are much simpler mechanically than pipes and mechanical motions, and electrical machinery is simply a combination of electric circuits with motion of rotation. The connections are easily shown by diagrams, and little mechanical skill is required to make them. The work of insulation can be so done that, under such conditions as exist in ship installations troubles which might involve difficulty of repair by unskilled persons are very improbable. In all the extensive uses of electricity in mills, mines, railways, and other industries, it has seldom failed to become popular immediately with the operating forces. In no case has this been more marked than in the ships which have been driven electrically. Large electrical apparatus is generally simpler than small, and the machinery used to propel a ship is in many respects simpler than that which is used to light it. Instead of introducing difficulties to the operating force, the adoption of electric drive will eliminate them and make ships much less dependent upon the skill and resourcefulness in their crews."

ADVANTAGES OF ELECTRIC PROPULSION.— tages of electric propulsion have already been noted. T very fully treated by Mr. W. L. R. Emmet in numerous pape from which much of the following is quoted.

Ease of Disconnection and Repair of Propelling following is quoted from Mr. Emmet: "In a geared equ has a system of turbines, gears, bearings, thrust-balancing cating systems all mechanically locked together. With hi any kind of trouble with any of these parts will almost the immediate stoppage of the whole system. To keep a running out of balance or with bearing trouble is impossil part would present almost equal difficulty. In the event o of such character a ship would have to be stopped until cleared. The work necessary to uncouple and disconnec very heavy apparatus would be a serious matter involving that required to stop the ship.

"If it was found impracticable to make this disconnecti was such that the shaft could not be allowed to revolve, it to lock the shaft to hold the propeller. A dragging prop serious drag on a vessel travelling at even moderate spee dragging screw may add 20 per cent to the horsepower and materially reduce the maneuvering qualities of the vessel.

"In the electrically-driven ship there is no mechanica shaft to anything but the rotors of motors. These are self- structures and cannot by any possibility be subject to mec The shafts are subject to the same possibilities of bearing shafts in other ships, but the presence of the motors do danger, and the speed being low it is remote in any case. any motor, generator or turbine, if in any kind of troub disconnected without stopping the ship and with only a highest speed capacity. Such a disconnection is made by s

Referring specifically to 180,000-horsepower, 33.5-knot (1920) being built for the U. S. Navy, Mr. Emmet cont changeability as this power of disconnection gives constitu important advantages of electric drive in such a ship. of eight in trouble, only one-eighth of the maximum cap ship's maximum speed is impaired by only about 1 knot turbine is in trouble, the maximum speed is reduced only a two generating units and four motors out the ship can mak three generators and four motors out she can make 19 k trouble, they are simply cut out and repaired at leisure or The value of this interchangeability in a warship can hard It largely overcomes the military danger incident to acci power, a danger which has always been of primary import

Mud in Condensers. — In addition to the foreg advantage when maneuvering an electrically propelled muddy water in and around harbors, provided the ship is than one turbine and condenser. Under these conditio generator is needed to drive the ship and, in case the con plugged with mud, it can be immediately switched off switched on to the driving motors.

In cases where turbines are mechanically connected to pellers, under similar conditions of operation, it would be the turbines together with their condensers. If such a sh

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condensers might become plugged at once but, if only one became plugged, the maneuvering qualities of the ship would be dangerously impaired. Commander Robinson states:

"As an actual experience the 'New Mexico' while entering New York harbor had to shift main generators twice owing to the plugging of her condensers with mud, and these shifts were made so quickly that they did not affect the operation of the ship at all."

Backing Power. — Again quoting Mr. Emmet: "In turbine-driven ships, not electric, it is necessary to provide backing turbines which must run idle in the reverse direction when the ship is going ahead. These backing turbines involve complications which are very objectionable, and if these are reduced to a desirable minimum the backing power will be greatly inferior to that easily provided with electric drive. Experiment has shown that a turbine forced in an opposite direction involves about ten times as much friction loss as when driven in its normal direction. This loss, therefore, is very appreciable in the backing turbines of ships. There are also serious difficulties and dangers in high-speed apparatus incident to the abrupt and wide changes of temperature where steam is suddenly admitted to a cold reversing or ahead turbine. With electric drive the turbine never need be stopped when the ship is under way, and its operation is easier than in a power station because the load is steadier; with modern high-speed turbines superheat affords large gains in fuel economy, and the ability to safely use high degrees of superheat may constitute one of the important reasons for adopting electric drive.

Efficiency of Transmission. — "Various statements and estimates have been published concerning losses in high-speed gearing for which the authority is not known by the writer. Tests at Schenectady have shown losses about double those generally estimated, with rapid diminution of efficiency as load falls.

"With the electric drive in these battle cruisers (the 180,000-horsepower vessels now building for the U. S. Navy) the losses from turbines to propeller shaft at full speed will amount to 6 per cent, and by adjustment of voltage the transmission efficiency can be kept nearly as good at all speeds. Considering gearing losses, reversing turbine losses, losses incident to necessary subdivisions of the turbine and additional packings, it is believed that the actual transmission from turbine blades to shaft at full speed cannot be made more than 2 per cent better in the geared equipment than it is in the electric. At reduced loads the geared equipment will be much less efficient. The normal cruising speed of these ships will require less than one-tenth of full load, and the drag of gearing, bearings, reversing turbines and idle parts of main turbines will be very serious."

Cruising Economy. — "With the electric design, the number of motors and turbines used can be adapted to the demand for power, while with the other all parts must be kept running. This gives very important gain in economy at all speeds below the maximum. At 19 knots (in the case of the 180,000-horsepower battle cruisers for the U. S. Navy), only one turbine is required to drive the ship, and electrical arrangements are made by which it can be run at full speed instead of running at half speed, as it would if the ratio was fixed as by gearing. Thus the steam efficiency at 19 knots, a desirable cruising speed, is equal to the best attainable at any speed. Assertions which have been made by ship builders and others that equal cruising results can be obtained by the use of cruising turbines are obviously absurd. The cruising turbines themselves would be greatly inferior to the single main turbine so used, and they would be burdened with all the drags which are mentioned above. Cruising economy gives increased cruising radius without renewal of fuel supply. This

has always been considered a matter of the greatest importance in warship it is a feature in respect to which electric drive can have no rival."

Flexibility of Installation. — A military advantage of great importance in connection with electric propulsion is the "flexibility of installation." The following is quoted from Commander Robinson (*General Electric Review*, April 1919):

"The tendency in building modern capital ships is to provide for more and more torpedo protection and it becomes necessary to crowd the machinery away from the sides of the ship as much as possible. This arrangement is also desirable from the point of protection against gunfire for a similar reason. In this respect, electric drive has an enormous advantage over any other type of machinery in which the prime mover is mechanically connected to the propelling shaft. The main turbine-generators may be placed in any part of the ship that is most desirable; they may be placed in compartments forward of each other and they may be raised up enough to place the main condenser underneath them—in fact, there is practically no limit, other than the head room, as to the position of the main turbine-generator in the ship. This gives an enormous advantage to electric drive over all other types of machinery and enables the Naval Constructor to give far more adequate protection to the ship and machinery against damage by torpedo and gunfire. Those parts of the machinery—the main motors—which it is necessary to connect mechanically to the shafts, are comparatively small and take up only a small space so that they can be placed in small isolated compartments which will not menace the ship in case of flooding; since no main auxiliaries are required for the motors, the flooding of a motor room will not entail any loss in that respect. Also, the motors may be placed very much farther aft than can steam-driven turbines and therefore the length of the main shafting can be very materially reduced. This constitutes a big advanatge; both on account of less liability to derangement of the shafting itself, due to injury to the ship, and also of less danger to the ship itself because of the shafting not having to pierce a number of watertight bulkheads. These advantages of installation constitute the real and main reason for the adoption of electric drive for capital ships and any other advantages are minor compared with them. Utilizing these advantages to the fullest extent makes it possible to build capital ships which are far superior to any others fitted with any other form of machinery. In addition to advantages from the point of view of protection, there are also the advantages from an engineering standpoint. The shorter lengths of shafting make it easier to keep the shafts in line; the grouping of boilers around the machinery makes short and direct steam pipes with a consequent reduction in weight and complication and a smaller drop in steam pressure. The same may be said of practically all the other piping systems of the ship, such as feed lines, oil lines, exhaust lines, etc."

Use of Superheated Steam. — As is well known, superheat greatly improves the efficiency of steam turbines by reducing the friction and windage loss of turbine blades and disks. There is also a considerable gain due to increase in the available energy of the steam incident to increase in temperature. It is generally conceded that the steam consumption is reduced at least 1 per cent for every 12.5° F. of superheat. With some installations there is also a gain in boiler efficiency caused by increased heating surface exposed to the flue gases. Superheated steam also increases the life of the turbine blades and nozzles.

In Europe superheat for ships has been used for some years and great saving in fuel has been realized. In 1912, Mr. Ljungstrom in Sweden equipped the "Mjolner," a small coastwise vessel with electric drive. This ship is only 225 feet long, 56 feet beam, and 15 feet draught, requiring one SHP. The

steam conditions are 218 pounds pressure, 200° F. superheat. This ship uses 12.3 per cent less fuel than a sister-ship, the "Mimer," which is equipped with as triple-expansion engine. Since that date larger cargo ships have been equipped in a similar manner, using still higher degrees of superheat.

Superheat has also been used successfully for a number of years in Europe with engine-driven ships. The following extract from a letter from Van Nievelt, Goudriaan & Co., Rotterdam, Holland, illustrates the superheat possibilities in engine-driven ships:

"We are using during the last five years, in our multi-tubular boilers 3½-inch tubes, very high funnels and Diamond blowers, and have no trouble at all in getting sufficient steam. We have practically no leakage at the connections of the pipes and boxes. The original pipes are still in use. The capacity of a 10-ton evaporator is sufficient for supplying feed water.

"Three of our steamers have been running half a year without superheaters with a coal consumption of 24 to 25 tons. After fitting superheaters the consumption was about 22 tons, making a saving of at least 10 per cent."

In America superheat has, for a number of years, been extensively used in central stations but has not been applied to any extent on ships.

Superheat and Reversing Turbines. — Whereas high superheat is beneficial to the operation and life of turbines, it has caused serious trouble in reversing turbines due to expansion strains set up by rapid changes in temperature, and reversing turbines are necessary when mechanical connections between turbine and propeller are adopted. In the case of electrically driven ships, no reversing turbine is needed, the turbine-generator unit revolving continuously in the one direction regardless of the direction of rotation of the propellers.

When steam expands without doing work, its temperature remains nearly constant and, if work is done upon it by a reversed turbine, this temperature is considerably increased. With superheated steam these temperatures may be extreme and might be injurious to the main turbine as well as the reverse turbine, since it also must be used for reversal of direction and since the two often occupy the same casing.

Fig. 4 illustrates the possible steam temperatures which may be reached when maneuvering a ship equipped with reversing turbines. The turbine in this test was first run at full speed in the extremely high vacuum given on the record until a constant temperature was shown by the pyrometer. A little steam was then admitted and a constant temperature was again reached at 825° F. when more steam was admitted and the temperature then rose so quickly that the steam had to be shut off. In the General Electric Company's shops it has been discovered that the reversing wheels of marine turbines turn blue with heat when operated at normal speed in a vacuum of 20 inches.

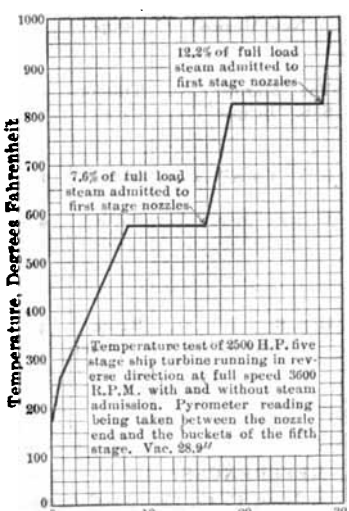


Fig. 4

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When high superheat is used in combination with a reversing turbine, precautions can be adopted to preserve the turbine from damage. Various arrangements have been proposed. One is to reduce the steam temperature before it enters the reversing turbine by injecting a spray of water, or by passing the steam through a cooler. Another method is to install a steam pipe connected between the boiler drum and the superheater — this also requires special maneuvering valves. Precautions must also be taken to prevent the superheater from burning during maneuvering operations. These complications and dangers are, however, entirely eliminated by the adoption of electric drive which abolishes the astern turbine.

TYPICAL ELECTRICALLY PROPELLED SHIPS. — The following is a list of some of the more important types of electrically propelled ships:

Name	Type	No. of screws	Total S.H.P. at full speed	Type of motors	No. of motors	Reference
"Graeme Stewart".. and "Joseph Medill"	Fire-boats	2	500	Direct current	2	1
U. S. S. "Jupiter"...	Collier	2	5,600	Induction with external resistors	2	2
The "Mjolner".....	Cargo	1	900	Induction with external resistors	2	3
U. S. S. "New Mexico"...	Battle-ship	4	31,197	Induction double-squirrel cage type	4	4
The "Mariner".....	Trawler	1	400	Direct current	1	5
S. S. "Eclipse".....	Cargo	1	3,000	Induction with external resistors	1	None to date
S. S. "Cuba".....	Cargo	1	3,000	Synchronous	1	None to date
U. S. S. "Iowa"....	Battle-ship	4	60,000	Induction with high and low resistance Rotor windings	4	None to date
U. S. S. "Lexington"	Battle Cruiser	4	180,000	Induction with high and low resistance Rotor windings	8	6

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SHOCK, ELECTRIC. — The physiological effects of a shock by lightning or by artificially-produced electricity may be classified into two groups, the major effects, cessation of respiration or heart action and the minor effects, fractures and internal injuries due to falls, and burns due to contact with electric arcs.

Removal of Victim from Circuit. — If a switch or circuit breaker in the circuit is close at hand, open the circuit at once or cut away the conductors with a wooden-handled hatchet. If the circuit cannot be opened immediately, break the contact of the victim with the conductor by moving the conductor or the victim, using any available dry non-conductor such as a board, rope or clothing. *Do not touch the victim with the bare hands under any circumstances unless insulated thoroughly from the ground.*

First Aid for Slight Shock. — If the victim is seen to be breathing, administer heart stimulants such as alcohol, ether or ammonia either by the mouth or hyperdermically, produce external warmth by rubbing the body or by application of hot substance, loosen constricting clothing about the neck and chest and present aromatic spirits to the nostrils to excite consciousness. Give plenty of fresh air.

Artificial Respiration. — If the victim does not breathe, send for the nearest doctor, remove any foreign body (tobacco, gum, false teeth, etc.) from his mouth and throat and begin artificial respiration at once, even if the victim appears to be dead. Proceed as follows:*

(*a*) Lay the subject on his belly, with arms extended as straightforward as possible and with face to one side, so that nose and mouth are free for breathing; see Fig. 1. Let an assistant draw forward the subject's tongue.



Fig. 1.

(*b*) Kneel, straddling the subject's thighs and facing his head: rest the palms of your hands on the loins (on the muscles of the small of the back), with fingers spread over the lowest ribs, as in Fig. 1.

(*c*) With arms held straight swing forward slowly so that the weight of your body is gradually but not violently brought to bear upon the subject, see Fig. 2. This act should take from two to three seconds. Immediately swing backward so as to remove the pressure, thus returning to the position shown in Fig. 1.

* Report of Commission on Resuscitation from Electric Shock issued by National Electric Light Association.

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(*d*) Repeat deliberately twelve to fifteen times a minute the swinging forward and back — a complete respiration in four or five seconds.

(*e*) As soon as this artificial respiration has been started, and while it is being

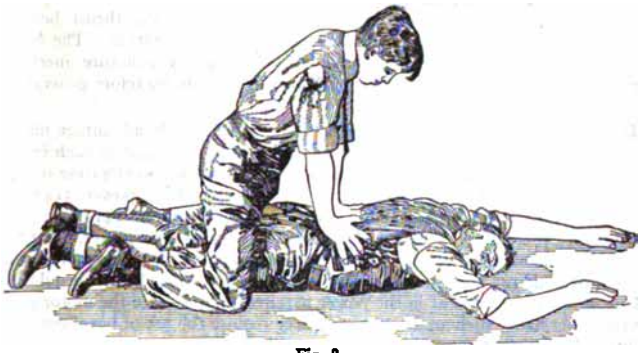


Fig. 2.

continued, an assistant should loosen any tight clothing about the subject's neck, chest or waist.

(*f*) *Continue the artificial respiration, if necessary at least an hour, without interruption,* until natural breathing is restored, or until a physician arrives. If natural breathing stops after being restored, use artificial respiration again.

(*g*) Do not give any liquid by mouth until the subject is fully conscious.

Other Methods of Inducing Respiration are: (1) withdraw the tongue and allow it to recede periodically, the whole manipulation occurring about fifteen times in a minute; (2) dash cold water upon the face; (3) rub spine with ice; (4) massage chest in region of heart; and (5) administer oxygen gas (obtained at drug stores) by placing cone over mouth and nose.

After Treatment. — After the victim breathes again, treatment may be administered as outlined above in the case of a slight shock. If any bones have been fractured or if the victim appears to have received internal injuries, do not move the victim any more than is necessary and prepare for removal to the nearest hospital.

Treatment of Burns and Blisters. — If the victim has received burns, raw or blistered surfaces should be protected from the air. Blisters should not be opened. Cut around any clothing that sticks and saturate the adhering cloth or cotton dressing with picric acid (0.5 per cent) or a solution of baking soda (one teaspoonful to a pint of water). Wounds may be coated with a paste of flour and water or may be protected with machine, transformer, linseed or olive oil or vaseline. The dressing should be covered with cotton, gauze, lint, clean waste or clean handkerchiefs held tightly in place by bandages. Oil should not be applied to dry charred burns, a light, dry bandage being preferable.

Indication of Death. — Efforts to revive the victim should not cease until death is indicated by the following appearances:* "complete cessation of breathing and heart action, eyelids half-closed and pupils dilated, jaws clenched, tongue appearing between teeth with frothy mucus about mouth and nostrils, fingers semi-contracted with increasing coldness and pallor of surface."

* J. A. Austin, M.D., *Manual of First Aid.*

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SHOVELS, ELECTRICAL OPERATION OF. — (*See also Cranes; Motors, Industrial Applications of.*) The operating cycle of an electrically-operated shovel is about 20 seconds, the component times being: hoist 8 to 10 seconds, thrust 10 seconds and swing 10 to 12 seconds, the thrust being in operation at the same time as the hoist and swing are operating. The motors to meet these requirements must have a sufficiently low armature inertia to permit of rapid acceleration under small power, and are therefore generally of the crane or mill-type construction.

Hoist Motors. — In the case of the hoist, considerable advantage may be gained in this respect by using two motors of one-half the capacity each instead of one motor of the full capacity, as the power required for accelerating is much less. For example: Assume a shovel that requires a 225-horse-power, 514 r.p.m. motor for the hoisting operation. Such a motor requires 144 horse-power seconds for bringing up to full speed, whereas if two 115-horse-power, 600 r.p.m. motors are substituted in its place, each motor requiring 63.5 horse-power seconds or both 127 horse-power seconds to bring up to speed, there would be a saving of about 12 per cent in the power required to accelerate the motor alone. On the other hand, such an arrangement may require the use of bevel gears and additional shafting.

Swing Motor. — This motor, although not subject to the severe overloads and shocks encountered on the hoist motors, is subject to frequent reversals, and, as rapid acceleration is required, a motor of similar design as for the hoist should be used.

Thrust Motor. — This motor differs somewhat in its operation in that it is practically stalled during the digging operation, although it may revolve or overhaul according to conditions, and is operated at full speed only after the hoist operation is completed. Its duty is to keep the dipper against the bank, and it must therefore stand still and exert torque most of the time. For this reason its design should be very rugged, and the motor should be able to develop a heavy torque for short intervals of time while standing still, or rotating very slowly.

Location of Motors. — The hoist and swinging motors are as a rule located on the car and are geared to the drums through suitable reducing gears, while the thrust motor as a rule is mounted directly on the boom and communicates its motion to the bucket staff through reducing gears connected to a pinion engaging a rack on the staff.

Type and Size of Motors. — It is possible to obtain successful operation with a-c. induction motors but it can only be done at the expense of larger capacities and increased power consumption, owing to the characteristic of the motor, which radically differs from that of the steam engine ordinarily used on shovels and from the d-c. series motor.

A careful analysis of the typical steam-shovel engine reveals a characteristics which is not unlike that of the series direct-current motor in that it speeds up under light loads, slows down under heavy loads and possesses a certain elasticity in operation which minimizes mechanical strains on the shovel. Because of these facts it is not only desirable but advisable to adhere to the direct current series motor on the electric shovel. Practically all large power supplies are alternating current, but the smaller capacities in d-c. series motors permit the use of a synchronous motor generator set mounted on the shovel at practically the same cost as the a-c. induction motors with transformers, with the advantages in operating characteristics and power consumption all favorable to the direct-current equipment.

The most recent development in electric shovels has been in connection

ith large strippers, which are now being built with differential wound generaors and shunt-field control.

The approximate size of motors required for the various operations of a number of different size shovels may be obtained from the following table.

Weight of shovel in tons	Size of dipper in cubic yards	Average cycles of operation per minute	Horsepower of motors			Kw.-hr. per shift
			Hoist	Swing	Crowd	
135	6	2	210	46	40	890
120	5	2	210	46	40	790
105	4	2	150	46	40	725
95	3¼	2¼	150	37	30	580
80	2½	2½	86	27.5	30	482
65	2	2¾	86	27.5	20	381
45	1½	3	55	15	13	292
25	¾	3½	55	9	9	193

Control Equipment. — The magnetic contactor control is preferable for all he motors on the shovel. (*See Controllers.*) The hoist and thrust motors are hen provided with a notching-back arrangement which will automatically cut esistance into the circuit when the current exceeds a certain limiting value due to he motors becoming stalled by digging too deep or striking rocks or other bstructions, thus protecting the motors from damage. Sometimes the hoist nd swing motors are provided with automatic magnet control while the thrust otor is hand controlled, an ordinary drum controller being provided for this otor.

Brakes for the different shovel motions are generally of the air-brake type, a nall air compressor being provided on the shovel for this purpose.

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SHUNTS. — (*See also Ammeters; Galvanometers; Voltmeters; Wattmeters*) When heavy currents are to be measured it is impracticable in many cases to pass the entire current through the coils of the instrument proper. In such cases it is necessary therefore to pass the bulk of the current through a parallel circuit or shunt and measure only a known fraction of the total current.

CONSTRUCTION. — For laboratory work standard resistance units (*see Resistors, Standard*) are commonly employed as shunts when a high degree of precision is required. Special forms of resistance boxes, usually called shunt boxes, are also used. For switchboard work shunts made of sheets of manganin or other high-resistance metal of low temperature coefficient (*see Wires, Resistance*) are usually employed. Several sheets of metal are used in order to provide a large radiating surface. These sheets are brazed into heavy copper terminals for clamping to the bus-bars or other heavy conductors; heavy terminals are necessary to insure a uniform distribution of current in the sheets. The contact surfaces must be kept bright and the bolts tight.

THEORY OF SHUNTS. — Fig. 1 shows diagrammatically a simple shunt such as used with an ammeter or galvanometer. The galvanometer (or ammeter) current is

$$I_G = \frac{S}{G+S} \cdot I_B,$$

where G and S are the resistances of galvanometer and shunt respectively and I_B is the total current from the battery or other source.

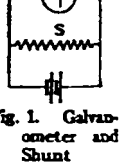


Fig. 1. Galvanometer and Shunt

For example, if the galvanometer has a resistance of 9900 ohms and the shunt a resistance of 100 ohms, the galvanometer current will be $\frac{1}{100}$ of the battery current. Shunt boxes made on this principle are usually provided with resistance coils giving a ratio of currents of $\frac{1}{10}$, $\frac{1}{100}$ and $\frac{1}{1000}$ when used with a galvanometer having a given resistance. The corresponding readings of the ammeter or galvanometer, multiplied by 10, 100, 1000, or 10,000 will then give the current in the battery circuit.

"Universal" Galvanometer Shunts. — Simple shunts such as above described give even ratios of currents only when used with a galvanometer of a certain definite resistance. A set of coils arranged as shown in Fig. 2, when used as described below, will give even ratios when used with a galvanometer of any resistance. A shunt of this kind is known as a universal shunt. The Ayrton and Mather shunt is arranged on this principle.

A study of the circuits will show that if the galvanometer is calibrated (*see Galvanometers*) with the terminal a at b, that is, with all the resistance R in parallel with the galvanometer, the same calibration may be used for a connected to any other terminal x, provided the current values from the calibration curve are multiplied by the ratio R/r_x, where r_x is the resistance in the box between that terminal and A. The various resistances are usually arranged so that these ratios or "multiplying powers" of 10, 100, 1000, and 10,000 may be obtained. The galvanometer should have a relatively low resistance compared with the total resistance of the shunt.

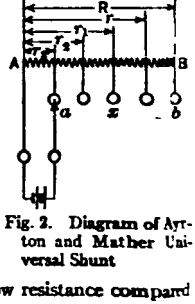


Fig. 2. Diagram of Ayrton and Mather Universal Shunt

Effect of Temperature Changes. — The resistivity temperature coefficient of a shunt made of manganin is very much lower than the temperature coefficient of the copper circuit of the ammeter or galvanometer. Consequently changes

ature will produce a change in the relative resistances of the shunt
ter or galvanometer, thus changing the multiplying power. For
easurements a correction should therefore be made in the nominal
g power of the shunt. With a universal shunt and a relatively low-
galvanometer the effect of temperature changes is less marked, since
nces r_x and R are both in the same box and are usually made of man-
her metal having a low temperature coefficient.

(**Pre-war prices**).—A 4-value laboratory shunt box for use with an
lvanometer and giving multiplying ratios of 10, 100, 1000 and 10,000
t $20. Switchboard shunts cost from $3 to $90 depending upon
nt-carrying capacity, the lower figure applying to a 10-ampere shunt
gher figure to a 10,000-ampere shunt.

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SIGNALING, RAILWAY. — Railway signaling is the art of conveying information to the person or persons in immediate charge of the movement of a train. The means for conveying the information are various, including simple movements of the hands and arms, positions or combinations of positions of semaphore arms by day, or colored lights by night, positions or combinations of positions of rows of lights visible both day and night, and colored lights or combinations of colored lights visible both day and night.

CARDINAL PRINCIPLE OF RAILWAY SIGNALING. — The cardinal principle of design of all signal circuits, apparatus and systems, is that any failure of any part, such as breaks, open or short circuits, grounds, etc., if having any effect on the signal whatever, shall result in a stop indication.

CLASSIFICATION OF SIGNALING SYSTEMS. — The two main divisions of railway signaling are block signaling and interlocking signaling. The former has to do with keeping trains which are running on the same track properly spaced. The latter has to do with the handling of trains over tracks which intersect at points of crossing or divergence, and has for its object the prevention of conflicting movements, the proper routing of trains, and the insurance that the movable parts of the track are in their right positions before the signals governing movement over them can be made to give a proceed indication.

Block signals may be divided into two main classes: non-automatic and automatic. In the United States there are 76,466 miles of track protected by the former as against 60,992 miles of track protected by the latter. Of the non-automatic blocks, those on 72,952 miles of track are operated by telegraph or telephone.*

NON-AUTOMATIC BLOCK SIGNALING. — Systems in this class are of two kinds, non-controlled and controlled.

Non-controlled Manually Operated System. — The manually-operated signals used in connection with the telephone or telegraph blocks are located at passenger stations, junctions or other convenient points where operators are available. They are put in the proceed position to permit a train to enter the next block provided information has been received by the operator from the next station in the direction of traffic that the preceding train has passed out of the block. They are placed in the stop position on the passage of the train.

The operators have blanks on which they enter the designation numbers of each train they admit to a block, together with the time of entrance. On the same sheet is checked off the departure of the train from the block as advised by the operator at the leaving end of the block. The train despatcher, located at some central point, is also kept informed of all train movements, so that in case the schedule is deranged for any cause he can give the necessary orders to expedite traffic, such as changing orders for passing points and giving superior rights to certain trains.

Defects of Non-controlled Manually Operated System. — The defects of the system are obvious, as misunderstandings may arise between operators, trains may be checked off by mistake as having left a block when such is not the case, or trains may part and the fact not be noted by the block operator because of his failing to note the absence of the tail lights carried by the rear car of a train when the first division passes his station.

Controlled Manually Operated System. — These defects are partially overcome by the use of controlled manual block signals. In such systems electric locks are applied to the levers operating the manual signals. The locks are included in circuits running between block stations, and so arranged that when an operator wishes to place a signal in the proceed position he has

* From tables compiled by the Interstate Commerce Commission, January 1, 1910.

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first to ask (by bell signal or otherwise) for an unlock from the next station in the direction of traffic, and coöperate with the operator at that station in the proper manipulation of the circuits to get his unlock. A further check on the operators is sometimes obtained by the use of track circuits at the stations to effect a certain degree of control of the apparatus locking the signal levers by the passage of the trains themselves. These systems, however, are all inferior, in the degree of protection given, to the automatic blocks with signals controlled by continuous track circuits, which are described below.

Staff System. — Another form of controlled manual block signal is the staff system in which the possession of a small metal cylinder, or "staff," gives the engineer permission to run through a block. These staffs are normally in one or the other of a pair of instruments called staff instruments, one of a pair being at each end of a block. Only one staff can be taken from a pair of instruments at a time because of their locking features, controlled by circuits between the instruments, requiring the coöperation of two people, one at each instrument, to abstract a staff. Until this staff is replaced in one or the other instrument, no other staff can be withdrawn. Following movements with more than one train in the block can be accomplished by using a divisible staff, made in several sections which must be screwed together in a specified order to permit the insertion of the staff in an instrument when the last train has brought the remainder of the staff through the block.

There is also an automatic staff system in which the coöperation of the second person is not required.

There are about 511 miles of track equipped with the staff system in the United States.*

AUTOMATIC BLOCK SIGNALING. — This subject will be treated under three main headings, in the order stated: Track Circuit, Signals and Their Mechanisms, and Location of Block Signals.

TRACK CIRCUIT FOR AUTOMATIC BLOCK SIGNALS. — The standard means of control of automatic block signals is the track circuit. It is the safest means known because the control is continuous and reliable.

Steam-road Track Circuit (Fig. 1). — The figure shows the elements of a steam-road track circuit. They are a source of electrical energy, means for limiting the flow of current from the source, a section of the rails of a track

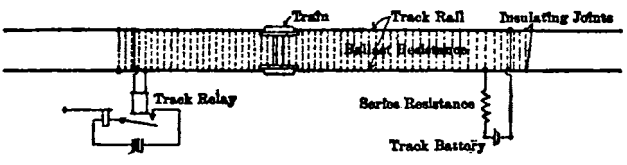


Fig. 1. Elements of a Steam-road Track Circuit

insulated by special rail joints from adjoining rails, the leakage path constituted by the ties and ballast, and an electromagnetic type of relay. The contacts of the relay open and close the circuit which effects the operation of the signal. When there is no train on the track circuit, the contacts of the relay are closed due to the energizing of the relay by current flowing over the rails, which act as conductors from the source of electrical energy. The signal is made to indicate the absence of a train on the track circuit under these conditions. The

* From tables compiled by the Interstate Commerce Commission, January 1, 1920.

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presence of a train on the track circuit, or any other cause depriving the relay of energy, causes the relay to open its contacts, which results in the signal taking the stop position. The use of means for limiting the flow of current is to prevent exceeding the capacity of the source when a train shunts the rails, and at the same time to cause such drop of potential across the rails as will insure the opening of the relay.

Electric-road Track Circuit. — The track circuit for a road using electric propulsion, if a direct-current track relay is used, must, in order to avoid false clear signals, have the voltage point at which the relay closes its contacts higher than any voltage which may exist across its terminals, with a train on the track circuit, due to the flow of the propulsion current through the rails. Standard practice, to avoid the possibility of such false closing of the relay contacts, is the use of an alternating-current relay which is not operative to close its contacts under the influence of the propulsion current.

Single-rail Track Circuit (Fig. 2). — Fig. 2 shows an arrangement for d-c. propulsion roads where only one rail is used as the main return for the

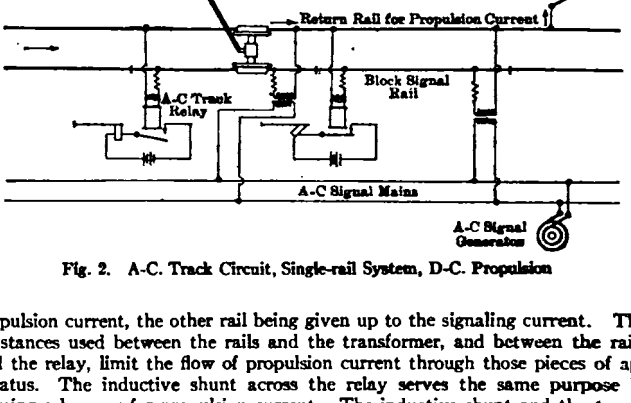


Fig. 2. A-C. Track Circuit, Single-rail System, D-C. Propulsion

propulsion current, the other rail being given up to the signaling current. The resistances used between the rails and the transformer, and between the rails and the relay, limit the flow of propulsion current through those pieces of apparatus. The inductive shunt across the relay serves the same purpose in forming a by-pass for propulsion current. The inductive shunt and the transformer supplying the track circuit have cores with open magnetic circuits to minimize the magnetizing effects of such direct current as may flow through their windings. An arrangement like the above is limited in practical use to those situations where the drop in voltage due to the propulsion current, along the length of continuous rail opposite any section of block rail, is under 50 volts. It finds its greatest application in subway and terminal or interlocking work. Where the number of tracks and shortness of track circuits bring the maximum voltage across the terminals of the relay, due to propulsion current, down to about 5 volts, a relay may be used with resistance enough in its winding to render unnecessary the use of the inductive shunt and resistance between it and the rails.

With a signaling current of higher frequency than the propulsion current and a selective relay, the single-rail track circuit is applicable to a-c. propulsion roads.

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Double-rail Track Circuit (Fig. 3). — Where the conductivity of the return propulsion circuit is not sufficient to permit giving up one rail to the signaling current, the arrangement shown in Fig. 3 is used. Both rails are sectioned by insulating joints and the return propulsion current is carried around the insulating joints by means of impedance bonds (i.e., coils having a high inductance and low resistance) which are joined electrically at the middle points of their windings. The flow of the propulsion current is opposed

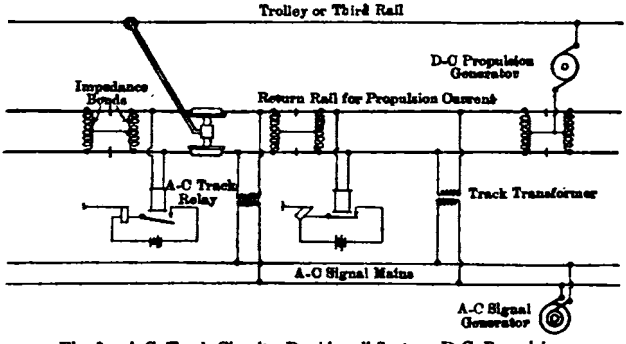


Fig. 3. A-C. Track Circuits, Double-rail System, D-C. Propulsion

only by the ohmic resistance of the bonds and their connections. The full impedance is, however, offered to the flow of the alternating signaling current from rail to rail, and it is, therefore, possible to maintain a difference in potential across the rails sufficient to operate the track relay.

Where the propulsion current is alternating, a higher frequency is used for the track circuit and the relay made correspondingly selective. 25-cycle current is ordinarily used for the signals on direct-current propulsion roads and 60-cycle current on alternating-current propulsion roads.

Source of Energy for Track Circuit. — The source of electrical energy for supplying the track circuit is generally in steam-road practice a primary battery of the caustic potash type with an external resistance. Generally three cells are used in multiple, but where the leakage between rails is high, larger numbers are used in series-multiple combinations. The storage battery is used to a limited extent and is especially advantageous on two- or four-track systems where the number of track circuits and amount of apparatus per unit distance is relatively large.

Use of Alternating Current. — Alternating current is rapdily coming into use for signaling on steam roads. Where alternating current is used for track circuits, it is almost universally used to operate the signals and supply the lamps for the night indications. 25- or 60-cycle current is used, the former generally resulting in slightly lower power consumption and being generally favored where the current has to be generated for the signalling system alone and no commercial emergency sources are available. Where such commercial emergency sources *are* available, as is generally the case in thickly-settled districts, the frequency of such sources being ordinarily 60 cycles, that frequency is often chosen for the signaling system.

Transformers for Track Circuits. — The source of alternating current for each block is either a low-voltage (5 to 20 volts) secondary of a transformer whose primary is connected to the transmission line, or a similar secondary

of a small special air-cooled transformer with a 110-volt primary. In the latter case the special transformer may be housed with other signal apparatus and its primary supplied from the 110-volt wires brought from the commercial transformer, whose primary is connected to the transmission line. The same 110-volt wires may be used also to supply the motors, line relays and "hold clear" devices, and carbon lamps used for lighting the signals. If Tungsten lamps are used, they may be supplied from suitable taps on the 110-volt primary of the special transformer or from taps on the low-voltage track secondaries.

Track circuits are generally supplied with current at about one-half the voltage of the source, due to the drop over the intermediate impedance.

Location of Energy Supply. — The source of energy (battery or transformer) is usually placed at the end of the block. If, however, the block is long and impedance bonds are used, resulting in large leakage from one rail to the other, the source of energy for the track circuit is sometimes placed at the center, and the control wires for the signal carried through the contacts of the two track relays, one being located at each end of the track circuit. Under these conditions, because of the voltage drop of the signaling current in the rails, there is only a limited distance extending either side of the point of supply in which a train will shunt both track relays simultaneously. This is taken advantage of in some systems of signaling, an example being given in Fig. 7.

D-C. Track Relay. — The direct-current track relay most commonly used on steam roads has two or four contacts closed when energized, and has a resistance of four ohms. The working voltage across its terminals is generally 0.4 or 0.5 volt under good weather conditions, but may be as low as 0.35 volt during wet weather.

A-C. Track Relay. — There are two types of a-c. track relays called, respectively, "single-energizing-circuit type" and "two-energizing circuit type," according to whether they take all of the energy to operate them from the track, or part from the track and part from a local source. These types are built on either one or both of two distinct principles: (1) on the principle of the electrodynamometer (q.v.) and (2) on the principle of the induction motor; (see *Motors, Polyphase Induction* and *Watthour Meters*).

The induction-motor type has the advantage over the electrodynamometer type, in that, its angular motion being unrestricted, a given pressure at the contact points can be produced with a less expenditure of energy. There is a limitation to this, however, due to the friction of the reduction gearing, which must not be so great that it cannot be overcome by the counterweight provided to open the contacts when the relay is deënergized.

With all types of railway signal relays, the addition of "back" contacts to be closed when the relay is deënergized, means the expenditure of more energy to satisfactorily close the "front" contacts, because of the extra counterweighting necessary to develop the necessary pressure on the back contacts.

Single-energizing-circuit Type of Track Relay. — Relays of this type are made on the induction motor principle in order to make them selective between the signal and propulsion currents. The following forms of construction are typical:

(1) Segment of sheet aluminum set in motion by the shifting magnetic field due to the "shaded" pole pieces of a laminated "C"-shaped core which carries the winding. This form is very largely used on short track circuits on d-c. propulsion roads.

(2) Double segment of sheet aluminum acted upon differentially on either side of its axis by the two sets of "shaded" poles of a double "C"-shaped

core is so designed that one or the other set of poles is stronger, on the respective amounts of propulsion or signaling current traversing winding. This form is used on a-c. propulsion roads, being made between 25 and 60 cycles, the latter frequency being used for the current.

rifuge driven by split-phase induction motor. This form is used ulsion roads. It is selective by virtue of the centrifuge being designed e the contacts when driven at a speed corresponding to the lower f the propulsion current.

-phase induction motor with gearing or link connection from rotor ntact supporting member.

ower figures at the working points are as follows:

equency	Volt-amperes	Volts *	Power factor	Number of contacts closed when energized
25	5.0	3.0	0.55	4
60	8.5	5.0	0.55	4
60	20.0	3.1	0.55	2
60	6.0	2.3	0.70	10
25 / 60	10.0	5.0	0.70	6

* Track windings of relays.

-energizing-circuit Type of Track Relay. — The following onstruction are typical: (1) Electrodynamometer; used on d-c. roads and to some extent on steam roads. (2) Induction motor g; the rotor is a cylindrical shell of copper or aluminum with a laminated core; used on d-c. propulsion roads and very largely on s. (3) Centrifuge driven by induction motor; used on a-c. proads; see also preceding section.

l windings of all two-energizing-circuit relays are generally sup- m 10 to 110 volts. The objection to the higher voltage is the small and consequently greater liability to damage by lightning.

wing typical power figures are for "two-position" relays, i.e., relays

re-ency	Track			Local		Number of contacts closed when energized
	Volt-amperes	Power factor	Volts	Volt-amperes	Power factor	
25	0.70	0.90	0.35	36	0.70	4
60	1.60	0.80	1.60	33	0.34	4
25	0.038	0.65	0.15	2.4	0.70	10
60	0.024	0.65	0.15	11.0	0.70	10
60	1.30	0.55	0.3	20	0.95	6
25	0.13	0.80	0.35	45	0.35	6
60	0.16	1.00	0.4	44	0.25	6

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with one energized and one deënergized position. Relays which are caused to assume two energized positions by reversals of the current in one of the windings are termed "three-position" relays and generally require twice as much power in one of the windings as two-position relays.

The adjustment of the phase relations of the currents in two-energizing-circuit relays has to be carefully cared-for in the choice of the impedance used between transformers and rails, and between local windings and the source of energy supply.

Single- Versus Two-circuit Types. — As a track circuit is, from an engineering point of view, nothing but a very inefficient transmission circuit,* track circuits above a certain length can be worked most economically with a two-energizing-circuit type of relay, as the amount of energy transmitted over the rails can be reduced to a certain point by increasing the amount of energy supplied economically to the second winding from a local source. For track circuits below a certain length, however, the energy supplied to the track circuit for the single-energizing-circuit type of relay is less than the total supplied to the track circuit and the local winding of the two-energizing-circuit type.

The above consideration, taken in conjunction with the fact that a relay with one energizing circuit usually is cheaper than one with two energizing circuits, and does not require the installation of a source of energy supply for a local winding, generally points to the choice of the single-energizing-circuit type for track circuits less than 1500 feet in length. On the other hand, as the single-energizing-circuit type of relay may be falsely energized by current from an adjacent track circuit, due to broken-down insulating joints, it does not give the same degree of protection against this failure as the two-energizing-circuit type, with the source of current supply to adjacent track circuits of opposite instantaneous polarity.

Impedance Bonds. — Impedance bonds are wound with strap copper varying from 57,000 cir. mils for 22,000-volt, 25-cycle propulsion to 220,000 cir. mils for ordinary d-c. 600-volt interurban work, and 800,000 cir. mils for heavy 600-volt d-c. traction work. The corresponding resistances across rails are respectively about 0.014, 0.0014 and 0.00045 ohm. The respective continuous propulsion current per rail ratings are 50, 500 and 1500 amperes. Typical impedance values from rail to rail are respectively 10 ohms at 2 volts and 60 ohms at 9.2 volts, 60 cycles; and 0.3 ohm at 1.5 volts, and 0.18 ohm at 15 volts, 25 cycles.

Though the resistance of the connection around an insulating joint formed by an impedance bond may be relatively high as compared with the resistance of the ordinary rail joint bond, the small number of impedance bonds in a system compared to the number of rail joint bonds results in but a very slight percentage increase in the total resistance of the return propulsion circuits.

The impedance bonds for direct-current propulsion roads are provided with an air gap in the magnetic circuit to limit the change in impedance due to un-

* The inefficiency of the track circuit as a transmission line is due to the drop through the current limiting means between the source of energy and the rails (and in the single-rail system between the relay and the rails), the high reactive drop in the rails, the distributed leakage of ballast and ties, and, in the two-rail system, the concentrated leakage through the impedance bonds. The voltage at which the track winding of a relay is designed to operate is selected first, to obtain safe and reliable operation, and second, to obtain as high a degree of efficiency of the track circuit as is permitted by the characteristics of the track circuit. This generally results, with relays taking a comparatively large amount of energy from the track, in higher voltages for track windings of relays used on steam roads than for those used on electric roads, though the total energy put into the track circuit is less in the former than in the latter case.

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EDANCE OF BONDED RAILS TO SIGNAL CURRENTS

Ohms per 1000 feet of track

Bonding*	27.5-ft. rails				30-ft. rails				33-ft. rails			
	25~		60~		25~		60~		25~		60~	
	z	P.F.	z	P.F.	z	P.F.	z	P.F.	z	P.F.	z	P.F.
capacity	0.10	0.40	0.25	0.40	0.10	0.40	0.25	0.40	0.10	0.40	0.25	0.40
o. 6 copper	0.13	0.72	0.28	0.56	0.13	0.70	0.28	0.56	0.13	0.69	0.27	0.54
o. 8 iron o. 6 copper	0.17	0.83	0.30	0.65	0.16	0.82	0.30	0.63	0.15	0.79	0.29	0.62
o. 6 c.c. — 40%	0.19	0.87	0.32	0.69	0.19	0.86	0.32	0.69	0.17	0.84	0.31	0.68
o. 6 c.c. — 30%	0.25	0.91	0.36	0.75	0.22	0.91	0.35	0.74	0.20	0.88	0.34	0.73
o. 8 iron	0.40	0.97	0.50	0.88	0.36	0.96	0.47	0.87	0.34	0.96	0.44	0.85
capacity	0.10	0.43	0.26	0.43	0.10	0.43	0.26	0.43	0.10	0.43	0.26	0.43
o. 6 copper	0.14	0.73	0.29	0.58	0.13	0.72	0.28	0.58	0.13	0.70	0.27	0.54
o. 8 iron o. 6 copper	0.17	0.83	0.31	0.67	0.16	0.82	0.31	0.64	0.16	0.80	0.29	0.62
o. 6 c.c. — 40%	0.19	0.87	0.33	0.71	0.19	0.87	0.33	0.70	0.17	0.84	0.31	0.68
o. 6 c.c. — 30%	0.23	0.91	0.36	0.76	0.26	0.91	0.36	0.76	0.20	0.89	0.34	0.73
o. 8 iron	0.40	0.97	0.51	0.89	0.37	0.97	0.48	0.88	0.35	0.96	0.45	0.86
capacity	0.10	0.46	0.26	0.46	0.10	0.46	0.26	0.46	0.10	0.46	0.26	0.46
o. 6 copper	0.14	0.74	0.29	0.60	0.13	0.73	0.29	0.59	0.13	0.71	0.28	0.58
o. 8 iron o. 6 copper	0.17	0.84	0.32	0.68	0.17	0.83	0.31	0.67	0.16	0.81	0.30	0.65
o. 6 c.c. — 40%	0.19	0.88	0.33	0.72	0.19	0.87	0.33	0.69	0.18	0.85	0.32	0.70
o. 6 c.c. — 30%	0.23	0.91	0.37	0.77	0.23	0.91	0.36	0.77	0.21	0.89	0.35	0.76
o. 8 iron	0.41	0.97	0.52	0.89	0.37	0.97	0.49	0.88	0.35	0.96	0.46	0.84
capacity	0.11	0.48	0.26	0.48	0.10	0.48	0.26	0.48	0.11	0.48	0.26	0.48
o. 6 copper	0.14	0.75	0.29	0.62	0.14	0.73	0.29	0.60	0.13	0.72	0.29	0.60
o. 8 iron o. 6 copper	0.17	0.81	0.32	0.69	0.17	0.81	0.31	0.68	0.16	0.82	0.31	0.67
o. 6 c.c. — 40%	0.20	0.88	0.34	0.73	0.20	0.88	0.34	0.73	0.18	0.85	0.33	0.71
o. 6 c.c. — 30%	0.23	0.91	0.38	0.78	0.23	0.91	0.27?	0.78	0.21	0.89	0.36	0.76
o. 8 iron	0.41	0.97	0.53	0.89	0.37	0.97	0.49	0.88	0.35	0.96	0.47	0.87
capacity	0.11	0.52	0.27	0.52	0.11	0.52	0.27	0.52	0.11	0.52	0.27	0.52
o. 6 copper	0.15	0.77	0.30	0.65	0.14	0.76	0.30	0.65	0.14	0.75	0.30	0.64
o. 8 iron o. 6 copper	0.18	0.86	0.33	0.72	0.17	0.85	0.33	0.71	0.17	0.82	0.32	0.70
o. 6 c.c. — 40%	0.20	0.89	0.36	0.75	0.20	0.89	0.35	0.75	0.18	0.86	0.34	0.74
o. 6 c.c. — 30%	0.24	0.92	0.39	0.80	0.24	0.92	0.38	0.81	0.22	0.90	0.37	0.78
o. 8 iron	0.42	0.97	0.54	0.90	0.38	0.97	0.51	0.89	0.36	0.96	0.48	0.87

* c.c. = copper clad.

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RESISTANCE OF BONDS TO SIGNAL CURRENTS

Ohms per 1000 feet of track

Bond wires per joint	27.5-ft. rails	30-ft. rails	33-ft. rails	
2 No. 6 copper	0.057	0.052	0.048	Bond wires 48 in. long. No allowance is made for conductance of the splice bars.
1 No. 6 copper and 1 No. 8 iron	0.098	0.089	0.082	
2 No. 6 copper clad—40%	0.124	0.112	0.103	
2 No. 6 copper clad—30%	0.166	0.150	0.138	
2 No. 8 iron	0.348	0.315	0.291	

equal amounts of propulsion current flowing in the two halves of the winding. Good practice is to provide for satisfactory operation with a maximum difference equal to 20 per cent of twice the rated capacity per rail, e.g., a 1500-ampere per rail bond should operate satisfactorily with a difference of 600 amperes between the currents in the two rails.

Impedance of Track Circuits. — The table on page 1415 gives the impedance per 1000 feet of track under various conditions of bonding in common practice and for the values of current commonly used for the energization of the track elements of relays. Where propulsion current is flowing in the rails, the power factor corresponding to the value of the propulsion current should be used to determine the most adverse conditions of drop of potential of signaling current between the point of supply to the track circuit and the relay.

Resistance of Leakage Path. — The resistance of the leakage path between rails in ohms per thousand feet of track varies with the nature of the ballast, the condition of the ties and the weather conditions. Two ohms per thousand feet is a low wet weather value for track with gravel ballast.

In connection with the calculations involving the values of rail impedance given in the table on p. 1415 the following values for resistance of ballast and ties between rails may be used. They are given for ballast clear of the rails.

	Ohms per 1000 feet of track
Wet gravel	3
Dry gravel	6
Wet broken stone	6
Dry broken stone	16

Transmission-Line Voltages. — Transmission-line (between generator and signal transformers) voltages in standard practice vary from 1100 to 4400 volts inclusive, though in some special cases of subway and elevated road work, or where the mains are carried on existing telegraph poles, they may be lower.

SIGNALS AND THEIR MECHANISMS. — Signal indications for block and interlocking work are given in standard railroad practice by semaphores. The semaphore consists of a wood, or enameled steel, blade or arm, fastened at its inner end to a "spectacle." The spectacle is a casting, or combination casting and metal stamping, embodying the hub for the shaft on which the semaphore rotates, and the colored glass roundels which change position before a lamp fitted with a clear lens, to give the night indications corresponding with the positions of the semaphore. The lamp is provided with a long-time oil burner (usually seven days) or incandescent bulbs.

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Weight and Torque of Semaphores. — The weight of the semaphore is

distributed to give a maximum torque (tending to return the semaphore to the stop position) varying with different types of operating mechanisms from about 30 to 100 pound-feet. As the torque curve is necessarily a sine curve, a spectacle moving through 90° is generally designed to have maximum torque at about 55°.

Spectacles operated manually, which can be pulled to the stop position, may be lighter than those which, in returning to the stop position, have to return parts of the mechanism which cause them to assume the proceed position.

In automatic signals gravity is depended on almost universally to return the signal to stop.

Semaphore Positions and Colors of Lights. — The three fundamental signal indications are:

1. Stop,* 2. Proceed with caution, 3. Proceed. The standard method of giving these indications is in the upper right-hand quadrant as indicated in Fig. 4, the respective positions of the semaphore arm being respectively at 0°, 45°, and 90°. The corresponding colors of the night lights differ with different

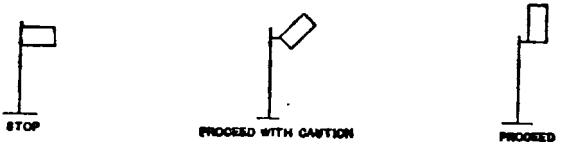


Fig. 4. Standard Semaphore Positions

roads; a common practice is to use red for stop, green for proceed with caution and white for proceed, but on account of the danger of a white light being falsely displayed because of the breakage of the colored roundels it is considered best practice to use red, yellow and green, for the respective indications enumerated above.

It is also good (but less up to date) practice to give these indications in the lower right-hand quadrant, the horizontal position of the semaphore arm always indicating stop. Where the view to the right of the signal mast is obscured, as by the poles along a trolley road, or where clearances are small, due to high walls close to the right-of-way, as through a city, the semaphore is sometimes operated in the upper left-hand quadrant.

Two-position semaphores, indicating stop and proceed only, are also largely used, the proceed indication generally being given at from 60° to 90° depending on the individual road.

Power Mechanisms. — Power signals are operated by "bottom" or "top post" mechanisms. Electricity, compressed air and gas are used as motive power. Of the track mileage protected by automatic semaphores approximately 90 per cent has electrically-operated mechanisms. Compressed gas and air for automatic blocks are limited in use to very few roads, though these include some of the most important ones. The gas is supplied in tanks. The air is distributed in pipe mains.

Electrically-operated Bottom-post Mechanism. — Electric bottom-post mechanisms generally consist of a motor which, by gearing and levers, transmits the movement necessary to clear the semaphore through a vertical rod extending inside the mast between the mechanism and a crank arm on the

* An automatic signal in the "stop" position may be passed "according to rule" after bringing train to stop. An interlocking signal in the "stop" position may be passed only after bringing train to stop and receiving authority to pass the stop signal from an authorized person.

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hore shaft. The type most generally used has interposed in the move transmission system, as near the connection to the vertical rod as possible, ctric latching device called a *slot*. The operation of the semaphore to, naintenance in, a proceed position depends on this latch being energize motor cutting out automatically after performing its work. The location *slot* in the movement system close to the vertical rod reduces to a minimum mber of parts moved by the return of the semaphore to the stop positi the influence of gravity, and, consequently, reduces the possibility of gnal sticking in the proceed position due to the development of any fri-

e control of the circuit supplying the motor and slot is effected by the cts of the track relay.

Electrically-operated Top-post Mechanism. — In top post mecha the motor acts directly on the semaphore shaft through a train of gears emaphore in its return to the stop position has to drive the gear train and ly the motor. The ratio of gearing in top-post mechanisms is made comparively low (about 120 : 1) to diminish friction when going to the stop position. he motors are consequently very slow speed. The latching of the sema in the clear position is accomplished by electromechanical means or by etic induction. The latter method obviates the danger of the signal ng in the proceed position due to the adhesion of contacting surfaces in tching device.

Power Required for Electrically-operated Signal Mechanisms. — motors and latching devices are generally supplied with current from local ry or storage batteries at from 8 to 10 volts. With a maximum semaphore e of between 30 to 50 pound-feet and clearing 90° in about 10 seconds, the s will consume between 2 and 2½ amperes. The latching device con- from 0.008 amperes to 0.02 amperes, depending on the voltage and ng resistance.

der the same conditions as given for d-c. motors, a-c. commutator motors onsume slightly less than 1 ampere at 110 volts at about 0.8 power factor. nduction motors will consume between 2.8 and 3.5 amperes at the same ge but at about 0.5 power factor.

e electric latching device consumes approximately from 5 to 10 watts in c. mechanisms, the power factor varying widely with the design.

Pneumatically-operated Signal Mechanisms. — The pneumatic mech is the simplest of those used for operating signals, consisting of merely a by 4-inch cylinder with a metal-packed brass piston, a magnet valve ntrolling the admission of air and suitable mechanical connections to the hore shaft. The electromagnet valve controlling the admission of air d as the "slot," as its deënergization shuts off the air and exhausts the der to atmosphere. The pneumatic mechanisms are readily adaptable ttom- or top-post operation. The air pressure carried varies from 40 to ounds. Ninety pounds is a common pressure.

e advantages of the pneumatic mechanisms are their simplicity, reliability ver-load capacity.

Gas-operated Signal Mechanisms. — The gas-operated mechanisms milar in principle to those operated by air, but are complicated by the atus incidental to the tank supply being at a very much greater pressure hat at which the gas is used in the signal cylinder.

y-light Signals. — Powerful light signals are sometimes used to give ay, as well as night, indications in place of the semaphore. Notable ples of this are the position light signal installations on the Pennsylvania

system, especially in the neighborhood of Philadelphia, and the installation of color day-light light signals on the Chicago, Milwaukee & St. Paul, to say nothing of numerous installations on electric interurban roads.

These light signals are generally hooded to make them more visible in sunlight. They are provided with concentrating lenses, and sometimes with specially-constructed reflectors arranged so that light entering from the exterior through the lens will not be reflected out again and give a false indication when the lamp behind the lens is not lighted.

The candle-power behind the lens varies from 5 to 120, depending upon the type of lamp, the efficiency of the lenses and reflectors, and the color density of the glass. The indication given is sufficiently powerful even in bright sunlight to permit of the satisfactory operation of the highest speed trains.

LOCATION OF BLOCK SIGNALS. — Automatic block-signal systems have to take care of such varied fundamental conditions as are found, on the one hand, on single-track roads where the distances between passing sidings may be as great as four miles or more, and the traffic relatively infrequent and, on the other hand, on roads of four tracks, or more, where the traffic is dense, the headway short, and trains of both high- and low-speeds have at times to be handled over parts of the same tracks.

Home and Distant Signals. — The signal at the entrance to a block indicating the presence or absence of a train in that block is called the "home signal." In order that a train may be given warning in time to stop at the entrance to an occupied block, a second signal, called the "distant signal," indicating the position of the home signal at the entrance to the block, is located at a point sufficiently distant to enable the runner to act on the indication and bring his train to a standstill with a reasonable factor of safety before passing the stop signal. This distance will vary with the conditions of grade, curvature of track, and character of train equipment and may be from 3500 to 4200 feet or more.

In three-position signaling the semaphore at the beginning of a block is used to give the home signal for that block and the distant signal for the next block ahead. In two-position signaling the position of the home signal is repeated by a semaphore of distinctive shape, displaying a distinctively-colored light at night. This distant signal may, where the blocks are short, be located on the same mast with the preceding home signal. If the blocks are long and the rules of the road require a train to be immediately brought under control when advance information is received that the home signal is at stop, it is best to avoid loss of time by placing the signal giving the advance information on a separate mast at the proper distance from the home signal. This applies also to three-position signaling.

With distant signals it is, therefore, evident that in order to have following trains run continually under clear signals, they must be separated by a distance equal, at least, to the distance run by the preceding train during the time occupied by the clearing of the home and distant signals plus the length of the intervening block plus the distance between the home and distant signals.

The relations stated above give the basis for the theoretical location of automatic block signals to safely obtain maximum traffic capacity. In practice one must consider character of traffic, congested conditions at approaches to terminals, busy passenger stations and junction points, and local conditions such as view and opportunity for suitable foundations, in their effect on signal location.

Arrangement of Signals on Single-track Road. — Fig. 5 shows one arrangement of single-track signaling in both directions used by a large western

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system. The horizontal lines terminating at one end opposite signals and at the other end opposite insulating joints (the latter indicated by the short marks

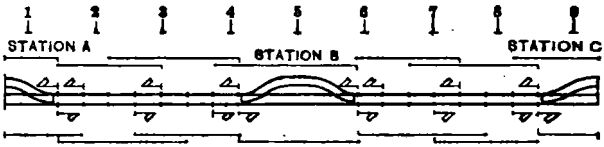


Fig. 5. Arrangement of Single-track Signaling in Both Directions

across the lines representing the rails) show the extent of track governing each signal by virtue of the track circuit.

Even where the distance between stations (or sidings) is less than a mile, it is important that intermediate home signals be placed between stations (or sidings) in order to prevent a train on the main track at a station from causing possible detention to an incoming train. It will be noticed by reference to the figure that eight signals are used to protect traffic, six between stations, and two within station limits. This number of signals is necessary to adequately protect all traffic and at the same time to insure proper flexibility, since, with this arrangement, trains can move up to the station limits under full protection from both directions, even though the main line may be occupied within these limits. This is because a train in a station affects only the entrance signals, and consequently does not affect approaching traffic on either side of the station, neither does a train on one side of a station influence traffic on the other side.

Fig. 6 shows the circuits for the system shown in Fig. 5.

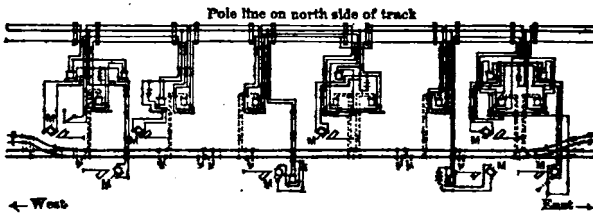


Fig. 6. Circuits for System Shown in Fig. 5

Another very typical system of single-track signaling is that which gives station to station protection for opposing moves and signal to signal protection for following moves. It is called the Absolute Permissive Block System or Traffic Direction System, generally abbreviated to A. P. B. System.

Special Arrangement for Single-track Interurban Road.— Fig. 7 shows a system of signaling which is particularly applicable to interurban single-track signaling where special conditions sometimes render it extremely desirable to permit more than one car, moving in the same direction, between sidings, and yet give both head-on and rear-end protection.

Because of the impedance of the rails and the characteristics of the voltage supply to the track circuit, track relay at signal "A" is deënergized only by a train between "A" and "X." Similarly, track relay at signal "B" is deënergized only by a train between "B" and "Y." Signals "A" and "B" are

connected so that both will go to "stop" on the entrance of a car at either end of the block, but for following cars the signal at the entering end will clear up after

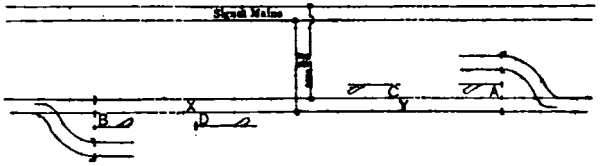


Fig. 7. System for Single-track Interurban

any preceding car has gone half the distance between sidings plus half the distance X–Y. X–Y is generally about 3000 feet where distance A–B is about 2 miles. If, by any misunderstanding, cars going in opposite directions should enter a stretch of track between sidings, they would be stopped by signals "C" and "D," located sufficiently far apart to allow for a proper factor of safety in stopping.

Trolley Wheel Operated Signals. — Block signals controlled from a contactor operated by the trolley wheel do not meet the requirements of high-speed signaling as to reliability, and are of value principally in preventing the loss of time due to two cars moving in opposite directions entering the same stretch of track, where conditions of vision and speed are such that there is small chance of harm resulting from a collision.

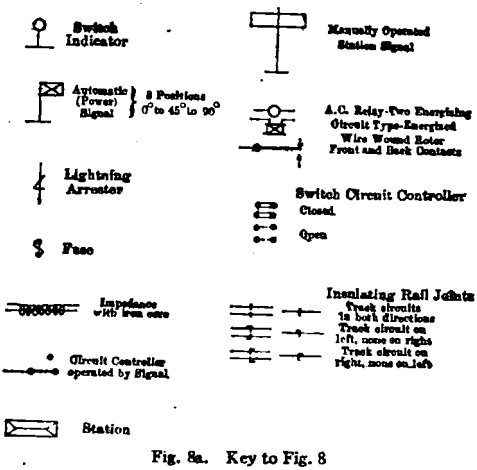


Fig. 8a. Key to Fig. 8

Arrangement of Signals on Double-track Road. — Fig. 8 shows a typical a-c. automatic block-signaling system with circuits for a two-track road. It will be noted that the *control* of the third position of the signals is obtained by the use of *line wires* running between the signals and supplied with current by circuit controllers operated by the signals.

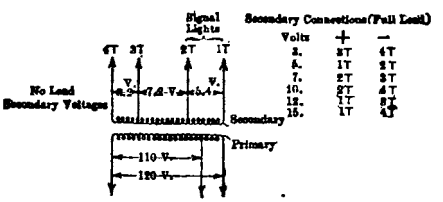
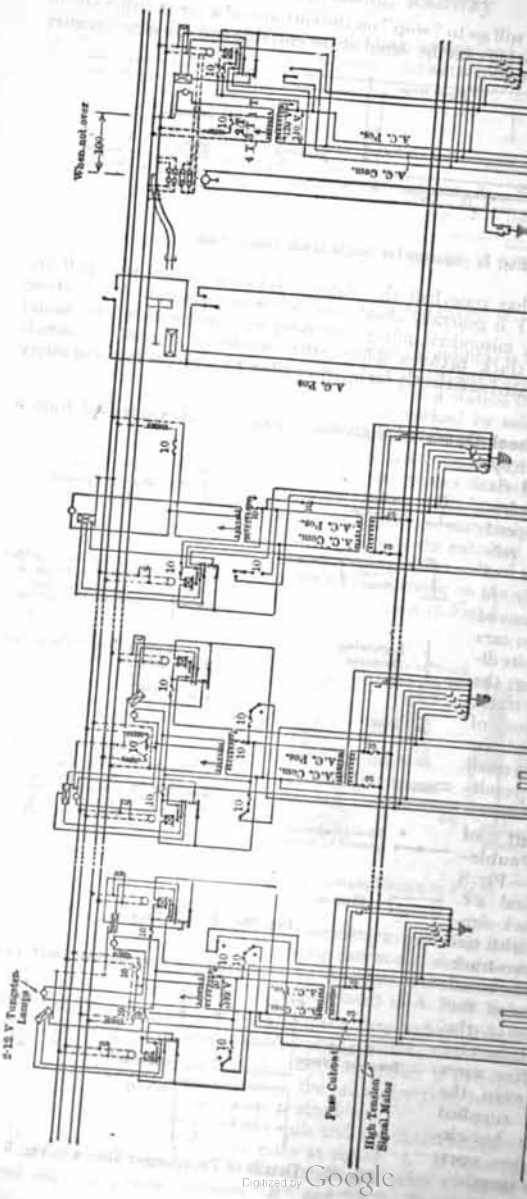


Fig. 8b. Details of Transformer Shown in Fig. 8

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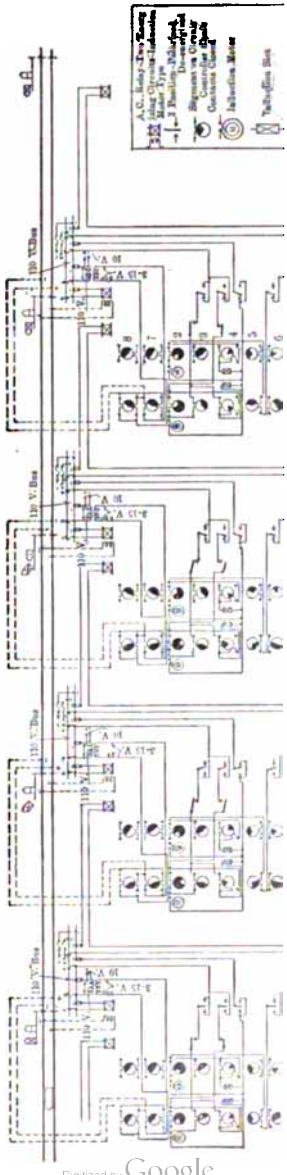
The use of two-energizing-circuit track relays as *polarised* relays permits *dispensing* with *control line wires*, in obtaining the control of the third position of three-position signals. The polarized relays close contacts in two positions according to direction of current in track winding and open them when deënergized, as by the presence of a train on the track circuit. The polarity of the current supplied to the track circuit in the rear of any signal depends on the position of that signal and the circuit controllers attached to it. This method is known as *polarised wireless control* and has its counterpart in direct-current signaling.

Maximum Capacity Arrangement. — Fig. 9 shows the latest development of signaling to give maximum capacity where high- and low-speed trains are run on close headway. The main idea is to make possible proper *speed control*. It will be noted that the high-speed trains receive sufficient warning to stop at the proper point in spite of the spacing of signals being made close to get maximum capacity with low-speed trains, which may run for short distances on the high-speed tracks.

Beginning with the first signal behind the occupied block at the left, the indications are respectively "Stop, then proceed according to rule," "Proceed, prepared to stop at next signal," "Proceed, prepared to pass next signal at medium speed," "Proceed."

INTERLOCKINGS AT CROSSINGS, JUNCTIONS AND TERMINALS. — All interlockings are designed with the view of insuring that signals governing traffic over any movable track must be in the stop position before the track parts can be shifted, that the track parts cannot be moved under a train, that they must be locked in the proper position before the signals governing over them can be placed in the proceed position, and that conflicting signals cannot be given.

The apparatus at an "interlocking" consists of the signals and movable



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track parts with their operating mechanisms and intermediate apparatus, the central-controlling interlocking machine (sometimes called an "interlocker") located in a signal tower or station, and auxiliary apparatus. Three types* of interlockings are used: (1) mechanical interlocking, in which movement is transmitted to the signals and track parts by means of wire and pipe connections to the levers in the interlocking machine; (2) electric interlocking in which the signals and track parts are moved by electric motors controlled through the interlocking machine; and (3), electro-pneumatic interlocking in which the signals and track parts are moved by compressed air controlled electrically through the interlocking machine. The last two types are called power interlockings as contrasted with the mechanical interlockings.

Almost all large terminals in the United States use electro-pneumatic interlockings. On the smallest power interlocking installations, "all electric" predominates. For installations of intermediate size there are many factors governing the wisdom of the choice.

Signal Apparatus. — Interlocking signals differ from automatic signals in external appearance only in such details as are necessary to enable the runner to differentiate them. The differences are generally confined to shapes and markings of arms, locations on masts, etc., and call attention to modifications in the significance of some of the aspects of interlocking signals as distinguished from automatics, e.g., see section above on *Semaphore Positions*. In mechanical interlockings signals are operated by wire or pipe connections to the mechanical levers in the interlocking machine. Sometimes a low voltage electric operating mechanism is used, though the switches remain mechanically operated. In such cases the signals are controlled through contacts operated directly from the mechanical lever or from contacts on a small auxiliary lever properly interlocked with the other levers of the machine.

In power interlockings the signal-operating mechanisms are essentially the same as those used for automatic block signals and are described above in the section on *Power Mechanisms*. Their control and operating circuits replace the mechanically operated pipe and wire connections of the mechanical interlocking signals.

Track Apparatus. — The track apparatus comprises switches, movable point frogs, detector bars, derails, bolt locks, drawbridge locks, etc., with their operating mechanisms.

The detector bar is a piece of steel ⅜ inch or ½ inch thick, 2¼ inches wide and varying in length up to 55 feet. It is supported beside the head of the rail in the vicinity of a movable part of the track, so that it is capable of vertical motion above the head of the rail when no car is present over it.

On account of the fact that with power interlocking and a wide head of rail a mechanical detector bar is likely to be forced up outside the wheels of a car over a switch, mechanical bars are being supplanted by short track circuits, called detector track circuits, which are utilized to lock the switch-control lever in the interlocking machine against being thrown under a train while a train is over a movable track part.

In all types of interlocking the movable part of the track is locked in position by connecting to it a horizontal bar, called the lock rod, which moves with the track part at right angles to the track. The lock rod is provided with holes or notches into which a bar, moving in guides parallel to the track, may be moved when the switch, or other moving part, is in its correct position. This

* Combinations of (1) and (2) are rapidly coming into use, and are of great advantage when the tower space is restricted and a change of track layout calls for an increase of capacity over that of the existing "mechanical" machine. The combination is called "Electro-mechanical."

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which engages the lock rod, receives its motion from the connection ates the detector bar. The sequence of movements at the switch is: ng of the detector bars; (2) the withdrawal of the bar engaging the he latter operation not being capable of completion unless it has le to raise the detector bar to the full extent of its travel); (3) the of the switch, or other track part; (4) the lowering of the detector ie entrance of the locking bar into the hole or notch in the lock ed the moving part has made its full travel and is in its correct

diate Apparatus. — The movements enumerated in the above par- generally effected in mechanical interlockings by pipe connections parts and their locking devices to corresponding levers in the interlocking machine. Bell cranks are used in the pipe connections he direction of motion. Sometimes all the movements enumerated l in proper order by a device located beside the track, called a d lock movement," which may be operated by one pipe connec- nachine lever. In power interlockings switch and lock movements always used, power apparatus at the track and electric circuits he mechanically-operated pipe connections.

er Apparatus for Electric Interlockings. — The power supply for erlockings is derived from storage batteries, used in duplicate sets to charging, or in single sets charged while in service or floated on the rcuit. The nominal voltage is 110, but exceeds this figure if the re charged in operation, or floated, or if, as is sometimes the case, 55 cells are used. A 120-ampere-hour cell is a common size for iso- s. At such plants the charging is generally done two or three times a gas-driven generator. A switch motor operating a single switch echanical detector bars in two seconds takes an average current of mperes. With about 200 feet of detector bar the corresponding cur- ut 4½ amperes. A motor signal operating in the same time takes amperes to clear and one-tenth ampere to hold. Solenoid dwarf ich are quite commonly used, operate almost instantaneously and stance of about 12 ohms and require 0.3 ampere to hold, resistance n when the signal clears.

er Apparatus for Electro-pneumatic Interlocking. — Each signal electro-pneumatic interlocking is provided with an electromagnetic astened directly to the cylinder. The piston is metal-packed, single- self-sealing at the end of its stroke under pressure. The cylinder ches and the stroke 4 inches except where two cylinders act jointly three positions of the semaphore. Admission of air is obtained by ation of the magnet valve, and exhaust by the deënergization, the rning under the influence of the counterweight of the semaphore. ch cylinders are double acting, and vary from four inches to seven and ches in diameter, depending on the character of the load, and have a ring from a length equal to the throw of the switch up to 10 inches. r cylinders are used to act directly on the switch points without bars, ones to operate (through the medium of a switch and lock move- heavier movable-point frogs in connection with one end of a double neir complement of bars. The stroke of the larger cylinders is gen- hes. Air is admitted to the cylinder by a slide valve. The latter is two small single-acting pistons, the admission of air to which is con- electromagnetic pin valves similar to those used on the signal cylin- slide valve is locked in its extreme positions by a pin actuated piston controlled by a third electromagnet valve whose energiza-

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tion must precede the operation of either of the pistons which shift the slide valve.

The control of the various magnet valves is effected by contacts operated by the interlocking machine levers. Storage battery to give about fourteen volts is generally used and the individual currents may vary from 1/10 to 1/20 of an ampere. From 75 to 100 pounds air pressure is generally carried.

Interlocking Machine for Mechanical Interlocking. — The interlocking machine comprises the levers, or controller handles, corresponding to the apparatus governed, and the mechanical, or mechanical and electrical, interlocking devices between the levers themselves, and between the levers and the apparatus governed by them.

The mechanical locking between levers is effected in the "locking bed." This is an iron plate, with two sets of parallel grooves. One set of grooves contains cold-rolled steel bars of rectangular cross section connected to and moved by the levers. The other set of grooves, at right angles to the first, contains shorter bars with ends shaped to engage with projections or depressions on the bars connected to the levers. The cross bars engage with the lever bars in such a manner that a lever cannot be moved unless the lever bar affecting the other end of the cross bar is in a definite position.

In a mechanical interlocking the operation of the detector bar and locking bar operating in conjunction with a movable track part, is generally effected by a separate lever in the interlocking machine, called the lock lever. This lever is interlocked with the proper signal levers so that the latter must have been operated to put the corresponding signals to stop before the lock lever can be operated to raise the detector bar and unlock the switch. The switch lever is, in turn, interlocked with the lock lever so that if the lock lever cannot make its full stroke, due, for example, to a train being over the detector bars, the switch lever cannot be thrown. If, after the switch lever is thrown, the lock lever cannot be thrown fully back to its original position, due, for example, to the switch not having made full travel, and the locking bar not being able to properly engage the lock rod, the interlocking between the lock and signal levers prevents the latter from being operated to put the signals in the proceed position. In mechanical interlocking plants rods connected to the signals are also often made to engage with the lock rod of the switch.

Further protection is often obtained in mechanical machines by attaching to moving parts connected to the levers circuit controllers and electromagnetic locks. The electric locks act by gravity when deënergized to engage with a moving part connected to the lever. The circuit which energizes them may be carried through circuit controllers attached to the signal or track mechanisms, or through the circuit controllers on other levers.

Interlocking Machine for Power Interlockings. — In power interlockings the levers are small as they have to operate only the mechanical locking in the machine and contacts for controlling the various circuits. The strain which can be brought on the mechanical locking is thereby reduced, and it is made correspondingly smaller than in mechanical interlocking machines. In these types of machines where the levers give a rotary motion to the circuit controllers it is possible, by the use of the two extreme positions of the levers, to control signals governing over the same route in opposing directions by the same lever. Only circuits for signals in one direction are closed in an extreme position and the indication referred to below being received before the lever can be returned to the middle position, where it releases the mechanical lock and insures against signals being placed in the proceed position if opposing signals controlled by the same lever have not returned to stop.

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ng on the type, a power interlocking machine may occupy less than
r of the space taken by a mechanical machine, and require but one-
the operators. Space is also saved on the ground, as the pipe connec-
oundations are replaced by wires.
interlockings the completion of the stroke of a movable-track part
per locking is "indicated" on the machine by the energization of an
netic lock which allows the lever to complete its full stroke, thereby
ne proper mechanical locking in the machine. The circuit for the
ied through contacts on the moving mechanism on the ground. The
signal to the stop position is indicated in a similar manner.

trol of Current for Electric Interlockings. — The supply of cur-
e signals, switches, etc., may be effected directly by the controller
rlocking machine, or by simple or polarized secondary controllers
the various signals and switches, the windings of the secondary
being in turn supplied in whole or in part with current from the
lever contacts. The use of the secondary controllers permits the
een them and the interlocking machine to be small, the power for
he signals, switches, etc., being supplied through contacts operated
ndary controller from mains running through the plant.
unt of the small amount of current used to operate the secondary
compared to the amount used by the apparatus they supply, the
the interlocking machine may be as small and compact as in an
umatic interlocking machine, and therefore offer the same excellent
for intercontrol of circuits in the machine itself. This is particu-
rtant, for instance, where it is desired to effect *route locking* (see
ere it may be necessary to have certain signals and switches enter
variety of combinations.

ication Current for Power Interlockings. — Among the various
providing the current for "indication" may be mentioned: (1) the
same current as is used for control and operation, called "battery
" (2) the use of polarized apparatus in connection with the preceding,
ction with current of a different character from the operating cur-
tilization of the momentum of the operating electric motor to
ne indication current after the motor has completed the move-
e apparatus; (4) the operation of the electric motor as a moto
fter it has completed the movement of the apparatus, the gen-
ent being distinctive in character, viz., alternating or of greater
n the operating current and of such direction as to selectively operate
agnets.

liary Apparatus. — Various relays, indicators, annunciaters, emer-
lever releases and special circuits are used in connection with or
to the essential interlocking apparatus to expedite the handling of
o meet special conditions.

n Locking. — Where electric locking is effective while a train is
a signal which has been set for it to proceed, to prevent manipu-
vers or devices which would endanger that train, it is termed *ap-
ng.*

ocking. — When electric locking is so arranged that it takes effect
n passes a signal to prevent manipulation of levers which would en-
train while it is within the limits of the route entered, it is termed
.

ional Route Locking. — To minimize the limitation of trackage
ich results from route locking, especially when the route lies across
tracks, *sectional route locking* is used. This is route locking so

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arranged that a train in clearing each section of a route releases the locking affecting that section. The detector track circuits are used to accomplish this type of locking. When *route locking* is not used it is necessary, in order to safely obtain full trackage capacity, to space the signals so close that no considerable amount of track is locked by the clearing of any one signal. Where the track layout and traffic conditions are such that short switching moves predominate over through routing this latter method is superior in giving greater capacity and flexibility.

AUTOMATIC STOPS. — Automatic stops have been in use for a number of years in connection with elevated and subway roads. They have been operated by direct mechanical connection to the signals or by separate mechanisms working in conjunction with the signals, and have consisted of arms located on the roadbed so that when elevated they were in position to engage with and operate a connection to the brake system on the car. It is evident that as a train may travel a considerable distance after the brakes are applied, and as the engineman or runner is dependent on the signals for the knowledge necessary to the proper control of his train, the relation of signal and stop locations must be such that in case the signals are properly observed the brakes will not be automatically applied, while if the contrary is the case, the space intervening between the train causing the display of the danger signal and the automatic stop protecting it must be sufficient to allow a following train being brought to rest without a collision.

This may be accomplished in two ways: (1) by using an overlap (i.e., extending the control of a signal to a point sufficiently beyond the next succeeding signal), which increases the spacing of trains and diminishes the capacity of the road; (2) by giving the runner an advance indication of the position of the signal at which it may be necessary to make a stop, so that if necessary he may bring his train under control in time to stop at the proper point. In the latter case the automatic stop is located to bring the train to rest at the stop signal, in case the speed has not been properly reduced. Up to the present (1921) automatic stop installations have been almost universally on the overlap system.

On account of clearances and atmospheric conditions, the automatic stop problem for steam roads is very difficult of solution. The problem is further complicated by the fact that there are involved the different conditions affecting freight and passenger traffic, a differentiation between the absolute stop indication of an interlocking signal and the permissive stop indication of an automatic block signal, and a differentiation between the speeds permissable over different routes, as indicated by an interlocking signal, with two or more arms, located at a point of divergence.

The above considerations indicate that the satisfactory solution of the automatic-stop problem for the majority of roads must follow the trend of modern signaling, and be based on speed control.

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SKIN EFFECT. — (*See also Electricity and Magnetism, Principles of; Resistance and Conductance, Electric.*) A conductor of finite cross-section may be looked upon as made up of separate filaments, just as a beam may be looked upon as made up of separate fibers. The inductances of the various filaments which make up such a conductor are different, due to the fact that the exterior filaments are linked by fewer flux lines than the interior filaments; see *Electricity and Magnetism, Principles of,* and *Inductance and Inductive Reactance.* Consequently, when the same potential gradient (varying with time, however) is established through all the filaments of such a conductor, by connecting it to some external source of alternating or varying e.m.f., the self-induced back e.m.f. in the interior filaments will be greater than in those filaments nearer the surface, and therefore the resistance drop in the interior filaments must be less than in the surface filaments. This can be brought about only by the current distributing itself over the cross-section of the conductor in such a manner that the current density in the interior of the wire will be less than at the surface, i.e., the current is forced toward the surface filaments or "skin" of the wire; hence the term "skin-effect" for this phenomenon.

Factors upon which the Skin Effect Depends. — The self-induced e.m.f. depends not only upon the amount of flux set up but also upon the rapidity of its variation; hence the skin effect becomes more pronounced the greater the frequency of the impressed e.m.f. It is also greater the larger the cross section of the conductor, the greater the conductivity of the conductor and the greater its magnetic permeability. It also depends slightly upon temperature since the conductivity changes with temperature.

Change in Resistance and Inductance due to Skin Effect. — As a consequence of the skin-effect the effective resistance of a conductor to alternating currents is greater than to direct currents, but the *internal* inductance *decreases* with the frequency; the external inductance is not altered; see *Inductance and Inductive Reactance.* Whereas, however, the internal inductance with increasing frequency approaches a limiting value, the resistance increases indefinitely as the frequency approaches an infinite value. The change of resistance is always relatively much larger than the change in the total inductance.

The effects just described are, for the most part, negligible at low frequencies, except in the case of heavy conductors and in coils wound with stout wire in several layers. In the latter case, however, the diminution of the inductance, due to the irregular distribution of the current, is masked, to a greater or less degree, by the effect of the capacity between the windings of the coil, which gives rise to an *increase* of the inductance with the frequency. For the same reason the resistance is increased more than it would be by the eddy currents alone.

Unfortunately, the rigorous or approximate solution of the problem at high frequencies for the various cases which arise in practice is in many instances very difficult, if not impossible.

SKIN EFFECT IN STRAIGHT ROUND WIRES. — An accurate solution for the case of straight *solid** wires of circular cross-section has been given in a number of different forms by various scientists. A summary of the formulas is given in a paper by Rosa and Grover, *Bull. Bur. Stds., 1912, Vol.*

* Tests at the Massachusetts Institute of Technology (*Proc. A.I.E.E., Sept., 1915*), indicate that the formulas for solid wires also apply to round *stranded* wires of the *same cross-section of metal*, not the same over-all diameter, for frequencies up to 1200, but above this frequency there is an increase in the skin effect, due to the spiraling of the component wires of the cable.

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8, p. 172. The calculations are most conveniently made by the use of the tables given in Rosa and Grover's paper, which are given in a condensed form below. Let

f = frequency in cycles per second,
μ = permeability of the wire, *assumed constant*,
R = direct-current resistance, in ohms, of 1000 feet of the wire; see tables in the article on *Wires and Cables, Bare*.
L = direct-current inductance, in millihenries per 1000 feet, of a *non-magnetic* wire of the same *cross section* as that of the given wire, and at the given spacing between wires, taken from the tables in the article on *Inductance and Inductive Reactance*.

Calculate the quantity

$$x = 0.02768 \sqrt{\frac{\mu f}{R}}, \tag{1}$$

and take from the following table the corresponding values of K_1 and K_2. Then the alternating-current resistance at the frequency f is

$$R' = K_1 R \qquad \text{ohms per 1000 ft.} \tag{2}$$

and the alternating-current inductance of the given wire at the frequency f is

$$L' = L + 0.01524\,(\mu K_2 - 1) \qquad \text{millihenries per 1000 ft.} \tag{3}$$

For x greater than 7 the following relations hold to within less than 1 per cent, the error being less the greater the value of x:

$$R' = \left(\frac{x}{2.828} + 0.25\right) R, \tag{4}$$

$$L' = L + 0.01524 \left(\frac{2.828\,\mu}{x} - 1\right). \tag{5}$$

Example.—Take the case of a 1,000,000-circular-mil copper cable (assumed equivalent to a solid wire of the same cross section; see footnote on preceding page), frequency 60 cycles, and return wire 10 ft. away. Then at 25° C., R = 0.0108 ohm per 1000 ft. of wire, L = 0.3494 millihenry per 1000 ft., for direct current. The value of x is

$$x = 0.02768 \sqrt{\frac{1 \times 60}{0.0108}} = 2.06.$$

From the table below K_1 = 1.088 and K_2 = 0.957, and the alternating-current resistance at 25° C. is therefore R' = 1.088 × 0.0108 = 0.0118 ohm per 1000 ft., and the alternating-current inductance is L' = 0.3494 + 0.01524 (1 × 0.957 − 1) = 0.3487 millihenry per 1000 ft.

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SKIN-EFFECT FACTORS FOR SOLID ROUND WIRES

K_1	K_2	x	K_1	K_2	x	K_1	K_2
1.00000	1.00000	3.8	1.60314	0.71729	10.5	3.97477	0.26832
1.00000	1.00000	3.9	1.64051	0.70165	11.0	4.15100	0.25622
1.00001	1.00000	4.0	1.67787	0.68632	11.5	4.32727	0.24516
1.00004	0.99998	4.1	1.71516	0.67135	12.0	4.50358	0.23501
1.00013	0.99993	4.2	1.75233	0.65677	12.5	4.67993	0.22567
1.00032	0.99984	4.3	1.78933	0.64262	13.0	4.85631	0.21703
1.00067	0.99966	4.4	1.82614	0.62890	13.5	5.03272	0.20903
1.00124	0.99937	4.5	1.86275	0.61563	14.0	5.20915	0.20160
1.00212	0.99894	4.6	1.89914	0.60281	14.5	5.38560	0.19468
1.00340	0.99830	4.7	1.93533	0.59044	15.0	5.56208	0.18822
1.00519	0.99741	4.8	1.97131	0.57852	16.0	5.91509	0.17649
1.00758	0.99621	4.9	2.00710	0.56703	17.0	6.26817	0.16614
1.01071	0.99465	5.0	2.04272	0.55597	18.0	6.62129	0.15694
1.01470	0.99266	5.2	2.11353	0.53506	19.0	6.97446	0.14870
1.01969	0.99017	5.4	2.18389	0.51566	20.0	7.32767	0.14128
1.02582	0.98711	5.6	2.25393	0.49764	21.0	7.68091	0.13456
1.03323	0.98342	5.8	2.32380	0.48086	22.0	8.03418	0.12846
1.04205	0.97904	6.0	2.39359	0.46521	23.0	8.38748	0.12288
1.05240	0.97390	6.2	2.46338	0.45056	24.0	8.74079	0.11777
1.06440	0.96795	6.4	2.53321	0.43682	25.0	9.09412	0.11307
1.07816	0.96113	6.6	2.60313	0.42389	26.0	9.44748	0.10872
1.09375	0.95343	6.8	2.67312	0.41171	28.0	10.15422	0.10096
1.11126	0.94482	7.0	2.74319	0.40021	30.0	10.86101	0.09424
1.13069	0.93527	7.2	2.81334	0.38933	32.0	11.56785	0.08835
1.15207	0.92482	7.4	2.88355	0.37902	34.0	12.27471	0.08316
1.17538	0.91347	7.6	2.95380	0.36923	36.0	12.98160	0.07854
1.20056	0.90126	7.8	3.02411	0.35992	38.0	13.68852	0.07441
1.22753	0.88825	8.0	3.09145	0.35107	40.0	14.39545	0.07069
1.25620	0.87451	8.2	3.16480	0.34263	42.0	15.10240	0.06733
1.28644	0.86012	8.4	3.23518	0.33460	44.0	15.80936	0.06427
1.31809	0.84517	8.6	3.30557	0.32692	46.0	16.51634	0.06148
1.35102	0.82975	8.8	3.37597	0.31958	48.0	17.22333	0.05892
1.38504	0.81397	9.0	3.44638	0.31257	50.0	17.93032	0.05656
1.41999	0.79794	9.2	3.51680	0.30585	60.0	21.46541	0.04713
1.45570	0.78175	9.4	3.58723	0.29941	70.0	25.00063	0.04040
1.49202	0.76550	9.6	3.65766	0.29324	80.0	28.53593	0.03535
1.52879	0.74929	9.8	3.72812	0.28731	90.0	32.07127	0.03142
1.56587	0.73320	10.0	3.79857	0.28162	100.0	35.60666	0.02828

EFFECT IN THIN STRIPS AND TUBES. — The following are exact for a flat strip of **infinite width** and at an infinite distance other conductor carrying a current; they also apply with a close degree imation to a tube which has a circumference 10 or more times its thick- vided no other conductor carrying a current is closer than a distance es the thickness of the strip or tube.

thickness of strip, or *twice* the thickness of the wall of a tube, in centimeters,

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w = width of strip or *half* the mean circumference of tube, in centimeters,
l = length of strip or tube in centimeters,
ρ = specific resistance of conductor, in microhms per centimeter cube, at the given temperature,
μ = magnetic permeability of conductor in absolute units,
f = frequency in cycles per second,

$$x = 0.1987\, l \sqrt{\frac{\mu f}{\rho}}.$$

Then d-c. resistance is

$$R = \frac{10^{-9}\rho l}{wt} \text{ ohms.}$$

The d-c. internal * inductance is

$$L_i = 1.047 \times 10^{-9}\, l \frac{\mu l}{w} \text{ millihenries.}$$

The ratio of the a-c. to the d-c. resistance is

$$\frac{R'}{R} = \frac{x}{2}\left(\frac{\sinh x + \sin (57.3\, x)^\circ}{\cosh x - \cos (57.3\, x)^\circ}\right)$$

and the ratio of the a-c. to the d-c. internal inductance is

$$\frac{L_i'}{L_i} = \frac{3}{x}\left(\frac{\sinh x - \sin (57.3\, x)^\circ}{\cosh x - \cos (57.3\, x)^\circ}\right)$$

For x less than unity these ratios are unity to within 0.6% and 0.2% respectively, i.e., the a-c. resistance is practically equal to the d-c. resistance and the a-c. internal inductance is practically equal to the d-c. internal inductance. For x greater than 6 the following formulas are accurate to within 0.5%:

$$\frac{R'}{R} = \frac{x}{2} \quad \text{and} \quad \frac{L_i'}{L_i} = \frac{3}{x}.$$

To a very rough degree of approximation the skin effect in a conductor of any shaped cross section may be approximated by using the above formulas for a strip, taking for the effective width w one-half the perimeter of the section (in centimeters) and for its effective thickness twice the area of the section (in square centimeters) divided by its perimeter. In general, then, for the same area the skin effect will be less the greater the perimeter of the section. If the section approaches more nearly that of a solid circle than that of an elongated rectangle, the formulas for a solid round wire will give more accurate results.

Skin Effect in Bus-bars (Strips of Finite Width).—The formulas given above are for strips of infinite width; the skin effect in narrow strips, such as used for bus-bars, is much greater than the theoretical value for infinite strips, due to the crowding of the current to the edge of the strip. This latter effect has been called the "edge effect." Experimental results obtained by Kennelly, Laws

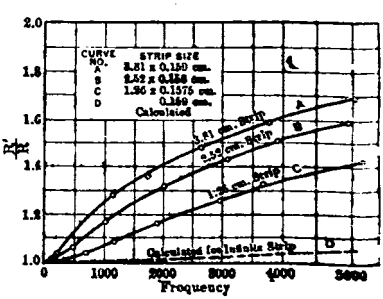


Fig. 1

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e (Proc. A.I.E.E., Sept., 1915), for strip conductors, outgoing and
nductor 60 cm. apart, are given in Fig. 1. For other spacings the
aper should be consulted.

Journal of the Franklin Institute for March, 1918, are reported tests
bus-bars 4 inches by ¼-inch, showing a ratio of a-c. to d-c. resistance
60 cycles and 1.1 at 24 cycles. It is stated that this increase in
is due chiefly to the crowding of the current toward the edge of
and not to the sides. Three such bars in parallel with an air space
ch between them gave a ratio of a-c. to d-c. resistance of 2.2 at 60

EFFECT IN WIRES, STRIPS AND TUBES AT HIGH FRE-
. — Kennelly and Afel, from a series of tests at frequencies up to
cles per second, reported in the *Proceedings of the Institute of Radio*
(*May, 1916*), draw the following conclusions:

skin-effect resistance ratio of round copper wires has been found to
to the standard Heaviside-Kelvin Bessel-function formulas, within
of experimental error.

skin-effect resistance ratio of a copper conductor formed of seven
parallel round bare strands (six surrounding a central seventh),
to be the same as that of the equisectional solid round wire up to
cles per second, within the limits of observational error. It is there-
ed that the subdivision of a round wire into a round cable of uninsu-
acting strands does not alter the skin effect.

effect of simple spiraling of strands in the same direction increased
nce ratio.

resistance ratio of a subdivided wire, with parallel insulated strands,
that of the equisectional solid wire, and diminished rapidly with the
r degree of strand separation.

braiding of strands, so as to effect their transposition in the cross-
frequent intervals, was found to diminish the skin effect.

skin effect in copper strips was found to be usually, but not invariably,
that of equisectional round wires.

easing the width of a copper strip within the limits reported was found
e the skin-effect resistance ratio; owing to what may be called "edge

ir of parallel going and returning flat strips, separated by a thin insu-
er, was found to have a skin effect depending only on the strip thick-
t is, without perceptible edge effect.

ng a flat strip into the form of a slit tube destroyed the edge effect,
ed the resistance ratio to a minimum dependent only on the strip

ting longitudinal slits with a sharp knife in a thin flat copper strip,
not appreciably to affect its skin effect resistance ratio.

order to employ a stranded wire of minimum skin effect at radio-fre-
seems desirable to employ thick insulation on the strands, such as
tton, to transpose the strands by braiding, and to avoid spirality in
he same direction.

order to employ a flat strip conductor most effectively, it is necessary
lling it out laterally when the increasing edge effect more than offsets
ion in skin effect.

hollow tubular form seems to be the most efficient type of radio-
metallic conductor, since, with proper mechanical internal support,
ffect can be indefinitely diminished by diminishing the wall thickness,
dge effect is absent.

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SKIN EFFECT IN IRON AND STEEL CO
also Trolley Systems, Overhead). Kennelly, Achard and
of tests reported in the *Journal of the Franklin Institute*
following conclusions:

1. The maximum observed skin-effect resistance ratio
at 25 cycles per second, varied between 5.35 and 10.1, a
between 10.92 and 13.4.

2. The maximum observed skin-effect resistance rat
substantially as the square root of the impressed freque
of 25 and 60 cycles per second.

3. The effective skin depth of alternating-current pe
per second, among all the twelve rails tested, varied b
1.8 mm.

4. The values of the mean superficial r.m.s. magnetic
the maximum skin effect developed, were between the
gilberts per centimeter. These were but little influenc
were in good agreement with the values of H for maxim
direct-current permeameter.

5. The best workshop method of measuring the skin e
in this case, found to be based on the use of a particular

6. The effective alternating-current conductance of a r
mation, inversely as the square root of the frequency, and

is directly proportional to the perimeter, and to the squa

7. It is therefore, in general, useless to increase the con
in a rail if the permeability μ is thereby increased in the

8. From the results here reported, it would seem tha
ance ratio of a rail, to a given alternating-current frequenc
can be approximately predetermined from measurements
and permeability μ of the steel, by applying an expe
factor to cover edge effect and other discrepancies. Thi
called the "edge-effect coefficient," appeared to be not
maximum skin-effect ratio.

9. The best form of rail for current-carrying capacity s
the effective perimeter is a maximum while allowing suff
Among the worst forms are probably a thick solid pris
hollow cylinder may be greatly improved by slitting it,
to its interior surface.

Skin Effect in Copper-clad Steel Wires. — The
from tests made in the Electrical Engineering Resear
Massachusetts Institute of Technology, on samples fu
Metals Co. For a comprehensive treatment of effective
ance of bimetallic and also of iron wires, see Miller,
Bureau of Standards, 12, p. 207, 1915.

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Size of wire, B. & S. gage, or diameter in inches	Solid 12	Solid 8	Solid 4	Stranded 3/16"	Stranded 1/4"	Stranded 1/2"
Per cent conductivity, manufacturer's rating	30	30	40	30	30	30
Total metal cross section in circular mils	6530	16,510	41,740	28,750	45,710	183,750
Ratio of A-C. to D-C. resistance at 20° C.:						
At 25 cycles per sec.	1.00	1.00	1.00	1.00	1.00	1.01
At 60 cycles per sec.	1.00	1.00	1.00	1.00	1.00	1.06
At 500 cycles per sec.	1.02	1.07	1.11	1.14	1.15	1.59
At 1000 cycles per sec.	1.05	1.14	1.16	1.31	1.31	2.05
At 5000 cycles per sec.	1.24	1.29	1.27	2.01	2.22	3.16
Increase in inductance, † ΔL, millihenries per 1000 ft.:						
At 25 cycles per sec.	0.18*	0.100	0.031	0.119	0.089	0.07*
At 60 cycles per sec.	0.18*	0.099	0.030	0.117	0.088	0.07*
At 500 cycles per sec.	0.15*	0.068	0.007	0.086	0.059	0.023
At 1000 cycles per sec.	0.085	0.038	−0.002	0.057	0.038	0.007
At 5000 cycles per sec.	0.011	−0.002	−0.009	0.010	0.003	−0.014

* Approximate.

† Calling L the inductance of a solid round, non-magnetic wire of the same cross section and on the given spacing, taken from the tables in the article on *Inductance and Inductive Reactance*, the alternating-current inductance of the copper-clad wire on his spacing, is

$$L' = L + \Delta L \qquad \text{millihenries per 1000 ft.}$$

BIBLIOGRAPHY. — See references in text. Complete bibliography will be found in the papers by Kennelly, et alia.

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SMOKE PREVENTION. — The direct cause of smoke from boiler furnaces is that the gases distilled from the coal are not completely burned in the furnace before coming in contact with the surface of the boiler, which chills them below the temperature of ignition.

Smoke may be prevented from forming if each particle of gas, as it is made by distillation from coal, is immediately mixed thoroughly with hot air. Even if smoke is formed by the absence of conditions for preventing it, it may afterwards be burned if it is thoroughly mixed with air at a sufficiently-high temperature. It is easy to burn smoke when it is made in small quantities, but when made in great volumes it is difficult to get the hot air mixed with it unless special apparatus is used. In boiler firing the formation of smoke must be prevented, as the conditions do not usually permit of its being burned.

Essential Conditions. — The essential conditions for preventing smoke in boiler fires may be enumerated as follows:

1. The gases must be distilled from the coal at a uniform rate.
2. The gases, when distilled, must be brought into intimate mixture with sufficient hot air to burn them completely.
3. The mixing should be done in a fire-brick chamber.
4. The gases should not be allowed to touch the comparatively-cold surfaces of the boiler until they are completely burned. This means that the gases shall have sufficient space and time in which to burn before they are allowed to come in contact with the boiler surface.

Every one of these four conditions is violated in the ordinary method of burning coal under a steam boiler. (1) The coal is fired intermittently and often in large quantities at a time, and the distillation proceeds at so rapid a rate that enough air cannot be introduced into the furnace to burn the gas. (2) The piling of fresh coal on the grate in itself chokes the air supply. (3) The roof of the furnace, or tubes of the boiler, is a cold shell instead of a fire-brick arch, as it should be, and the furnace is not of a sufficient size to allow the gases time and space in which to be thoroughly mixed with the air supply.

Methods of Prevention. — In order to obtain the conditions for preventing smoke it is necessary: (1) That the coal be delivered into the furnace in small quantities at a time. (2) That the draft be sufficient to carry enough air into the furnace to burn the gases as fast as they are distilled. (3) That the air itself be thoroughly heated either by passing through a bed of white-hot coke or by passing through channels in hot brickwork, or by contact with hot fire-brick surfaces. (4) That the gas and the air be brought into the most complete and intimate mixture, so that each particle of carbon in the gas meets before it escapes from the furnace its necessary supply of air. (5) That the flame produced by the burning shall be completely extinguished by the burning of every particle of the carbon into invisible carbon dioxide.

If a white flame touches the surface of a boiler, it is apt to deposit soot and to produce smoke. A white flame itself is the visible evidence of incomplete combustion.

Anthracite Coal. — The first remedy for smoke is to obtain anthracite coal. If this is not commercially practicable, then obtain, if possible, coal with the smallest amount of volatile matter. Coal of from 15 to 25 per cent of volatile matter makes much less smoke than coals containing higher percentages. Provide a proper furnace for burning coal. Any furnace is a proper furnace which secures the conditions named in the preceding paragraphs. Next, compel the firemen to follow instructions concerning the method of firing.

Bituminous Coal. — It is impossible with coal containing over 30 per cent of volatile matter and with a water-tube boiler, with tubes set close to the grate

l gas passages, as in an anthracite setting, to prevent smoke even by killful firing. This style of setting for a water-tube boiler should ly condemned. A Dutch oven setting, or a longitudinal setting with affle walls, is highly recommended as a smoke-preventing furnace ch a furnace it is necessary to use considerable skill in firing.

Jets and Mechanical Stokers. — Mechanical mixing of the gases by steam jets is sometimes successful in preventing smoke, but it iversal preventive, especially when the coal is very high in volatile en the firing is done unskillfully, or when the boiler is being driven normal capacity. It is essential to have sufficient draft to burn operly and this draft may be obtained either from a chimney or a e is no especial merit in forced draft, except that it enables a tity of coal to be burned and the boiler to be driven harder in case cy, and usually the harder the boiler is driven, the more difficult it ss smoke.

aft furnaces and mechanical stokers (q.v.) of many different kinds fully used for smoke prevention, and when properly designed and nd handled skillfully, and usually at a rate not beyond that for are designed, prevent all smoke. If these appliances are found ke, it is always due either to overdriving or to unskillful handling. ary, however, that the design of these stokers be suited to the quality l and the quantity to be burned, and great care should be taken to ufficient size of furnace with a fire-brick roof and means of introduc- nake them completely successful.

GRAPHY. — Kent, Wm., *Steam Boiler Economy*; Kent's *Mechani- ers' Pocket-Book*. For a comprehensive, authoritative treatment ject see Report of the Chicago Association of Commerce, *Smoke nd Electrification of Railway Terminals in Chicago*.

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SPARK GAP FOR MEASURING HIGH VOLTAGES. — One of the simplest methods of obtaining a measure of the value (maximum value in case of an alternating voltage) of a high voltage is to determine the length of air gap between two electrodes across which the given voltage will just cause a spark to pass. The voltage (maximum value) required to break down such a gap depends upon: 1. the shape and size of the electrodes; 2. the presence of other conductors in the vicinity of the gap; 3. the time of application of the voltage; and 4. upon the temperature and pressure of the air. The dependence of the break-down voltage upon the shape and size of the electrode is due not only to the effect of these factors upon the potential gradient in the gap but also to the fact that the maximum potential gradient at which air breaks down is dependent upon the distribution of the electrostatic field in the gap (*see article on Corona*) and is greater for very short gaps (0.5 cm. or less) than for long gaps.

For the same *maximum* value of the voltage it has been found that the striking distance is independent of the wave shape and frequency, and is the same for direct as for alternating voltages.

Time of Application of Voltage. — Air (and other gases) will stand for a short period of time (i.e., a few seconds) a much larger potential than it will stand for an indefinitely long period of time; this phenomenon is known as dilatation. After a voltage has been applied to a gap for about one minute, the apparent dielectric strength becomes sensibly constant. When measurements must be made with great rapidity, dilatation may be prevented by illuminating the gap by an arc-lamp. This procedure reduces the value of the sparking voltage, but only to a slight extent. (The theory of the action is that the ultra-violet light from the arc-lamp ionizes the air in the gap, thereby enabling the spark to pass at once.)

NEEDLE SPARK GAP. — Steinmetz in 1898 (*Trans. A.I.E.E., Vol. 15, p. 281*) made a careful determination of the voltages required to produce a spark between spherical, cylindrical and pointed (needles) electrodes. Steinmetz concluded that the sparking voltage between needle points (a sine wave of potential being used) was especially constant for any given set of conditions and that after the curve connecting spark potential and distance between needle points had been carefully ascertained, the needle spark gap offered a very valuable means for measuring high voltages. Although the needle spark gap is less trustworthy than the sphere gap, the Standardization Rules of the A.I.E.E. state that the needle gap may be used for voltages between 10 and 50 kilovolts. At higher voltages it has been found difficult to duplicate conditions nearly enough for different observers to obtain results which are in agreement.

Needle Spark-gap and Spark-over Voltages. — The needle spark-gap shall be between new sewing needles, supported axially at the ends of linear conductors, which are at least twice the length of the gap. There must be a clear space around the gap for a radius at least twice the gap length.

The sparking distances in air between No. 00 double long sewing-needle points for various root-mean-square sinusoidal voltages shall be assumed to be as shown in Table I.

SPHERE SPARK-GAP. — In 1913, Farnsworth and Fortescue (*Trans. A.I.E.E., Feb., 1913*) showed that a spark-gap between two spheres is a much more reliable measure of high voltage than the gap between needle points. The sphere spark-gap is now (1922) generally recognized as standard.

Besides giving more consistent results the sphere spark-gap occupies much less space for high voltages than the needle-gap. In addition to this advantage the sphere spark-gap breaks down with a sharply-defined spark discharge

TABLE I.—NEEDLE-GAP SPARK-OVER VOLTAGES

(At 25° C. and 760 mm. barometer)

R. M. S. Kilovolts	Millimeters	R. M. S. Kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41		

The values in this table refer to a relative humidity of 80 per cent. Variaons from this humidity may involve appreciable variations in the sparking istance.

thout previous formation of corona, provided the distance of separation is s than the diameter of either sphere. For greater distances of separation e corona forms first and the sparking voltage for a given length of gap becomes ore or less variable. Another advantage of the sphere spark-gap is that the rminals do not have to be renewed after each discharge, as is the case with the edle-gap.

Construction of Sphere Spark-gap. — Fig. 1 shows the arrangement commended by Farnsworth and Fortescue. The top sphere is stationary it slightly adjustable in height as just to make contact with e lower sphere when it is set for ro separation. The lower sphere mounted on a piece of brass bing which carries a threaded ishing on its lower end. This ishing works on a carefully-readed rod having a pitch of 10 per centimeter. The bushing ing graduated to fiftieths on its rcumference, separation may be easured to the nearest $\frac{1}{500}$ cm. rectly, thus providing a micro-eter adjustment. This arrange-ent is mechanically strong and e spheres are kept in constant ignment. The frame work may be conveniently mounted on wheels, to render easily moved.

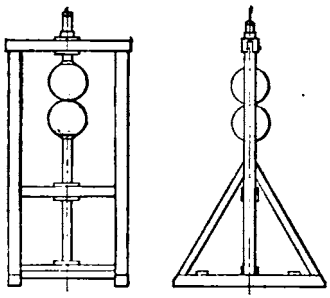


Fig. 1. Sphere Spark Gap.

A.I.E.E. Sphere Spark-gap and Spark-over Voltages. — The standard here spark gap shall be between two suitably mounted spheres. No extraneis body, or external part of the circuit, shall be nearer the spheres than rice their diameter. The shanks shall be not greater in diameter than $\frac{1}{8}$ the here diameter. Metal collars, etc., through which the shanks extend, shall be small as practicable and shall not, during any measurement, come closer to e sphere than the maximum gap length used in the measurement. The here diameter should not vary more than 0.1 per cent, and the curvature, easured by a spherometer, should not vary more than 1 per cent from that

a true sphere of the required diameter. When used as specified, the accuracy obtainable should be approximately 2 per cent.

The sparking distance between spheres for various r.m.s. sinusoidal voltages shall be assumed to be as shown in Table II, when the air density is that corresponding to a barometric pressure of 760 mm. mercury and a temperature

TABLE II.—SPHERE-GAP SPARK-OVER VOLTAGES

(At 25° C. and 760 mm. barometric pressure)

Kilovolts	Sparking distance in millimeters							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	.....	.....	.....	.....	.....	.....
20	8.6	8.6	.....	.....	.....	.....	.....	.....
30	14.1	14.1	14.1	14.1	.....	.....	.....	.....
40	19.2	19.2	19.1	19.1	.....	.....	.....	.....
50	25.5	25.0	24.4	24.4	.....	.....	.....	.....
60	34.5	32.0	30	30	29	29	.....	.....
70	46.0	39.5	36	36	35	35	.....	.....
80	62.0	49.0	42	42	41	41	41	41
90	.....	60.5	49	49	46	45	46	45
100	.....	.....	56	55	52	51	52	51
120	.....	.....	79.7	71	64	63	63	62
140	.....	.....	108	88	78	77	74	73
160	.....	.....	150	110	92	90	85	83
180	.....	.....	.....	138	109	106	97	95
200	.....	.....	.....	.....	128	123	108	106
220	.....	.....	.....	.....	150	141	120	117
240	.....	.....	.....	.....	177	160	133	130
260	.....	.....	.....	.....	210	180	148	144
280	.....	.....	.....	.....	250	203	163	158
300	.....	.....	.....	.....	.....	231	177	171
320	.....	.....	.....	.....	.....	265	194	187
340	.....	.....	.....	.....	.....	.....	214	201
360	.....	.....	.....	.....	.....	.....	234	221
380	.....	.....	.....	.....	.....	.....	255	235
400	.....	.....	.....	.....	.....	.....	276	257

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25° C. For any other air density the voltage at which the gap breaks down, any given spacing, is equal to the break-down voltage for this spacing at ındard pressure and temperature multiplied by the correction factor given Table III. The relative air density is found from the formula:

$$\text{Relative air density} = \frac{0.392b}{273+t}$$

ıere b = barometric pressure in mm. and t = temperature in degrees C.

It is important that the surface of the spheres be kept perfectly clean, i.e., ee from dust and moisture (*Marvin, R. H., Elec. W., 67, p. 649, 1916*).

The sphere-gap is more sensitive than the needle-gap to momentary rises of ltage and the voltage required to spark over the gap should be obtained by owly closing the gap under constant voltage, or by slowly raising the voltage th a fixed setting of the gap. Open arcs should not be permitted in proximity the gap during its operation, as they may affect its calibration.

ABLE III.—AIR DENSITY CORRECTION FACTORS FOR SPHERE-GAPS

Relative air density	Diameter of standard spheres in mm.			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

CORONA VOLTMETER. — The corona voltmeter, described in detail in Vol. 39 of the Trans. A.I.E.E., may often be used to advantage for measuring high voltages, in preference to a sphere-gap. See the article on *Corona*.

BIBLIOGRAPHY. — In addition to the references in the text see the following: Peek, F. W., *Sphere Gap for Measuring High Voltages*, Proc. A.I.E.E., 33, p. 889, 1914; Clark and Ryan, *Sphere-gap Discharge Voltages at High Frequencies*, Proc. A.I.E.E., 33, p. 937, 1914; Work, W. R., *Measurement of High Voltages*, Proc. A.I.E.E., 35, p. 203, 1916.

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SPECIFICATIONS AND CONTRACTS. — (*See also Standardization Rules and Standard Specifications; also under name of apparatus.*) Webster defines a specification as a written statement containing a minute description or enumeration of particulars, and a contract as a formal writing which contains the agreement of parties, with the terms and conditions, and which serves as a proof of the obligation. A "preliminary" specification is a description or enumeration of a purchaser's requirements when calling for bids. A "contract" specification is a description or enumeration of labor and material to be supplied under a contract of which the specification is an integral part. A "manufacturer's" specification is a description or enumeration of secondary details peculiar to the work of the individual manufacturer. This also is often made an integral part of a contract.

POLICY TO BE FOLLOWED. — When writing a specification the engineer should bear the following points in mind:

1. A preliminary specification is a commercial instrument designed to describe labor, material or results desired by a purchaser, with the object of enabling competitive bidders to estimate with equal facility upon the amount of a contract.

2. As a rule, contractors are as honest as the struggle for commercial existence permits them to be, and every unnecessary or unfair clause in a specification has its part in limiting competition and lowering the standard of honesty among contractors. A similar remark applies to requirements of which the purchaser cannot ascertain or enforce the fulfillment.

3. The standards of the national engineering societies should be followed unless local conditions prohibit them, and manufacturer's standards should be followed if low bids are to be expected.

4. No specification should contain a blanket clause covering the furnishing of unnamed contingencies unless all bidders are to have an equal opportunity to ascertain what such contingencies are likely to be. If such a clause is made very broad, it is unlikely that the courts would hold it valid.

5. Before drawing the specifications, determine to what extent the contractor is to be made responsible for the final results.

6. Avoid specifying proprietary articles or material as far as possible in order not to restrict competition.

7. Quality is an important factor in cost, hence unless the very best materials and workmanship are required, in spite of the higher cost, it is necessary to adopt some fair commercial standard.

8. There are many minor items in specifications which cannot be minutely described without making the specifications unduly long. In such cases it is good practice to specify that these items shall be made "to the reasonable satisfaction of the inspector," the word "reasonable" saving the contractor from arbitrary and unjustifiable actions of the inspector by enabling him to refer the reasonableness of such actions to the arbitrament of the courts.

FORM OF SPECIFICATIONS. — All specifications should be written in clear, concise language, free from ambiguity, and should be in convenient form for reference purposes.

It is desirable to number the paragraphs or clauses of all specifications to facilitate reference, and every item of the work should be alloted a separate clause.

There are two general classes of specifications. In one class results only are specified and all requirements should be rigorously exact. In the other class details of construction are specified and requirements can be stated in approximate terms only. Wherever practicable the former class of specification should be used. A combination of the two classes is also commonly adopted, but is

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agreement as to results does not bind the contractor if the methods these results are also specified. (*See J. C. Wait, Eng. News;* . In either case considerable study should be given to securing a m between brevity and elaboration of details. The degree of detail verned very largely by the magnitude and importance of the work. ing is suggested as a suitable plan to follow in drawing up specifica- erials. It is the result of a study of this subject by a special com- American Society for Testing Materials.

form is adopted should be closely adhered to in writing all the for a given job.

ecification shall be divided into eight "Parts."

es of these Parts shall be in large upper-case type centered over the eded by a Roman numeral.

les of these Parts shall be as follows unless conditions necessitate on. In case a Part is omitted, the Roman numerals shall be con- unbroken sequence.

nufacture.

mical Properties and Tests.

sical Properties and Tests: Mechanical, Electrical, Magnetic, Thermal, etc.

ndard Sizes, Dimensions, Weights, Gauges, etc.

rkmanship and Finish.

king, Marking and Shipping.

pection and Rejection.

nition of Terms. (If a specification contains numerous terms that admit of ambiguity, they shall be defined under this sub-title.)

Part" of a specification shall be divided into "Clauses" or "Sec- n shall be numbered continuously throughout the specification in rals. Every Section or Clause of printed specifications shall have heading in bold-face type, briefly indicative of its content. If are on one side of the paper, the clause titles shall be in the left- ; if printed on both sides, as in a book, the clause titles shall be in nargins.

ection or Clause may be subdivided into paragraphs distinguished e italics in parenthesis.

y after the title of the specification insert sections of an intro- scriptive or general character. No sub-title shall precede this h shall precede Part I.

l values, rather than permissible limits, shall be given, followed by with respect to permissible variations.

ar as practicable, specified values shall be expressed in tabular form.

yle sheets of the A.I.E.E., A.S.T.M., etc., should be followed in ertaining to typography, standard terms, abbreviations, spelling, etc.

"shall" and "will" are used in the following sense by the Ameri- for Testing Materials. Use "shall" wherever the specifications ade binding on parties of the first or second part. Use "will" e specifications are intended to express a declaration of purpose ory upon the parties of the first or second part. Many engineers to express a command binding on the Contractor and "will" to eclaration of purpose binding the Purchaser.

ons for machinery, apparatus or construction work may be written rm using different Part headings. In the case of apparatus and he following sequence of Parts has been found very practical by f this article.

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The object of the specification and general conditio
stated, the following parts follow:

I. Summarized Description of principal Charact
Service.
II. Style and Description of Apparatus; Details
III. Dimensions, Weights, Drawings and Schedul
IV. Work to be done by other Contractors.
V. Performance and Tests.
(a) Performance which may be checked b
(b) Factory Tests.
(c) Performance and Tests after Erection.
VI. Workmanship and Finish.
VII. Packing, Marking, Shipping and Delivery.
VIII. Inspection and Rejection.
IX. Guarantees.
X. Conditional Payments. (The details of cond
ing upon results of inspection and tests.
XI. Definition of Terms. (If a specification cont
admit of ambiguity, they shall be define

It will be observed that the sequence of topics in th
mately follows the order of the life history of the ma
extended upon this principle to cover any kind of worl

POINTS TO BE COVERED IN SPECIFIC
tion should often cover the following points.

Items 1 to 3 refer to preliminary specifications o
frequently included in the contract proper.

1. These specifications are intended to furnish such i
as will enable them to prepare detail plans upon whic
any Bidder consider the requirements of these specifi
free exercise of his skill, any suggestions made by hin
2. Before a contract is awarded, final specification
Company.
3. In comparing proposals due consideration will b
to availability, reliability, simplicity, cost of maint
delivery.
4. The Engineer agrees to consider all drawings
confidential, and that he will not show any such drawin
whether they are tendering under this specification or
5. Definition of words describing the parties to the
tractor," "Purchaser," "Company," "Engineer."
6. Person or persons concerned and their respective
7. Where work is to be done or material delivered.
8. The point where the work of two contracts
designated in both contracts, not merely in a general
the minutest detail.
9. The Contractor shall be responsible for the co
even after they are approved by the Engineer.
10. Materials ordered or work commenced prior to
ings will be at the Contractor's risk.
11. No approved drawing may be changed with
Engineer.
12. The Contractor shall inspect the work of othe
affects his and shall notify the Engineer of anything

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. The Contractor shall give these other contractors the privilege of
g his work in so far as it affects the acceptance of their work.
ontractor shall not drill or in any way impair the strength of buildings
ures except with the written consent of the Engineer.
l work shall conform to the requirements of the "National Board of
erwriters," and to all Government regulations.
ne Contractor shall obtain all necessary permits from the City or County.
l like parts shall be interchangeable as far as practicable.
ne Contractor shall install and maintain in his offices and at the site
rk such telephones as may be required by the Engineer, and shall place
he disposal of the Engineer or his representative for any purpose relating
ecution of the contract.
ne Standardization Rules of the A.I.E.E. and other similar documents
e followed wherever possible.
ne provisions of the preliminary specification and those subsequently
pon between Company and Bidder should be incorporated as part of
or contract specification.

TS TO BE COVERED IN CONTRACT. — In addition to items
above, the Engineer should make sure that the following points are
in the contract. The actual preparation of the contract, at least where
nt of money involved is large, should be left to a competent lawyer.

scription and value of bond and indemnity to be delivered by Con-
o Company.
tement of fire insurance to be secured by Contractor for Company.
otection of Company by Contractor against losses resulting from letters

e work to be performed in such a way as not to interfere with safety and
y of service.
sponsibility for damage to work from fire, floods, storm, earthquake,
her cause whatsoever.
ntiguous work by other contractors shall not be delayed.
tement of liquidated damages to be paid in the event of work not being
d on the date agreed.
e Contractor shall not transfer the contract without permission.
ne of commencement of work, rate of progress and date of completion.
ne character of the methods and appliances to be used and grade of
l to be employed.
ethod of payment, time of settlement and basis thereof.
rbitration and settlement of disputes.
xtras and claims therefor.
subject of Engineering contracts is more fully covered in the books by
nson and J. I. Tucker, cited in the Bibliography.)

IOGRAPHY. — American Electric Railway Engineering Association, *ns Governing the Style of Specifications*, Engineering Manual, 1919; n Society for Testing Materials, *Rules Governing the Form but not the e of Specifications*, Report of Committee E-5, 1912; Butler, H. L., *ions for Engineering Work*, Engineering and Contracting, 1909, Vol. 3; Cochran, J., *The Requirements and Theory of the Advertisement or Bidder on Contracts for Public Works*, Eng. N., 1911, Vol. 66, p. 306; ., *Engineering Specifications*, Trans. A.I.E.E., Vol. 30, 1911; Fowler, *Law and Business of Engineering and Contracting*, N. Y., 1909; John- ., *Engineering Contracts and Specifications*, N. Y., 1903; Tucker, J. I., *in Engineering*, N. Y., 1910; Wait, John C., *Engineering and Archi- urisprudence*, N. Y., 1898; *Law of Operations Preliminary to Construc- Y.*, 1910; *Law of Contracts*, N. Y., 1901.

STANDARDIZATION RULES AND STAN CATIONS. — (*The A. I. E. E. Standards are given in book.*) Numerous national and international societies rules and standard specifications dealing with testing machinery, apparatus and materials. Brief outlines standards of these engineering bodies, with direction for s are given in this article. Additional information can American Engineering Standards Committee. Brief st tions of the publications of the American Engineering the Bureau of Standards, and the International Electr are included.

AMERICAN INSTITUTE OF ELECTRICAL EN *tary, F. L. Hutchinson, 29 West 39th St., New York City.* a pamphlet (172 pages) entitled "Standards of the Amer trical Engineers" (price $2.00). These standards define tions which characterize the rating and behavior of ele special reference to the conditions of acceptance tests. generally accepted by the manufacturers and users of el apparatus in the United States. Standards for dimens struction are not given.

The standards of the A.I.E.E. comprise sixteen chapte

1. **General Principles.** — Heating, Mechanical and tion, Wave Shape, Dielectric Strength and Insulation Rating.

2. **General Rules.** — Operation, Rating, Tests, Cons

3. **General Definitions.**

4. **Standards for Rotating Machinery (General).** tion, Rating, Tests.

5. **Standards for Electric Railways and for Au Machines.** — Definitions, Operation, Rating, Tests, Cl Railway Motors, Selection of Railway Motor for Specified

6. **Standards for Transformers and Other S Apparatus.** — Definitions, Rating, Tests, Construction.

7. **Standards for Switching Control and Prote** Definitions, Operation, Rating, Tests.

8. **Standards for Meters, Instruments and Instru** — Definitions, Operation, Rating, Tests, Characteristics.

9. **Standards for Wires and Cables.** — Definitio Standard, Operation, Designation, Tests, Construction.

10. **Standards for Storage Batteries.**

11. **Standards for Illumination.** — General, Surfaces Luminous Flux, Illumination, Illuminants, Lamp Access

12. **Standards for Telephony and Telegraphy.** —

13. **Standards for Radio Communication.**

14. **Standards for Prime Movers and Generator**

15. **Standards for Transmission and Distribution**

16. **Miscellaneous Devices.** — Heating Devices.

AMERICAN ENGINEERING STANDARDS (*Secrtary, P. G. Agnew, 29 West 39th St., New York Cit*

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serves as a national clearing house for engineering and industrial standardization. The Committee is made up at present (1922) of representatives of, and is maintained by, nine national engineering societies, five government departments, and fourteen national industrial associations. Its functions are: to unify methods of arriving at standards; to secure nationally recognized standards, through cooperation between various interested organizations, thus preventing duplication of work and promulgation of conflicting standards; and to act as a general bureau of information regarding standardization.

Standards covering eighteen different subjects have already (1922) been adopted and active work is now in progress on about sixty projects, including a number of industrial safety codes. Information on the organization and the work will be sent free upon request.

AMERICAN ELECTRIC RAILWAY ENGINEERING ASSOCIATION. — (*Secretary, E. B. Burritt, 8 West 40th St., New York City.*) This Association issues an *Engineering Manual*, which contains all standards set by the Association, all practices recommended by it, and those practices which, while they have not been formally adopted either as standards or recommended practice, have been discussed and put forward by the Association's various committees. The *Manual* is in loose-leaf form, and is revised each year by the Committee on Standards. The contents are grouped under the headings: Buildings and Structures; Power Distribution; Equipment; Power Generation; Block Signals; Way Matters. The price of the *Manual*, including all sections in a binder, is $5.00 to non-members.

AMERICAN RAILWAY ASSOCIATION. — (*General Secretary, J. E. Fairbanks, 75 Church St., New York City.*) This is a general association representing the steam railroads of the country. There are now incorporated in it several technical associations which were formerly distinct.

Mechanical Division (Master Car Builders; Master Mechanics). — (*Secretary, V. R. Hawthorne, 431 South Dearborn St., Chicago, Ill.*) The Division, with its predecessor organizations, has numerous specifications covering parts and details of cars and locomotives, practices, etc., which are now (1922) being unified for publication in a loose-leaf manual.

Signal Section. — (*Secretary, H. S. Balliet, 75 Church St., New York City.*) The Section publishes a loose-leaf *Manual* containing specifications for primary batteries, storage batteries, bells, insulated wires and cables for various kinds of signal use, conduit, interlocking devices, lightning protection devices, relays, and various other signal apparatus and supplies; and standard designs for a large number of devices, and parts used in railway signal work.

Telegraph and Telephone Division. — (*Secretary, W. A. Fairbanks, 75 Church St., New York City.*) The present specifications of the division, which include specifications for various kinds of conduits and conduit fittings, telephone and telegraph equipment, protection against electrolysis and against lightning, transpositions of circuits are published in a *Manual* (1922).

AMERICAN RAILWAY ENGINEERING ASSOCIATION. — (*Secretary, E. H. Fritch, 431 So. Dearborn St., Chicago, Ill.*) This Association, which is closely allied to the American Railway Association, issues a *Manual* containing the various committee reports which have been formally adopted by the Association. The following items are covered: Roadway; Ballast; Ties; Rail; Track; Buildings; Wooden Bridges and Trestles; Masonry; Signs, Fences and Crossings; Signals and Interlockings; Records and Accounts; Rules and Organization; Water Service; Yards and Terminals; Iron and Steel Structures; Economics of Railway Location; Wood Preservation; Electricity.

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The last edition of the *Manual* (1915) is now out of print, but a new edition is in preparation (1922).

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. — (*Secretary, Calvin W. Rice, 29 West 39th St., New York City.*) The Boiler Code of this Society contains standard specifications for the construction, equipment and use of steam boilers ($1 to non-members). Official interpretations of the Code by the Boiler Code Committee are published separately. The Power Test Codes ($2 to non-members), are rules for the testing of boilers, engines, turbines, compressors, fans, power plants, locomotives, water-wheels, etc. The Standard Pipe Thread has been approved by the American Engineering Standards Committee as an "American Standard," the Society acting with the American Gas Association as joint sponsors. The work of committees of the Society on Shafting and on Pipe Flanges and Pipe Fittings is now being extended under the auspices of the American Engineering Standards Committee. A list of the publications of the Society will be sent free upon request to the Society.

AMERICAN SOCIETY FOR TESTING MATERIALS. — (*Secretary, C. L. Warwick, 1315 Spruce St., Philadelphia, Pa.*) This Society issues a triennial volume of "A.S.T.M. Standards," and annual supplements in intervening years. The last triennial volume was issued in September, 1921. The specifications and methods of tests cover a wide range, including Steel Rails, Structural Steel, Various Steel Objects, Steel Castings, Wrought Iron, Pig Iron, Iron Castings, Locomotive Material, Magnetic Tests of Iron and Steel (*see Magnetic Testing*), Various Kinds of Copper Wire and Wire Bars (*see Wires and Cables, Bare*), Spelter, Manganese Bronze Ingots, Cement, Lime, Clay Products, Preservative Coatings, Road Materials, Timber, Brass, Paints, Oils, and various other materials. The price of the 1921 Book of Standards is $11.00 to non-members. Single standards may be purchased for 25 cents.

BUREAU OF STANDARDS. — The Bureau of Standards at Washington is a branch of the U. S. Department of Commerce. It is the official custodian of the fundamental standards of measurement. In addition to making tests and comparisons of measuring apparatus, the Bureau carries on numerous researches related to the establishment and maintenance of the various standards and units of measurement, the development of measuring instruments and methods of measurement, the determination of physical constants and the properties of matter. The results of these investigations are published in pamphlet form issued in two separate series: (1) *Scientific Papers* and (2) *Technological Papers*. In addition, the Bureau issues a third series, *Circulars*, giving useful technical data, standard specifications for apparatus, description of the nature of the standard tests carried out at the Bureau, etc.

A complete list of the publications of the Bureau will be furnished by the Bureau upon request and free of charge; this list is contained in *Circular No. 21* which contains an index and a brief summary of each of the *Scientific* and *Technological Papers*, and *Circulars* most of which can be furnished by the Bureau upon request and free of charge. Others may be purchased from the Superintendent of Documents, Washington. D. C.

The *Bulletin of the Bureau of Standards* is a serial publication in which the *Scientific Papers* are published collectively. Each number of the *Bulletin* contains about 150 pages, the separate numbers being issued as material accumulates, at intervals of about three months. Four numbers constitute a volume. The bound volume is now (1921) issued under the title "Scientific Papers." Sixteen volumes had been issued at the beginning of 1921. The complete *Bulletin* is furnished free to educational and scientific institutions. Individuals may obtain separate numbers in paper covers (current or back num-

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5 cents per copy, complete volumes bound in cloth at $1.50 per volume, subscribe in advance at the rate of $1.00 per volume to receive the four numbers as issued. Orders and payments for the *Bulletin* should be to the Superintendent of Documents, Washington, D. C., and *not* to u of Standards.

ncipal publications of the Bureau dealing primarily with specifications lards of interest to the electrical engineer are: Electrical Units and (Circular 60); Specifications for Incandescent Lamps (Circular 13); Wire Tables (Circular 31); Wire and Cable Terminology (Circular 37); National Electrical Safety Code" (Circular 54), which is a general ing with safety, covering electrical supply stations, electrical line on, electrical utilization equipment, and electrical operation.

TRIC POWER CLUB. — (*Secretary, C. H. Roth, 1410 West Adams go, Ill.*) This Club is an association of companies engaged in the manu- f electric power apparatus. Its standardization rules, which are the Handbook of the Club, deal with the industrial standardization s, generators, transformers, and electric power control apparatus. phlet referred to may be obtained from the Secretary of the Club cents).

MINATING ENGINEERING SOCIETY. — (*General Secretary, L. Law, 29 West 39th St., New York City.*) The Committee on Nomen- nd Standards of this Society published a report in 1918. The defini- his report are substantially the same as those incorporated in the *ization Rules of the A.I.E.E.* (1921 edition). The Society has also Automobile Headlighting Specifications, and a Code of Lighting for Mills and other Work Places.

TUTE OF RADIO ENGINEERS. — (*Secretary, Alfred N. Gold- llege of the City of New York, New York City.*) See the reports of the s Committee of this Institute. The standard nomenclature adopted stitute is included in the *Standardization Rules of the A.I.E.E.* bear- dio matter.

ONAL ELECTRIC LIGHT ASSOCIATION. — (*Executive Mana- . Aylesworth, 29 West 39th St., New York City.*) The Apparatus Com- this Association has published Transformer Standards; Methods of nsulating Oils; and Rules for the Installation and use of Motors on tation Distribution Systems. The Underground Systems Committee shed Specifications for Lead Covered Paper Cables. Other committee eal with Railway Rates, Transportation, Accounting, Prime Movers, Line Construction, Lamps, Electrical Apparatus, Meters, Termi- rounding Secondaries, Underground Construction, Electrical Measure- t Values and Street Lighting.

.E.L.A. issues the *Electrical Meterman's Handbook*, prepared by the ee on Meters. This book is intended primarily for practical meter he *Meterman's Handbook* deals with the subject of metering in great ntaining over 1000 pages. It may be had from the Secretary of the on for $5.00.

ONAL FIRE PROTECTION ASSOCIATION. — This Associa- es the *National Electric Code* which contains the rules and require- the National Board of Fire Underwriters for electric wiring and appa- The *Code* is revised every two years, the next revision being in 1922. *Electrical Fittings* is also issued by the National Board of Fire Under- This is a list of fittings which have been examined and are suitable

for the use intended; this list is revised semi-annually. forth suggestions, rules and regulations of the Nation special installations of various kinds which involve fire to apparatus and equipment for fire protection. Sing and *List of Electrical Fittings* may be obtained free of ch Board of Fire Underwriters, 135 William St., New York

The Underwriters' Laboratories. — (*President, W.* St., *Chicago, Ill.*) This organization issues detailed covering inspection and approval of electrical fittings and tories.

The Associated Mutual Fire Insurance Companie *Lacount, 31 Milk St., Boston, Mass.*) This organization fittings and of fire-protection devices approved by thes general rules of the National Fire Protection Association

SOCIETY OF AUTOMOTIVE ENGINEERS. *C. F. Clarkson, 29 West 39th St., New York City.*) Th standards, recommended practices, and data sheets in Handbook. These include the automobile, aeronautic, fields, and are classified as follows: Miscellaneous Fitti Materials, Bearings, Engine Fittings, Lighting, Aerona Standards, Electrical Installations, Springs, Electrica Tractor, and Military Motorcycle. The price of the *Ma* of individual sheets, 6 cents each.

OTHER ENGINEERING BODIES. — The Bodie committee reports or otherwise, have published specifi or matter relating thereto. The Bureau of Standards is a publication on bodies interested in engineering and ind

American Electrochemical Society, *Secretary*, J. W. versity, South Bethlehem, Pa.

American Gas Association, *Secretary*, Oscar H. Fogg New York City.

American Society of Heating and Ventilating Engin Obert, 29 West 39th St., New York City.

American Society for Municipal Improvements, *Secret* 803 Lincoln Ave., Valparaiso, Indiana.

Associated Manufacturers of Electrical Supplies, *Se* 30 East 42nd St., New York City.

Association of Railway Electrical Engineers, *Secreta* C. & N. W. Terminal Bldg., Chicago, Ill.

Association of Iron and Steel Electrical Engineers, Empire Building, Pittsburgh, Pa.

Bureau of Mines, *Acting Director*, E. A. Holbrook, Was

National Association of Electrical Contractors and De W. H. Morton, 110 West 40th St., New York City.

National Screw Thread Commission, *Secretary*, H. Standards, Washington, D. C. This is a government bo (1921) has been issued.

INTERNATIONAL ELECTROTECHNICAL (*General Secretary's Office, 28 Victoria St., Westminster, Lo* This Commission, which was organized in London in 1906. Committees in about 25 countries. The United States (*Secretary, Dr. A. E. Kennelly, Harvard University,*

ed by the President of the American Institute of Electrical Engineers, eps in close touch with the A.I.E.E. Standards Committee. There present Special Committees on Prime Movers, Rating, Nomenclature, s, Units, and Standard Pressures.

Commission meets in full session about every two years. The last was in 1921. These meetings are for the purpose of discussing and pon the reports and recommendations of the Special Committees.

Central Office has, from time to time, published bulletins giving reports meetings of the different committees of the Commission. The list of *ional Symbols* (*see Symbols and Abbreviations*), and *the Rules for the Rat-lectrical Machinery*, published by the Commission, are printed as appen- the *Standardization Rules of the American Institute of Electrical Engineers*,

EIGN STANDARDIZING BODIES. — There are now national dizing bodies in Austria, Belgium, Canada, Czecho-Slovakia, France. y, Holland, Hungary, Italy, Japan, Sweden and Switzerland. These ations serve as clearing houses and bureaus of information on engineer- industrial standardization in their respective countries. Information he work of these organizations can be obtained from the American ring Standards Committee, 29 West 39th St., New York City, where of all specifications and standards approved by the various national re on file.

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STARTERS, MOTOR. — (*See also Controllers; Motors, Alternating-Current; Motors, Direct-Current; Rheostats.*) An auxiliary resistance which is used with a motor, either d-c. or a-c., during acceleration is called a starter, or a starting rheostat. A compensator, or induction starter, consists of an auto-transformer and a switch, by the operation of which a reduced voltage is supplied to the terminals of an induction motor for starting.

STARTERS FOR DIRECT-CURRENT MOTORS. — The starters in use with constant speed d-c motors consist usually of a resistance to be inserted in the armature circuit, this resistance being gradually cut out by the movement of a contact arm over a face plate as the motor comes up to speed. Such rheostats connect the motor field in circuit at the first step and are provided with various safeguards such as low-voltage release, overload release, etc.

Resistance Steps for D-C. Starters. — The resistance is designed to limit the starting current to about 1½ times full load current with enough steps to limit the voltage between contacts. Motors of 10 horsepower or less usually are brought up to speed in about 15 seconds and larger motors in about 30 seconds. Resistors should carry full load current for two minutes starting cold with an average temperature rise not exceeding 250° C. Resistors will withstand 500° C. without deterioration.

Fig. 1 shows the connections of a typical d-c. starter with low-voltage release. If the rheostat arm is moved from the off position shown in the cut to the contact $R-1$. current will flow from $L+$ to the arm; from this to contact $R-1$. through the regulating resistance to $R-11$, thence through the armature and series field of the motor to $L-$. The shunt field is connected from $R-1$ to $L-$. As the rheostat arm is being moved from $R-1$ to $R-11$ there is a small drop in voltage across the shunt-field circuit due to the field current flowing through the starting resistor but this is so small that it may be neglected and the field can be considered as having full voltage impressed upon it. The rheostat arm is provided with a spring which returns it to the off position when the handle is released during the starting of the motor. After the motor has been brought up to speed and the rheostat arm rests upon contact $R-11$ the low-voltage release magnet holds the arm in this position. Brush B bridges between the terminals M and N so that in the running position the current passes from $L+$ to terminal M, through the brush B to the terminal N, thence to the armature of the motor and through the series field to $L-$.

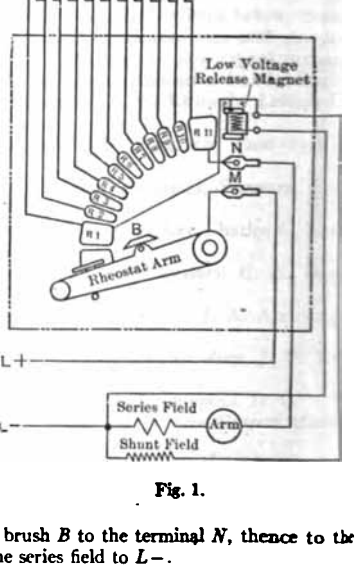


Fig. 1.

Overload Release. — An overload release is often furnished, especially with motors of large capacity. This device consists essentially of a solenoid which is connected in series with the motor armature and which, in case of a predeter-

ned overload, opens the circuit of the low-voltage coil. This action releases e contact arm and thus stops the motor.

Mounting of Starting Boxes. — Starting rheostats are occasionally mounted a small panel, together with the line switches and fuses or circuit breaker quired for the complete protection of the motor circuit.

Multiple Switch Starters. — With the larger d-c. motors, where the start-g conditions are severe, the face type of starter is not found satisfactory; course is therefore had to multiple switch starters, drum controllers, or con-ctors. Multiple switch starters consist essentially of a number of switches ounted on a panel and a separate resistor usually of cast-iron grids. The itches are mechanically interlocked so that it is necessary to close them in quence.

The type of starter shown diagrammatically in Fig. 2 is used with 110-volt otors up to 300 h.p. and with 220- and 500-volt motors up to 600 h.p. The st switch on the right of the dia-am is provided with magnetic blow-t-coils and acts as a circuit breaker. also has voltage release device. rotection against inadvertently leav-g part of the switches open when arting is provided by means of an uxiliary push-button switch that ust be held closed until the last witch on the left is closed, thus nergizing the coil of the low-voltage elease.

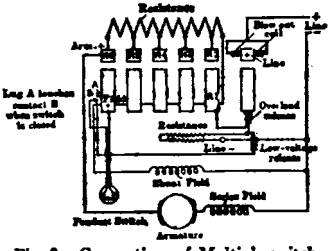


Fig. 2. Connections of Multiple-switch Starter

Starters with Automatically-perated Contactors. — In starting motor the energy required to over-ome the inertia of the motor and the apparatus it is driving must be admitted radually, which is accomplished by introducing resistance into the armature ircuit. If the time taken in starting is too long the resistor may be injured y overheating; if the time is too short the motor may be damaged, the sup-ly circuits seriously disturbed, or gears stripped on the driven machine. For his reason a motor starter that will automatically take care of the proper ate of acceleration presents many advantages. Such a starter can be devised y means of contactors and suitable relays, which are operated either by the ariation of the voltage drop across a resistor as the motor speeds up, or by he decrease in current that permits a solenoid to drop its core, or by other means of acceleration.

Contactor Starter with Series Relay Control (Fig. 3). — Acceleration by series relay control is satisfactory where the voltage does not vary more than 12½ per cent either way from a constant value. Fig. 3 shows the connections of a shunt motor controlled by means of two contactors, a push button station, and a series relay. When the push button is closed in the starting position, the coil of contactor No. 1 is energized, closing the contactor and completing the circuit through the series relay, the starting resistor,

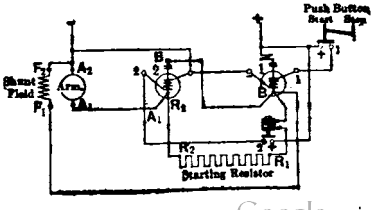
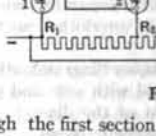


Fig. 3.

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and the armature of the motor. When the starting cu certain value the current in the series relay is no longe the contacts so that connection is automatically mad of contactor No. 2 closing that contactor and short resistors. With large motors several contactors with se

A Contactor with Counter E.M.F. Control is s this method of starting, the operating coils of the thr side connected to the motor brush farthest away from the starting resistor. The other sides of the operating coils are connected to the taps on the starting resistor, the coil on contactor 1, being connected to R_2 on the resistor. The voltage on this coil is equal to the line voltage less the drop in voltage through the first section speed of the motor increases the counter e.m.f., causes a ture current. This reduces the drop to the first section The voltage on the operating coil of contactor 1, is gr this closes. Contactor 2 has its operating coil connect ing resistor. The voltage on this coil is increased by th The increase in current causes a considerable drop i the starting resistor. As this current gradually decrea speed of the motor, contactor 2 closes. Contactor 3 motor armature and closes when the counter e.m.f. of th to the line voltage. The main contactors for closing cuits are not shown in the diagram.



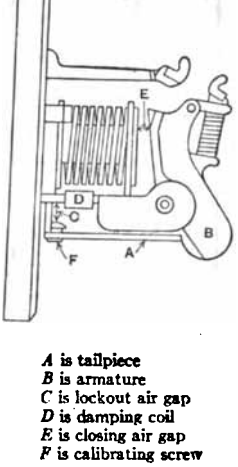
Series Lockout Contactor Method. — Another s frequently used is the series lockout method. With magnetic contactor is provided with a series coil and d rate relay for controlling it. The closing of the magn upon the saturation of the iron in one portion of the can be understood from the diagram of a contactor o Fig. 5. The flux or magnetism in the iron is caused through the operating coil. This flux passes through th ture of the contactors. Part of this flux passes from th armature brackets to the magnetic yoke and thence to the part of the flux passes from the armature through the t yoke. The flux through this last circuit exerts a pull w tactor from closing. The magnetic path through the a small cross-section so that when the current flowing thr exceeds a certain value it becomes saturated and forces through the tail piece holding the contactor open. As the flux in the saturated armature bracket remains through the tail piece decreases until it is not sufficient open. The switch can be adjusted to close at a predeter ing the air gaps between the tail piece and the magne calibrating screw.

The success of starters with acceleration control such depends largely on the contactors or contactor switches. or circuit breakers which are held in the closed position b such as a solenoid or compressed air. A typical conta the lockout contactor shown in Fig. 5, using a shunt c coil and omitting the damping coil and similar features shunt coil is energized the contactor is closed against th

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'ontactors are built both for d-c. and a-c. operation and are made single ole and multiple, single throw and double throw, in various capacities. The ıain arcing contacts are usually protected by ıeans of a magnetic blowout.

These contactors are ordinarily used in conection with a master switch or controller and rotective relays of various kinds to insure the erformance of various functions, such as the utomatic cutting in and out of resistance in he secondary of an induction motor to mainain constant input to a flywheel set or any imilar feature that may be desired such as verload, low voltage and field protection reays limit and sequence switches, etc.



A is tailpiece
B is armature
C is lockout air gap
D is damping coil
E is closing air gap
F is calibrating screw

Fig. 5.

STARTERS FOR INDUCTION MOTORS may be divided into two classes: 1) those used with motors having a squirrel cage or short-circuited secondary, and (2) those or motors having a wound secondary. In the ormer case the starting is done by impressing on the primary a voltage sufficient to induce n the short-circuited secondary the current equired to develop the proper starting torque, nd then transferring the primary connections o full voltage. With induction motors having hase-wound secondaries the method of startng is to connect the primary circuit directly o the line, with the secondary winding hort-circuited through a resistance which is cut out in one or more steps.

With squirrel-cage motors up to about 7½ horsepower it is usually feasible to connect the primary immediately to the full line voltage without drawing an abnormal current from the line. The limiting feature is the power disturbance and its effect on other loads, particularly lighting. With larger squirrel cage motors this is not feasible and consequently there have been developed various means of reducing the voltage impressed on the motor. Motors with special windings and all leads brought out, can be arranged for series parallel grouping of coils, delta-star connections for three phase, and other similar schemes but these are not used to any appreciable extent in America.

Starting Compensators. — Under normal conditions the most satisfactory means of obtaining the reduced voltage for starting induction motors with squirrel-cage secondaries is by the use of auto-transformers or compensators (q.v.). The auto-transformers supplied for starting induction motors are provided with taps permitting the choice of any one of several voltages. The auto-transformers are designed for starting service only and are not intended to be left permanently in circuit.

Connections of Starting Compensator (Fig. 6). — The connections of the starting compensator for a two-phase motor are shown diagrammatically in Fig. 6, the switching mechanism being omitted for the sake of simplicity. Two auto-transformers are used with a two-phase motor; with a three-phase motor there would be used either three Y-connected or two V-connected auto-transformers. In the starting position the voltage at the motor primary which is connected to the auto-transformer is cut down by the auto-transformers from 200 to 130 in this particular case.

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The auto-transformers are provided with taps giving 50 of line voltage for starting, though it is usually found that gives the proper conditions for average service. With the

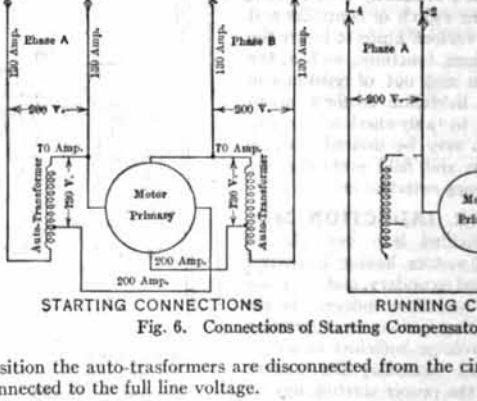


Fig. 6. Connections of Starting Compensato

position the auto-trasformers are disconnected from the ci connected to the full line voltage.

Switch Mechanism. — The auto-starter switches or made of various types, with contacts suitable for the cur The equivalent of a double throw switch is usually furnished ing auto-transformers and connecting the motor to low-volt and the second throw connecting the motor directly to full The second throw always disconnects enough circuits so t through any part of the winding of the transformer and so disconnects the auto-transformers from the circuit. The has three positions and locks automatically in the off an but has to be held in the starting position. In starting a first moved very quickly to the starting position and held t gets up to speed; the handle is then moved quickly past th running position where it becomes locked. A mechanical de ing the handle to the switch from the off position to the runn moving first to the starting position.

Automatic protection with auto-starters is usually secure load trip coils, either connected directly in the circuit or op transformers. Usually the overload protection is only in t With certain types of auto-starter switches the overload r of two solenoids with plungers in two different phases and on each solenoid plunger gives an inverse time element f contacts usually trip independently of the handle so that t held closed on an overload.

Resistance Starters for Induction Motors. — With mo secondary it is customary to connect the primary to full lin and to short-circuit the secondary through a resistor. As t this secondary resistance is cut out in one or more steps u secondary is short-circuited. By properly designing the r ous service instead of for intermittent service, this type of for speed regulation as well as for starting purposes (*see Co*

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With constant-speed induction motors up to 200 h.p. output it is sometimes possible to mount the starting resistor upon the rotor spider, and to control it by butt-contact switches operated by a rod which passes through the hollow rotor shaft. By moving this rod out or in by means of a knob at its outer end the resistance may be connected into the secondary circuit for starting or be disconnected therefrom after the motor has come up to speed. With large motors the terminals of the secondary windings are connected by means of slip rings and a drum controller to the resistor, which in this case consists of three resistors mounted separately from the motor. Each resistor has one terminal connected with one of the three phases of the motor secondary.

The other terminals of the resistors are usually connected in star but sometimes in delta, depending on the current in the motor secondary, the capacity of the resistors, etc. When in star, the neutral is usually grounded to the frame of the controller. The drum of the controller short-circuits the various sections of the resistor by steps.

Resistance Steps for Induction Motor Starters. — Wound secondary motors at standstill act as transformers and the resistance in the secondary circuit has to absorb practically the entire input to the motor; as the motor speeds up, the secondary voltage drops off and resistance is cut out of circuit at such a rate that the motor draws from the line about 50 per cent more than full load primary current. Grid resistors for starting service will rise about 250° F. in two minutes. Grid resistors for speed regulation are designed for the same rise on continuous service.

Starters for "Self-starting" Synchronous Motors. — Where self-starting synchronous motors are used they are provided with a squirrel-cage winding on the rotor in addition to the usual field poles and field coils. Owing to this squirrel-cage winding they are started up as induction motors and controlled by the same type of starting devices. Suitable auxiliary apparatus, such as field rheostats and field switches, must be provided.

CALCULATION OF STEPS FOR RESISTANCE STARTERS.* — (*See also Rheostats.*) Resistance starters usually have from four steps for small motors to seven or ten for large sizes. The number of steps used is commonly somewhat larger than the computed values as a safeguard against excessive starting currents due to improper handling by inexperienced operators. Starters for motors starting under heavy loads are frequently designed with two or three extra steps by which it is permitted to switch the loaded machine on the line with a low current and to raise the current step-by step. On the other hand, in stations where experienced operators are available, large motors and synchronous converters are often started on three or four steps.

Calculation for Shunt-motor Starters. — The design is usually based on a fixed maximum current on each step of the starter, as well as on a fixed minimum current for each step. The minimum current must not be taken as less than the load current required for the maximum load with which the motor is to be started.

Let

I_m = the maximum current on each step of the starting rheostat,
I_0 = the lowest current for which the steps are to be designed,
E = the fixed line voltage,
$C = I_m + I_0$.

Let $K - 1$ be the number of steps required in the rheostat, and let R_1, R_2, . . . R_k be the total resistances in the circuit, including the resistance of the motor, for the successive positions of the contact arm. K is the number of working

* By O. R. Schurig.

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contacts over which the contact arm moves, the first c
the resistance of the rheostat is in the circuit and the Kth
to all the resistance of the rheostat cut out; whence R_K
ance and $R_1 = E \div I_m$. This equation does not take into a
of the motor resistor.

It can be shown that the successive resistances form a
the ratio C, whence

$$K = 1 + \frac{\log\left(\frac{E}{rI_m}\right)}{\log C}, \qquad \text{and} \qquad R_1 = \frac{E}{I_m}, \quad R_2 = \frac{R_1}{C},$$

The value of C must be so chosen that K is a whol
motors which are likely to start under load, the value of
For machines which are started with no load, a larger value
the limiting value being determined by the ratio of maxi
at starting to current at no load. The maximum allowabl
limited to 1.5 times full-load current. Occasionally twi
taken, but the lower value is preferable, particularly if bo
services are connected to the same feeders.

Design of Series Motor Starters. — An algebraic me
tion of the various steps for series-motor starters is rathe
the field flux varies with the line current. A graphic m
fluctuations of current on each step of the starting rheost

Let E = the fixed line voltage, I_m the maximum allo
starting, and I_0 = the minimum allowable current during

Construct the rectangle AI_mOB as in Fig. 7, in which
allowable current during starting, and $(OR_1) = E \div I_m$
of the circuit when the contact arm of the starter is on the
Lay off (AI_0) equal to the minimum current during start
the magnetization curve of the machine, at
some definite speed the armature voltage E_0
for the current I_0, and the armature voltage
E_m for the current I_m at this same speed (*see Motors, Direct-current*). Lay off (OB_0) equal to $(OB) \times \frac{E_0}{E_m}$, and draw the two straight lines (I_mB_0) and (I_0B). Lay off (Or) equal to the resistance of the motor between terminals, and draw (rs) parallel to (OB), and find the point D where (rs) intersects (I_mB_0). Then draw the zig-zag line $I_0v_1C_1v_1F_1v_2 \ldots$ If this line does not meet the point D, then the ratio $I_0 \div I_m$ and the corresponding ratio $E_0 \div E_m$ and the distances (AI_0) and (OB_0) must be altered until meets the new point D. Then extend the horizontal li they cut the vertical axis, at R_2, R_3, . . . The resistances (resistances *between* successive contacts) are then equal t (R_2R_3), . . .

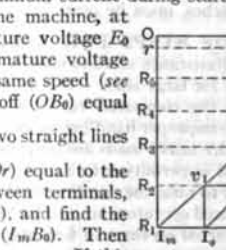


Fig. 7. Gr of Ser

For machines working on a straight line magnetizatio the starter would be equal, as the line (I_0B) would be para

Graphic Method for Shunt-motor Starters.—T also be applied to the determination of the steps of a s which case the point B_0 coincides with B.

COST OF MOTOR STARTERS. — The followin imate only and are intended merely to give a rough idea the common types of starters in 1921.

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COST OF STARTERS FOR 220-VOLT MOTORS *

Horsepower of Motor	1	5	25	100	250
Face plate type	....	$12	$38	$140	.....
Multiple switch type	....	....	.....	500	$600
Contactor type	$45	53	105	450	800
Compensators (auto starters)	....	80	90	200	590

* Starters for 110 or 550-volt motors cost more than 220-volt motors for most sizes.

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STARTING AND LIGHTING SYSTEMS FOR A

— (*See also Batteries, Storage; Generators, Direct-current; Ign. Incandescent; Motors, Direct-current.*) The items com starting and lighting equipment of a gasoline automobile a (2) storage battery, (3) starting motor, (4) lamps, (5) cut-outs, and fuses. In the so-called "single unit" syste starting motor are combined in a single unit. The batter supply energy for starting and lighting but also for ignition (

GENERATOR. — The generator employed is almo wound, and is driven directly by the engine through suit The purpose of the generator is to charge the storage ba nected across its terminals. In order to keep the termina erator substantially constant, which condition is requi charging of the battery, some auxiliary controlling device i wise the terminal voltage of the generator would vary direct engine.

Battery Cut-out. — The generator must of cour to the battery until its voltage is equal to that of the batt taken care of by means of an automatic switch which cl reaches a speed corresponding to a car speed of about 10 opens when the speed falls below this value.

Common Types of Voltage Control. — Numerous de posed and tried out for keeping the generator voltage s after the battery cut-out closes, but at the present time control are in common use, viz., (1) outside regulation, (2 tion, (3) reverse series-field regulation.

Outside Regulation. — A simple form of outside in Fig. 1, which embodies the principle of the Bijur reg resistance is included in the field circuit, which resistance is short circuited when the vibrator is in contact with the contact *C*. When the vibrator is pulled away from the contact *C* by the electromagnet the resistance is inserted in the field circuit and the field current is thereby reduced. As long as the vibrator is operating, the field current will vary between maximum and minimum values, and its average value will depend upon the rate of vibration. The turn will depend upon the voltage across the winding and a very small increase in this voltage will cause a relati the rate of vibration, and therefore make a substantial de value of the field current. Consequently, as the speed thereby tending to produce a varying voltage at the gene tendency is counteracted by the reduction in the field terminal voltage of the generator remains substantially c of the speed.

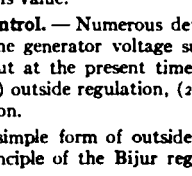


Fig.

A modification of this type of control is used by the We In the Westinghouse regulator, the position of the contact electromagnet connected across the terminals of the genera is actuated by an eccentric coupled to the armature shaf

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eases, the contact *C* is drawn away from the vibrator, with the re- resistance is inserted in the field circuit for a greater length of time. orm of outside regulation which is coming into favor on vehicles is hat of the train lighting systems (*see Lighting of Trains*). The machine is used and regulation is accomplished by passing the arma- through a solenoid which in turn controls a plunger linked to a of a small rheostat.

Brush Regulation. — In this system use is made of the distort- armature reaction (*see Generators, Direct-current*). When current h the armature, the resultant flux is skewed around in the direction ee Fig. 2), with the result that the number of lines of force entering from the leading pole- ed and a corresponding the number of lines of place at the trailing nsequently, referring to vident that the electro- generated between the d the third brush *C*, hown, will decrease as through the armature f the shunt field is con- een the brushes *A* and nt through the shunt refore decrease as the e main circuit increases, rn will reduce the electromotive force between *A* and *C* still nsequently, if the battery is connected across the main brushes *A* tendency for the current to the battery to increase when the generator increases is counteracted by the decrease in the field ch a generator when connected to a storage battery will tend to stant current machine, irrespective of the speed. As a matter of the effect of the short-circuit current in the coil passing under the ich current is practically proportional to the speed and which demagnetizing action, the current to the battery actually reaches value at a definite speed and then falls off.

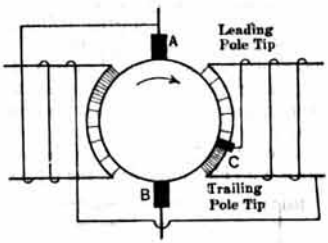


Fig. 2

m of regulation has come into extensive use, due to its simplicity. m current supplied to the generator is readily controlled merely the position of the intermediate brush. For a full treatment of f third brush regulation, see Langsdorf's *Principles of Direct-current*

rse Series-field Regulation. — In this system of regulation a com- d generator is employed, with the series field connected so as to shunt field, i.e., differentially compounded. Up to the present has found but little favor, on account of the inability to control It gives neither a constant voltage nor a constant current char- e current output rising rather rapidly to a maximum and then opping off, due chiefly to the cross magnetization of the armature

Y. — The lead-acid type of storage battery is almost invariably tteries, *Storage*). Batteries of from 6 to 24 volts are employed, 6-volt (3 cell) battery is rapidly becoming the standard. To starting requirements, an ampere-hour capacity of from 60 to 120 depending upon the size of car. A 60-ampere-hour, 6-volt bat-

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tery weighs about 45 pounds, and a 120-ampere-hour, 70 pounds.

STARTING MOTOR. — The conditions under whic operates are widely different from those encountered in c extremely high initial torque is required to overcome the There is also a constant variation in load, due to the and suction of the engine. As the service periods are motor is designed to give its maximum output for only a therefore relatively small compared with a motor desig maximum torque continuously.

The motor is compact and rugged to withstand vibra relatively large size and fitted with large bearings, to wi sudden engagement. Starting motors are usually designe voltage, although there are a few 12- and 24-volt systems average size engine an initial current of about 200 amperes At cranking speed this current drops to about 80 amperes

The torque required to start an engine is dependent upo the compression, the clearances, and the lubricant use above zero have little effect on the starting torque, but there is a decided increase in the torque required. Fig. 3

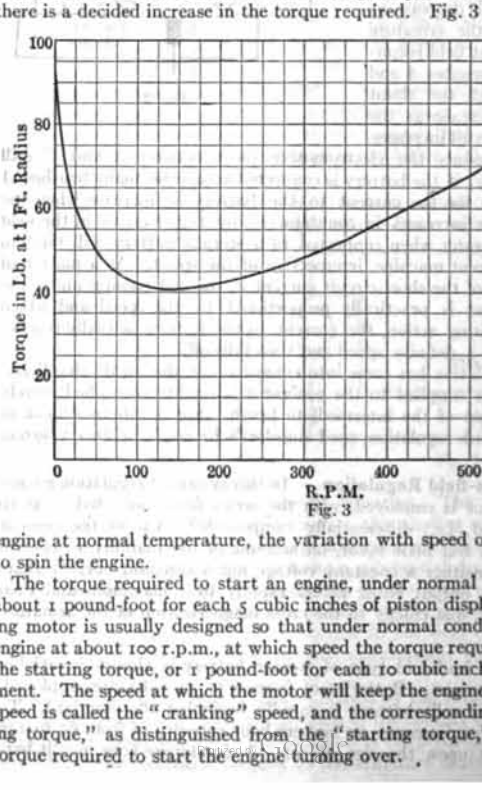


Fig. 3

engine at normal temperature, the variation with speed to spin the engine.

The torque required to start an engine, under normal about 1 pound-foot for each 5 cubic inches of piston displ ing motor is usually designed so that under normal cond engine at about 100 r.p.m., at which speed the torque requ the starting torque, or 1 pound-foot for each 10 cubic inch ment. The speed at which the motor will keep the engine speed is called the "cranking" speed, and the correspondi ing torque," as distinguished from the "starting torque, torque required to start the engine turning over.

ed of the starting motor when developing its cranking torque ranges to 3000 r.p.m., depending upon the design. The gear reduction emges from 8 to 1 to upwards of 25 to 1.

S. — There are two common types of lamps, namely, focusing and ng. In the focusing type, used for head and spot lights, the filament nto a compact spiral, which brings the source of light as near a point e. The non-focusing lamps are usually constructed with a looped ent. Lamps of this type are used for tail lights, cowl lights, and side

n filament lamps are now used almost exclusively. Both the vacuum the nitrogen filled type are employed, the former consuming about candle-power and the latter about ¾ watts per candle-power. The e lamps ranges from 100 to 300 hours under ordinary service condi-

owing table, taken from a paper by H. Schroeder (*Trans. Soc. Aut.*), shows the variation of the characteristics of tungsten lamps with on of the battery.

condition	Per cent, normal volts	Per cent, normal amps.	Per cent, normal watts	Per cent, normal C. P.	Per cent, normal W. P. C.
charged lts per cell)..	68	79	54	23	233
rged lts per cell)..	120	111	133	190	70

ING SWITCH AND FUSES.— Switches used on starting sysf two types, viz., (1) those completing the circuit directly and (2) a solenoid to complete the circuit.

rst, the so-called harpoon type is most generally used, consisting of onnections to laminated copper sections at either side of the switch ovable member extends through the cover and is held extended by a ow. Depressing this plunger completes the circuit. The solenoid ts of a plunger closing the main circuit to the motor after the coil xcited.

ile fuses are now made of standard capacity for maximum currents o amperes. Two sizes of fuses are used, namely,

1¼ in. length overall with ferrules ¼ in. in diameter,
1½ in. length overall with ferrules $\frac{13}{32}$ in. in diameter.

fuses are usually of the sight type.

G. — There are two common systems of wiring in use, i.e., the and the double-wire systems. The single-wire system is the more aving the advantage of cheapness and simplicity. In this system, ortions of the chassis are used to complete the circuit.

ple-wire system is used when leads are not located adjacent to the of the chassis. It has the disadvantages of being more expensive, nger from open circuits is twice as great as in the single wire.

ing circuits and connections between battery and switch, wires of 4 to No. 10 B and S. Gauge are generally used. It is well to use as it costs but little more, and there is a decided saving in electrical o. 14 stranded copper wire, rubber covered and cotton wrapped

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is generally used from switches to side lights, tail light
10 stranded copper wire, rubber covered and cotton wr
for the lines where heavier currents are carried, e.g., fr
switch to head lights, horn, etc.

The size of starting motor cable in general use range
and S. Gauge. The length should always be kept as sh
come excessive losses in voltage. A good rule is to use
for the length required the voltage drop in the cable wh
will not exceed 0.3 volt.

**SPECIFICATIONS FOR INSTALLING E
MENT.** — The following specification for electrical in
from the S.A.E. specification.

Insulation Requirements. — Electrical apparatus
be capable after installation of withstanding 500 volts
between conducting circuit and ground. Tests of t
entire circuit.

Exception. — Batteries will not be subjected to any in
working potential.

Use of Conduit. — Insulated conductors must be p
non-metallic conduit outside of insulation, except wh
from the elements or where out of contact with metal s

Metallic conduit ends must be provided with ferrule
and having a fit sufficiently tight to exclude free entran

Where wires are not protected by conduit, they are to
not exceeding 10 inches. Cleats may be of metal w
interposed between cleats and wire.

Clearance. — Where no conduit is used, as on wo
shall be at least two inches from exhaust pipe.

Connectors. — All connectors shall be so made th
the section which is alive will have all live parts recessed
end of shell of connector.

Springs used in connectors shall not be relied upon to

Protection against Accidental Short-Circuits. —
fuse and junction block or on instruments, generators
which must have live parts exposed, shall be so constructe
that an accidental short-circuit cannot be effected by met
minor repairs or adjustments.

Bulb Sockets. — Bulb sockets must be so made tha
return path is not impaired when lamp is subjected to v

In lamps, hinges shall not be relied upon to carry cur
tions must be either permanent or so spring held that
tight under vibration.

Protective Devices. — The current to all lighting a
be passed through protective devices.

Protective devices shall be on battery side of switches

Temperature Test. — All insulating material used
sockets, and similar devices for electrical apparatus for
mobiles shall be capable of withstanding for 30 minutes a

BIBLIOGRAPHY. — Moyer, J. A., *Gasoline Autos
Automobile and Gasoline Engine Encyclopedia;* Heldt,
mobile, Vol. 3; Hobbs and Elliot, *Gasoline Automobile*.

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— (*See also Boilers; Calorimeters, Steam; Pipes and Piping; Steam am Turbines; etc.*) Steam at a given pressure and at a temperature ay decrease in temperature, the pressure being kept constant, will lensation of water, is said to be "saturated." When the tempera- that a decrease of temperature, the pressure being kept constant, ce without the formation of water, the steam is said to be "super- d the number of degrees that the temperature can be lowered before n of water takes place is called the "degrees of superheat." Saturated contain fine particles of water in the form of spray or mist, in which am is said to be "wet," while if there is no such moisture present said to be "dry." (When the steam produced by a boiler is wet also said to be "primed," and the amount of moisture is called the priming.") Superheated steam is always dry. The weight of the steam in a pound of wet steam (steam and moisture) is called of the steam." The temperature of saturated steam at a given he same whether the steam be dry or wet, and is the same as the of water at that pressure. The temperature of saturated steam, g point, depends solely upon the pressure of the steam.

HEAT OF STEAM. — The amount of heat required to change f water at 32° F. into steam at any pressure, p, is called the "total saturated steam at this pressure. The number of B.t.u. required temperature of one pound of water from 32° to the temperature of d steam at the given pressure is called the "heat of the liquid." ce between the total heat and the heat of the liquid is called the poration."

e of superheated steam, heat is also required to raise the temper- steam from the temperature corresponding to saturation to the of the superheated steam. The total number of B.t.u. required e pound of water at 32° F. into superheated steam is given in the below.

Y OF STEAM. — (*See also Thermodynamics, Principles of.*) ith steam the change in entropy resulting from adding to one e water at 32° F. an amount of heat necessary to raise its temper- boiling point is called the "entropy of the water," the change in ng evaporation, i.e., the heat of evaporation divided by the abso- ture of the boiling point, is called the "entropy of evaporation," ropy of the water plus the entropy of evaporation is called the the steam." The entropy of the water is approximately the he heat added to 1 lb. from 32° to the boiling point divided by of these two temperatures above absolute zero.

TABLES. — Tables giving the values of the various properties the range of temperatures and pressures met with in practice have recomputed by Marks and Davis, using the latest experimental basis for their calculations. The following tables are condensed iven in their *Steam Tables and Diagrams* (N.Y., 1909).

Steam. — Using the symbols at top of the table:

Gage pressure in lb. per square in.	$= p - 14.7$
Vacuum, inches of mercury,	$= 29.92 - 2.036\, p$
Entropy of evaporation	$= N - n$
Pounds per cubic foot	$= \frac{1}{v}$.

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SATURATED STEAM

Inches mercury	Abs. Press., lb. per sq. in.	Temp., °F.	Spec. Vol., cu. ft. per lb.	Heat of Liq., B.t.u.	Heat of Evap. B.t.u.
	p	*t*	*v*	*h*	*L*
29.72	0.1	35.0	2935	3.02	1071.7
29.51	0.2	53.1	1524	21.18	1061.6
29.31	0.3	64.5	1042	32.57	1055.2
29.11	0.4	72.9	794	40.95	1050.6
28.90	0.5	79.7	643	47.74	1046.9
28.70	0.6	85.3	540.7	53.32	1043.8
28.49	0.7	90.2	466.8	58.20	1041.1
28.29	0.8	94.5	411.5	62.49	1038.7
28.09	0.9	98.3	367.9	66.28	1036.6
27.88	1	101.8	333.0	69.8	1034.6
25.85	2	126.2	173.5	94.0	1021.0
23.81	3	141.5	118.5	109.4	1012.3
21.78	4	153.0	90.5	120.9	1005.7
19.74	5	162.3	73.3	130.1	1000.3
17.70	6	170.1	61.9	137.9	995.8
15.67	7	176.9	53.6	144.7	991.8
13.63	8	182.9	47.27	150.8	988.2
11.60	9	188.3	42.36	156.2	985.0
9.56	10	193.2	38.4	161.1	982.0
7.52	11	197.8	35.1	165.7	979.2
5.49	12	202.0	32.4	169.9	976.6
3.45	13	205.9	30.0	173.8	974.2
1.42	14	209.6	28.0	177.5	971.9
0.00	14.7	212.0	26.8	180.0	970.4
Pounds gage					
0.3	15	213.0	26.3	181.0	969.7
5.3	20	228.0	20.1	196.1	960.0
10.3	25	240.1	16.3	208.4	952.0
15.3	30	250.3	13.7	218.8	945.1
20.3	35	259.3	11.9	227.9	938.9
25.3	40	267.3	10.5	236.1	933.3
30.3	45	274.5	9.39	243.4	928.2
35.3	50	281.0	8.51	250.1	923.5
40.3	55	287.1	7.78	256.3	919.0
45.3	60	292.7	7.17	262.1	914.9
50.3	65	298.0	6.65	267.5	911.0
55.3	70	302.9	6.20	272.6	907.2
60.3	75	307.6	5.81	277.4	903.7
65.3	80	312.0	5.47	282.0	900.3
70.3	85	316.3	5.16	286.3	897.1

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SATURATED STEAM (*Continued*)

Abs. Press., lb. per sq. in.	Temp., °F.	Spec. Vol., cu. ft. per lb.	Heat of Liq., B.t.u.	Heat of Evap., B.t.u.	Total Heat, B.t.u.	Entropy of Liq.	Total Entropy
p	*t*	*v*	*h*	*L*	*H*	*n*	*N*
90	320.3	4.89	290.5	893.9	1184.4	0.4644	1.6105
95	324.1	4.65	294.5	890.9	1185.4	0.4694	1.6061
100	327.8	4.43	298.3	888.0	1186.3	0.4743	1.6020
105	331.4	4.23	302.0	885.2	1187.2	0.4789	1.5980
110	334.8	4.05	305.5	882.5	1188.0	0.4834	1.5942
115	338.1	3.88	309.0	879.8	1188.8	0.4877	1.5907
120	341.3	3.73	312.3	877.2	1189.6	0.4919	1.5873
125	344.4	3.58	315.5	874.7	1190.3	0.4959	1.5839
130	347.4	3.45	318.6	872.3	1191.0	0.4998	1.5807
135	350.3	3.33	321.7	869.9	1191.6	0.5035	1.5777
140	353.1	3.22	324.6	867.6	1192.2	0.5072	1.5747
145	355.8	3.11	327.4	865.4	1192.8	0.5107	1.5719
150	358.5	3.01	330.2	863.2	1193.4	0.5142	1.5692
155	361.0	2.92	332.9	861.0	1194.0	0.5175	1.5664
160	363.6	2.83	335.6	858.8	1194.5	0.5208	1.5639
165	366.0	2.75	338.2	856.8	1195.0	0.5239	1.5615
170	368.5	2.68	340.7	854.7	1195.4	0.5269	1.5590
175	370.8	2.60	343.2	852.7	1195.9	0.5299	1.5567
180	373.1	2.53	345.6	850.8	1196.4	0.5328	1.5543
185	375.4	2.47	348.0	848.8	1196.8	0.5356	1.5520
190	377.6	2.41	350.4	846.9	1197.3	0.5384	1.5498
195	379.8	2.35	352.7	845.0	1197.7	0.5410	1.5476
200	381.9	2.29	354.9	843.2	1198.1	0.5437	1.5456
205	384.0	2.24	357.1	841.4	1198.5	0.5463	1.5436
210	386.0	2.19	359.2	839.6	1198.8	0.5488	1.5416
215	388.0	2.14	361.4	837.9	1199.2	0.5513	1.5398
220	389.9	2.09	363.4	836.2	1199.6	0.5538	1.5379
225	391.9	2.05	365.5	834.4	1199.9	0.5562	1.5361
230	393.8	2.00	367.5	832.8	1200.2	0.5586	1.5344
235	395.6	1.96	369.4	831.1	1200.6	0.5610	1.5327
240	397.4	1.92	371.4	829.5	1200.9	0.5633	1.5309
245	399.3	1.89	373.3	827.9	1201.2	0.5655	1.5293
250	401.1	1.85	375.2	826.3	1201.5	0.5676	1.5276
260	404.5	1.78	378.9	823.1	1202.1	0.5719	1.5244
270	407.9	1.72	382.5	820.1	1202.6	0.5760	1.5214
280	411.2	1.66	386.0	817.1	1203.1	0.5800	1.5185
300	417.5	1.55	392.7	811.3	1204.1	0.5878	1.5129
400	444.8	1.17	422	786	1208	0.621	1.489
500	467.3	0.93	448	762	1210	0.648	1.470
600	486.6	0.76	469	741	1210	0.670	1.453

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SUPERHEATED STEAM

v = specific volume in cubic feet per pound, h = total heat, fr
per pound, n = total entropy, from wate

Abs. pres., lb. per sq. in.	Temp. sat. steam, °F.		Degrees of superheat, F				
			20	50	100	150	200
20	228.0	v	20.73	21.69	23.25	24.80	26.3
		h	1165.7	1179.9	1203.5	1227.1	1250
		n	1.7456	1.7652	1.7961	1.8251	1.85
40	267.3	v	10.83	11.33	12.13	12.93	13.7
		h	1179.3	1194.0	1218.4	1242.4	1266
		n	1.6895	1.7089	1.7392	1.7674	1.79
60	292.7	v	7.40	7.75	8.30	8.84	9.36
		h	1187.3	1202.6	1227.6	1252.1	1276
		n	1.6568	1.6761	1.7062	1.7342	1.76
80	312.0	v	5.65	5.92	6.34	6.75	7.17
		h	1193.0	1208.8	1234.3	1259.0	1283
		n	1.6338	1.6532	1.6833	1.7110	1.73
100	327.8	v	4.58	4.79	5.14	5.47	5.80
		h	1197.5	1213.8	1239.7	1264.7	1289
		n	1.6160	1.6358	1.6658	1.6933	1.71
120	341.3	v	3.85	4.04	4.33	4.62	4.89
		h	1201.1	1217.9	1244.1	1269.3	1294
		n	1.6016	1.6216	1.6517	1.6789	1.70
140	353.1	v	3.32	3.49	3.75	4.00	4.24
		h	1204.3	1221.4	1248.0	1273.3	1298
		n	1.5894	1.6096	1.6395	1.6666	1.69
160	363.6	v	2.93	3.07	3.30	3.53	3.74
		h	1207.0	1224.5	1251.3	1276.8	1301
		n	1.5789	1.5993	1.6292	1.6561	1.68
180	373.1	v	2.62	2.75	2.96	3.16	3.35
		h	1209.4	1227.2	1254.3	1279.9	1304
		n	1.5697	1.5904	1.6201	1.6468	1.67
200	381.9	v	2.37	2.49	2.68	2.86	3.04
		h	1211.6	1229.8	1257.1	1282.6	1307
		n	1.5614	1.5823	1.6129	1.6385	1.66
220	389.9	v	2.16	2.28	2.45	2.62	2.78
		h	1213.6	1232.2	1259.6	1285.2	1310
		n	1.5541	1.5753	1.6049	1.6312	1.65
240	397.4	v	1.99	2.09	2.26	2.42	2.57
		h	1215.4	1234.3	1261.9	1287.6	1312
		n	1.5476	1.5690	1.5985	1.6246	1.64
260	404.5	v	1.84	1.94	2.10	2.24	2.39
		h	1217.1	1236.4	1264.1	1289.9	1315
		n	1.5416	1.5631	1.5926	1.6186	1.64
280	411.2	v	1.72	1.81	1.95	2.09	2.22
		h	1218.7	1238.4	1266.2	1291.9	1317
		n	1.5362	1.5580	1.5873	1.6133	1.63

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V OF STEAM THROUGH A NOZZLE. — The rate of flow of rough a nozzle increases as the difference in the pressures on the two the nozzle increases, until the absolute pressure p_0 of the atmosphere ch the nozzle discharges reaches 58 per cent of the initial absolute p of the steam. For greater differences in pressure, i.e., for $\frac{p_0}{p} < 0.58$, of flow through a given nozzle depends only upon the initial absolute of the steam. For $\frac{p_0}{p} < 0.58$ the percentage change in the volume of the it passes through the nozzle also remains constant, the ratio of initial o expanded volume being 1.624. The following formulas have been the authorities stated for the flow of steam through a nozzle when 3. The notation is P = initial absolute pressure in pounds per square = smallest cross section of nozzle in square inches; W = flow in pounds te; x = quality of steam = $\frac{100 - y}{100}$ where y is the per cent of moisture; rheat in degrees F.

	Dry saturated	Moist	Superheated
.....	$W = 0.857 A P$		
.....	$W = A P^{0.97}$	$\frac{A P^{0.97}}{x}$	$A P^{0.97} (1 + 0.00065 D)$

V OF STEAM THROUGH PIPES, VALVES, AND BENDS. — *s and Piping.*)

OGRAPHY. — Marks and Davis, *Steam Tables and Diagrams: Steam Tables;* Ennis, W. D., *Applied Thermodynamics.* See also phies in the articles on *Boilers, Steam,* and *Steam Engines.*

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STEAM ENGINES. — (*See also Condensers; Power Turbines.*) A steam engine is a machine in which the verted into mechanical energy by means of the pressu more parts of the machine. This article treats of the r steam turbines (q.v.) are treated in a separate article.

CLASSIFICATION. — The principal classificatio gines are the following:

Single- and Double-acting Engines. — If the ste of the piston it is a single-acting engine; if on both si

Throttling and Automatic Engines. — A throttlin the speed of the engine is governed by a throttle valve i vary the pressure of the steam admitted to the engine engine is one in which steam is always admitted at ful by a valve or valves at different points in the stroke a point at which the cut-off takes place being autom governor.

Throttling as a means of governing is seldom emplo engines. It affords a simple and reliable means of sp etc. Automatic regulation of cut-off is capable of clos permits higher ratios of expansion.

Condensing and Noncondensing Engines. — A c in which the steam is exhausted into a condenser, by me is reduced usually to within 1 to 3 pounds per square inch A non-condensing engine is one whose exhaust steam i atmospheric pressure. Any engine can be operated co ing, but certain minor modifications are usually made i when it is to be operated normally condensing.

Binary-vapor Engine. — This is a very spec engine. Sulphur dioxide, instead of water, is used as surface condenser. The sulphur dioxide in condensin itself vaporized and this vapor, under a pressure of abou inch, is used expansively in a secondary reciprocating sulphur dioxide is discharged into a surface condenser i cooling water, much the same as in refrigerating prac over again. This type of engine has never come into

High- and Low-speed Engines. — This classific (fly wheel) speed only; engines having a rotative spee minute or less are usually classified as low-speed engi speed is greater than 150 revolutions per minute the speed engine. A high-speed engine may have a lo low-speed engine; the relation between piston speed pends solely on the length of stroke.

Compound and Multiple-expansion Engines. — one in which the steam is partially expanded in a sm carried to one or more larger cylinders in which it is fu cylinders are in line with each other, using a common tandem compound; if the smaller and larger, or high-p cylinders are side by side it is called a cross-compoun simpler, lighter, cheaper and more compact, and serv ancing and uniform crank effort are not essential. vertical or horizontal. Vertical engines take up less fl costly than horizontal engines.

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ine in which the total expansion of the steam is divided into three gh-, intermediate- and low-pressure, is a triple-expansion engine; if stages, a quadruple-expansion engine. Multiple-expansion engines n compound) are seldom used for driving electric generators.

cation According to Valve Gear. — Engines are also classified to their valve gear (*see Valve Gear, below*), as Corliss engines, slide- nes, piston-valve engines and poppet-valve engines.

N AND CONSTRUCTION. — For a more complete treatment of and construction of steam engines see Kent's *Mechanical Engineers' ok.* A brief discussion of valves and governors is given below.

and Valve Gear. — Three types of valves are used to control the and exhaust of the steam to and from the cylinder, namely the slide liss valve and poppet valve.

de Valves. — Fig. 1 shows a cylinder with a plain slide valve of the type. The valve rests in a V-shaped groove in the bottom of the st, and is held up seat by pressure eam. The valve asses through a the back of the shown by the section of the and steam chest, ows the valve to nst its seat with- ging the valve

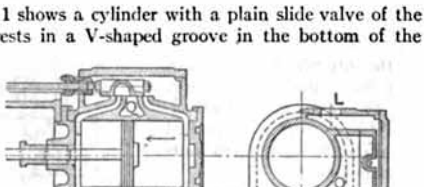


Fig. 1. Plain Slide Valve

lrawing, the valve is shown moved over to the left so as to allow the steam chest to pass into the head end of the cylinder and force toward the left. Steam from the crank end of the cylinder can flow cavity in the valve to the exhaust space *Q*. Steam enters by the

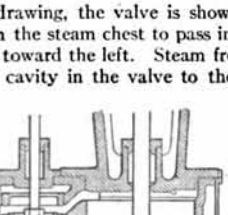


Fig. 2. Piston Valve

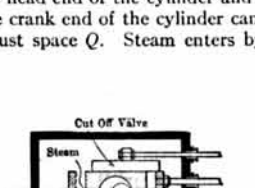


Fig. 3. Riding Cut-off Slide Valve

(transverse section) and escapes through the exhaust space *Q*. As moves toward the end of the forward stroke, the valve is moved by ric to the right, and it first shuts off the supply of steam from the head he exhaust from the crank end of the cylinder, and then opens the steam for the crank end and the exhaust for the head end just before stroke is begun.

ypes of slide valves are the piston valve and the riding cut-off valve. mer. Fig. 2, is used a piston filling an auxiliary cylinder which takes

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the place of the steam chest used with the common type. The riding cut-off slide valve, Fig. 3, is essentially a double slide valve. The riding cut-off controls the point of cut-off only, the points of admission, release and compression being controlled by the main valve. (*See Fig. 3 below.*)

Any adjustment of the simple slide valve changes all four events of the stroke, namely admission, cut-off, release and compression. With the riding cut-off slide valve the cut-off can be varied independent of the other events.

Corliss Valve. — To make all four events of the stroke independently adjustable, four separately controlled valves are necessary, One of the first successful four-valve engines was invented by George Corliss in 1848. Various modifications of the original Corliss valve gear have since been made, but the same general principle of operation is embodied in practically all modern four-valve engines.

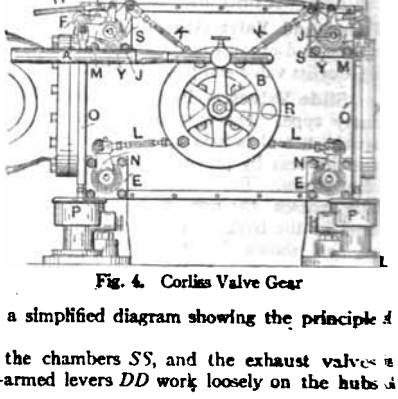


Fig. 4. Corliss Valve Gear

Fig. 4 shows the general external appearance of a simple Corliss valve gear and Fig. 5 is a simplified diagram showing the principle of operation.

"The steam valves work in the chambers *SS*, and the exhaust valves in the chambers *EE*. The double-armed levers *DD* work loosely on the hubs of the steam bonnets; they are connected to the wrist plate *B* by the rods *KK*; the levers *MM* are keyed to the valve stems *JJ*, and are also connected by the rods *OO* to the dashpots *PP*. The double-armed levers *D* carry at their outer ends steam hooks *FF*, these being provided with hardened-steel catch plates which engage with arms *MM*, making the arm *M* and the hook *F* work in unison until steam is to be cut off. At this point another set of levers or cams *GG*, connected by the cam rods *HH* to the governor, come into play, causing the catch plates on the hooks *F* to release the arms *MM*, the outer ends of which are then pulled downwards by the dashpot plunger, causing the steam valves to rotate on their axis and thus cut off steam. The exhaust valve arms *N* are connected to the wrist plate by the rods *LL*, and it is seen that all the valves receive their motion from the wrist plate *B*; the latter receives its motion from the hook rod *A*. This rod is attached to a rocker arm; to this arm the eccentric rod is also attached.

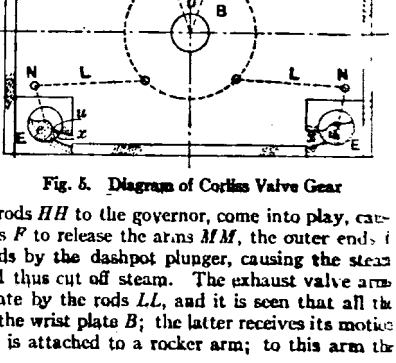


Fig. 5. Diagram of Corliss Valve Gear

"In order to obtain a greater range of cut-off in Corliss engines, a separate steam and exhaust eccentric is used. With two eccentrics the admission and

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valves can be adjusted independently, and steam may be cut off anyearly to the end of the stroke." (*From Types of Modern Engines and ve Setting, by M. C. Myers, Boston, 1910.*)

ppet Valves. — This type of valve for engine cylinders is largely urope, but only to a limited extent in this country. Fig. 6 illustrates of poppet valve and valve gear, known as the Sulzer valve gear.

mparison of Different f Valves. — Multi-valve re more expensive than ve types, but give better due to the independent of cut-off and other the stroke, and to the equirements of clearance space. Rotary valves are icult to make and keep t when used with superam than the poppet and ypes. The erosive action evere temperature strains superheat add much to lty of maintaining a good but the difficulties are in the best designs.

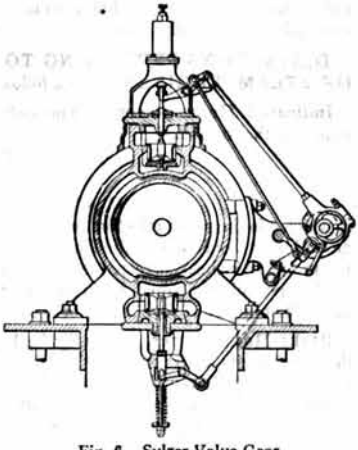


Fig. 6. Sulzer Valve Gear

ors. — Two types of govused, viz., the pendulum nd the flywheel types.

ndulum Governor.—The on of the pendulum governor is too well known to need description. of governor can be made to control the quantity of steam admitted nder either by opening or closing a throttle valve, or by varying f cut-off. In the latter case a suitable link motion (*see below*) must d.

wheel or Shaft Governor. — This type of governor is now largely ially for high-speed automatic engines

es governor, Fig. 7, one of the commonest forms of flywheel gov-

f the single-weight or inertia type. The ravity of the weight is located approxi-. The governor is shown in position for ff; the rotation is in the direction of the y increase in speed tends to make the avity of the weight seek a position further the center of the shaft and causes the wing on its pivot in a direction opposite to wheel; the eccentric is attached to the this movement brings the center of the arer the center of the shaft, and increases advance, thus effecting an earlier cut-off.

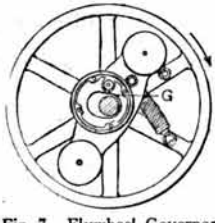


Fig. 7. Flywheel Governor

other types of shaft governors are described in detail in a small *ft Governors* (*Hill Pub. Co., 1908*).

tion. — Link motions, of which the Stephenson link is the most sed, are designed for two purposes: first, for reversing the motion e, and second, for varying the point of cut-off by varying the travel

of the valve. The Stephenson link motion is a combi called forward and back eccentrics, with a link conne the eccentric rods, so that by varying the position o may be put in direct connection with either eccentric ment controlled in part by one and in part by the oth link is moved by the reversing lever into a position such the valve rod is attached is at either end of the link, th imum travel, and when the link is in mid-gear the trav takes place early in the stroke.

DEFINITIONS PERTAINING TO RATING A OF STEAM ENGINES. — The following terms are

Indicated Horse-power. — The indicated horse-p found by the formula

$$P = \frac{pLAN}{33{,}000},$$

in which p is the mean effective pressure, in pounds per an indicator (*see below*), L the length of the stroke in fe ton in square inches (corrected for area of the piston rod) strokes per minute, equal to the number of revolutio twice the number of revolutions of a double-acting engi

Brake Horse-power. — The brake horse-power of delivered by its shaft as determined by a dynamomete equal to the indicated horse-power minus the power ab engine. In well-designed engines working under nor usually from 8 to 12 per cent of the indicated power; t in friction is nearly a constant at all loads, so that its 100 as the load decreases to zero, when the whole of the absorbed in overcoming friction.

Rated Horse-power. — When an engine is comme horse-power it is understood that it will deliver that those conditions for which it is designed, such as spee pressure, etc., and cutting off at that fraction of the s best economy. Its rated overload capacity is the po the same speed, steam pressure and back pressure, and point which the design of the valve motion will permit.

Indicator Diagram. — An indicator diagram is a showing the steam pressure in the engine cylinder at e Such a diagram may be actually obtained by means of a steam-engine indicator, which is an instrument which causes a pencil to record on paper the pressure in the cylinder at every point of the stroke. The diagram drawn by the pencil shows whether the valves are properly adjusted, and it is also used in figuring the power developed in the cylinder, and approximately the steam consumption. A diagram of a noncondensing engine in which the steam is cut off at about one-quarter of the stroke is shown in Fig. 8.

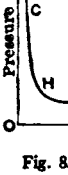


Fig. 8

The lines and points have the following significance.

Point of Admission, C, is the point at which t

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ssion Line, *CD*, shows the rise of pressure due to the admission of cylinder by opening the steam valve.

n Line, *DE*, is drawn when the steam valve is open and steam itted tc the cylinder.

of Cut-off, *E*, is the point where the admission of steam is the closing of the valve. It is often difficult to determine the t which the cut-off takes place. It is usually located where the e diagram changes its curvature from convex to concave.

nsion Curve, *EF*, shows the fall in pressure as the steam in the nds doing work.

of Release, *F*, shows when the exhaust valve opens.

ust Line, *FG*, represents the change in pressure that takes place aust valve opens.

-pressure Line, *GH*, shows the pressure against which the piston ts return stroke.

of Exhaust Closure, *H*, is the point where the exhaust valve annot be located definitely, as the change in pressure is at first radual closing of the valve.

ression Curve, *HC*, shows the rise in pressure due to the com- he steam remaining in the cylinder after the exhaust valve has

l Pressure is the pressure acting on the piston at the beginning of

inal Pressure is the pressure above the line of perfect vacuum xist at the end of the stroke if the steam had not been released s found by continuing the expansion curve to the end of the

Definitions. — In addition to the terms defined above, the fol- mmonly employed:

tle Pressure is the pressure in the steam pipe at the entrance to valve.

Effective Pressure is that equivalent constant pressure which ame amount of work on the piston per stroke as is done by the sure shown by the indicator card. This may be calculated by area of the card by the length and multiplying by the scale of the n the indicator.

ance. — The portion of the cylinder volume, including the steam wept through by the piston but which is nevertheless filled with admission occurs is called the clearance volume. It ranges from 1 he piston displacement in very large engines to 10 per cent or more -speed engines.

of Expansion is the ratio of the piston displacement (in low- nder in case of a multiple-expansion engine) to the volume of dmitted through the throttle valve at each stroke (or half stroke double-acting engine), the volume being that corresponding to the the engine side of the throttle valve.

Drawing, as applied to steam, is the reducing of its pressure, wing through restricted pipes and passages.

NCY OF A STEAM ENGINE. — By the thermal efficiency of ne is meant the quotient of the B.t.u. per hour equivalent to the

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indicated horse-power divided by the total number of B.
per hour; or, putting

W = pounds of steam supplied per hour per indicate
x = quality of the steam supplied (= lb. of dry ste
see article on *Steam*),
L = heat of evaporation per pound of steam at throt
pound,
h = heat of the liquid at throttle pressure, B.t.u. pe
h_0 = heat of the liquid of feed water, B.t.u. per
perature corresponding to the pressure in the exh
(*See A.S.M.E. code, 1913.*)

Then the thermal efficiency for saturated steam is

$$E_t = \frac{2546.5}{W(xL + h - h_0)}.$$

If the steam is superheated, let

H = total heat of superheated steam at throttle pres
heat, in B.t.u. per pound.

Then the thermal efficiency is

$$E_t = \frac{2546.5}{W(H - h_0)}.$$

The above formulas are also applicable to the calcul
ciency, including friction losses, if W is taken as the pou
hour per brake horse-power.

Efficiency of Rankine Cycle. — The maximum p
is that of an engine performing the ideal Carnot's cy
Principles of), but this cycle is not very closely simula
even when the losses are neglected. Instead the effi
cycle" is employed as a standard of reference. This
assumes that the work done by the engine is equal t
(*see Thermodynamics*) corresponding to an adiabatic
pressure to exhaust pressure and an isothermal cond
steam and a compression of the condensed water to thr

Rankine Efficiency for Dry Saturated Ste

H_1 = total heat, B.t.u. per pound, of dry saturated st
H_2 = total heat, B.t.u. per pound, of dry saturated st
h_2 = heat of the liquid, B.t.u. per pound, at exhaust t
T_2 = temperature of exhaust steam, in ° F.,
N_1 = total entropy of 1 pound of dry saturated steam
N_2 = total entropy of 1 pound of dry saturated stean

Then the efficiency is

$$E_r = \frac{H_1 - H_2 + T_2(N_2 - N_1)}{H_1 - h_2}.$$

Rankine Efficiency for Wet Steam. — In ad
bols let

H_w = total heat, B.t.u. per pound, of wet steam at th
N_w = total entropy of 1 pound of wet steam at throtl
T_1 = temperature of steam at throttle pressure, in °F

Then the efficiency is

$$E_r = \frac{H_w - H_2 + T_2(N_2 - N_w}{H_w - h_2}$$

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ankine Efficiency for Superheated Steam.—In addition to the
bols let

otal heat, B.t.u. per pound, of superheated steam at throttle pressure,
otal entropy of 1 pound of superheated steam at the given degree of
superheat at throttle.
efficiency is

$$E_r = \frac{H_s - H_2 - T_2 (N_s - N_2)}{H_s - h_2}.$$

cy Ratio Referred to the Rankine Cycle.—This is the ratio of
l efficiency of the actual engine (referred to indicated or brake horse-
he case may be) to the efficiency of the Rankine cycle between the
s of temperature and pressure as those observed in the actual engine.
e of steam turbines the thermal efficiency is referred to the brake
r. In the case of reciprocating engines it is usually referred to the
orse-power.

TEAM ENGINE EFFICIENCIES—SATURATED STEAM.

(*From Gebhardt's Steam Power Plant Engineering.*)

Noncondensing				Condensing — 1 lb. absolute pressure			
arnot cycle	Rankine cycle	Best actual (1907)	Eff. ratio %	Carnot cycle	Rankine cycle	Best actual	Eff. ratio %
7.5	7.3	5.5	76	22.6	21.0	11.6	55
11.2	10.7	8.5	80	25.7	23.5	13.5	60
13.7	13.0	10.4	80	27.8	25.3	15.9	61
15.7	14.8	12.0	81	29.5	26.7	20.2	76
17.3	16.3	13.5	83	30.8	27.8	20.3	74
18.7	17.5	14.3	82	32.0	28.8	21.6	75
19.8	18.5	14.8	80	32.9	29.6	21.9	74
20.8	19.3	15.2	79	33.7	30.2	22.6	75
21.6	19.9	15.5	78	34.5	30.6	22.6	74
22.4	20.5	....	..	35.1	31.0	....	..
23.0	21.0	....	..	35.6	31.3	....	..
23.6	21.4	....	..	36.0	31.5	....	..

al thermal efficiencies of multiple expansion engines using superheated
e from about 19 to 23 per cent.

Losses. — The actual efficiencies of steam engines are necessarily
than the efficiency of the Rankine cycle due to the thermal and
losses. These losses consist chiefly of (1) cylinder condensation,
eakage, (3) incomplete expansion and compression on return stroke,
, (5) clearance loss, (6) radiation and (7) the admission of wet

nder Condensation is due to the chilling of steam by the cooler
lls during admission and early expansion, thus reducing the active
expansion. Condensation increases with the range of expansion
and with the duration of the cycle. The condensation loss is

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augmented by the formation of a water film on the cylinder walls. It is successfully reduced by expanding the steam in several stages, thus reducing the range of temperature in each cylinder and rendering the heat carried to the exhaust in that cylinder available in succeeding cylinders. Other remedies for condensation are: increasing the rotative speed; steam jackets about the cylinders; and reheaters to dry the steam between cylinders. The most positive and effective remedy is superheat sufficient to keep the steam dry at least during admission.

Steam Leakage past valves, pistons and packing increases with the pressure difference. It is an important element of loss in all piston engines and tends to increase with the wear of moving parts. Leakage is especially serious in cylinders employing a wide range of pressures. Flow of steam through orifices, in pounds, increases directly as the pressure (Napier's rule), and through pipes as $\sqrt{\text{density}}$. (*p. 845* Kent's *Mechanical Engineers' Pocket-Book.*)

Incomplete Expansion and Compression. — As a rule the release occurs before the piston reaches the end of the stroke and the point of closure comes before the piston reaches the end of the back stroke. There is a consequent loss of expansion on the forward stroke. The piston also has to do work in compressing the steam remaining in the cylinder on the reverse stroke. These two features are, as a rule, necessary; the first to reduce cylinder condensation, and the second for its cushioning effect. The first always, and the second usually, results in a net loss.

Friction varies with the type and condition of the engine, is greater in compound engines than in simple engines, and is nearly independent of the load, increasing but slightly as the load increases. It ranges from 4 to 20 per cent of the rated output.

Losses Due to Radiation, Clearance and Moisture. — With well-lagged cylinders radiation losses are small. Some clearance is necessary in every engine, but the amount is much greater for high speeds than for low speeds. The loss due to it is trifling in slow-speed engines of long stroke. Moisture dilutes the steam admitted but has little effect on the consumption of *dry* steam; the consumption of the fluid (steam and moisture) is of course increased in proportion to the percentage of moisture present.

ECONOMY OF STEAM ENGINES.* — The performance of a steam engine is frequently expressed in terms of the number of pounds of steam per hour required per indicated horse-power, per brake horse-power or per kilowatt (if used to drive an electric generator). The number of pounds of steam per unit of output is called the "economy" of the engine or of the combined engine and generator unit.

Such data may be very misleading unless comparisons are based on identical conditions of steam pressure, superheat, vacuum, etc. A true measure of economy applicable to all conditions may be expressed in net heat units consumed per unit of output, as B.t.u. per kilowatt-hour. In such determinations of economy all heat returned from the exhaust to the boiler should be credited to the engine or turbine.

The commonest means of gaining good engine economy are: raising the initial pressure, compounding, condensing and superheating.

Effect of Steam Pressure on Economy and Capacity. — There can be no universal rule connecting initial pressure and working economy. Compound

* Adapted from lecture notes of Prof. W. E. Wickenden.

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ngines are better adapted to high pressures than simple engines. Experience ndicates that the following gauge pressures are desirable:

Simple, condensing engine without steam jackets	60 lb.
Simple, condensing engine with steam jackets.....	80 lb.
Simple, non-condensing engine without steam jackets .	100 lb.
Compound, non-condensing engines	175 lb.
Compound, condensing engines	150 lb.
Triple-expansion, condensing engines	175 to 200 lb.
Quadruple-expansion condensing engines	200 lb.

An important advantage from the use of high pressures is the greater capacity which can be developed from a given engine. The ratio of pressure and capacity s nearly a direct one. High pressures tend to improve economy but not to the extent theoretically available, due to the counteracting effects of condensation and steam leakage with increasing pressure ranges. High steam pressures, however, usually add to the expense of piping and its maintenance. From an examination of a large number of engine performances Stevens and Hobart give the general relation of pressure and economy as shown in Fig. 9.

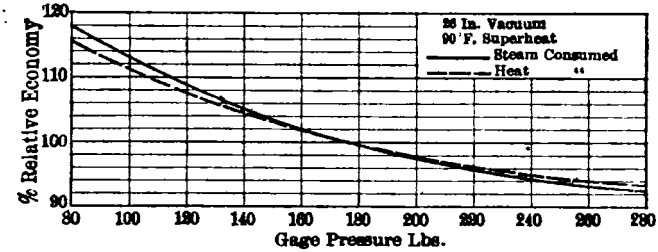


Fig. 9. Effect of Steam Pressure on Economy of Compound Piston Engines

Effect of Multiple Expansion on Economy. — The loss due to cylinder condensation increases with an increase of the difference of temperature of the steam during admission and exhaust, and therefore tends to become greater as the initial pressure is higher. By dividing the total range of expansion into two or more stages, the range of temperature in any one cylinder is decreased, and this lessens the total loss due to cylinder condensation.

Triple and quadruple expansion afford substantial economies with constant load as in pumping and marine service, but have little advantage with the variable loads of electric service to compensate for their great weight, complexity, bulk and cost. Compound engines with high cylinder ratios permit more complete expansion, but have less overload capacity than engines of smaller ratios. For electric service more than 18 expansions is seldom profitable. A cylinder ratio of 1 : 2.5 is well adapted to a pressure of 100 pounds; 1 : 3 to 125 pounds; 1 : 3.5 to 150 pounds and 1 : 4 to 175 pounds or above. Compound engines are relatively uneconomical at light loads, but have a greater economical range of overloads than simple engines. Compound engines, with a moderate cylinder ratio, usually give their best economy at ¼ cut-off in the high-pressure cylinder and will safely carry an overload of 50 per cent.

Effect of Condensing on Economy. — Condensing serves to increase both the capacity and economy of engines. The theoretical gain from condensing to various back pressures is indicated in Fig. 10. Actual engines can avail themselves of but a part of this gain, the proportion falling as the vacuum is increased due to the added condensation and leakage. Expansion to very

low pressures requires cylinders of excessive volume. Condensing equipment, especially that for high vacuum, adds much to the first cost of a plant and hence

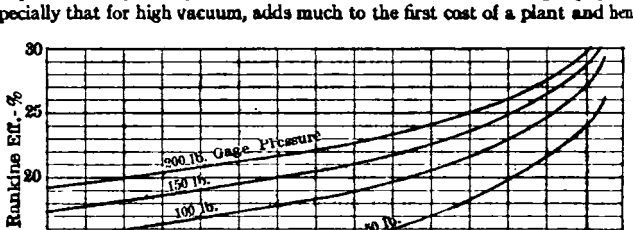


Fig. 10. Effect of Vacuum on Theoretical Efficiency

to its burden of fixed charges. (*See article on Condensers.*) Condensers require from one to three pumps and the thermal gain is reduced by the amount of their heat consumption. The temperature of the exhaust steam is lowered as the vacuum increases and so reduces the heat which can be reclaimed in the feed water. It is of great importance that the net gain rather than the apparent gain be considered in determining the economics of various vacua. Reduced steam consumption lessens the necessary investment in steam-generating equipment and piping, and this tends to somewhat counterbalance the investment in condensing apparatus. (*See article on Power Stations.*)

Effect of Superheating on Economy. — Superheating the steam is more effective than using steam jackets and reheaters as a preventive of cylinder condensation under the usual central-station conditions. With proper valve structures there is a decided net saving in heat consumption as the superheat is increased within reasonable limits, but this procedure usually adds to the

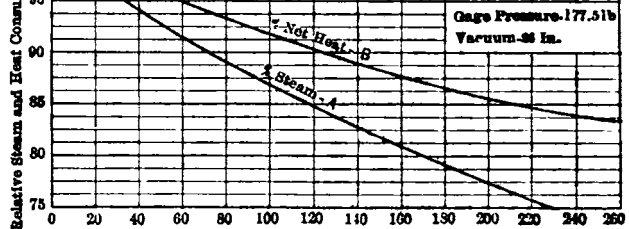
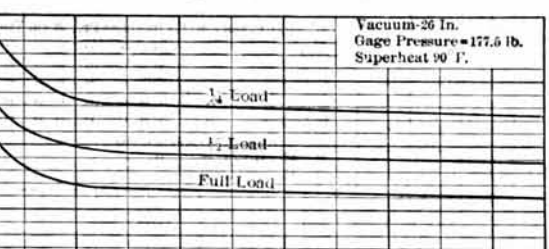
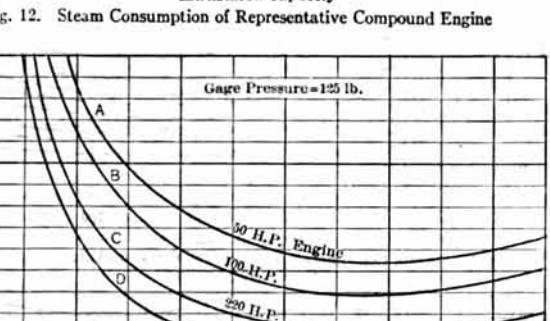


Fig. 11. Effect of Superheat on Piston-engine Economy

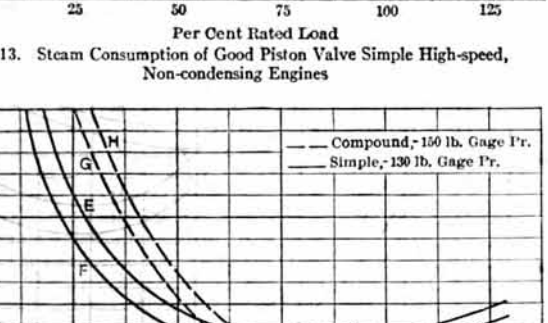
cost of piping, fittings and their upkeep. Stevens and Hobart report the mean relationship between superheat and economy in compound and multiple expansion engines, as shown in Fig. 11. It is especially important that economic comparison be based on the heat unit consumption as in Curve B. Additional advantages from superheating are the reduction of condensation, radiation losses and pressure drop in steam pipes.



g. 12. Steam Consumption of Representative Compound Engine



13. Steam Consumption of Good Piston Valve Simple High-speed, Non-condensing Engines



14. Steam Consumption of Good 4-Valve Non-condensing Engines

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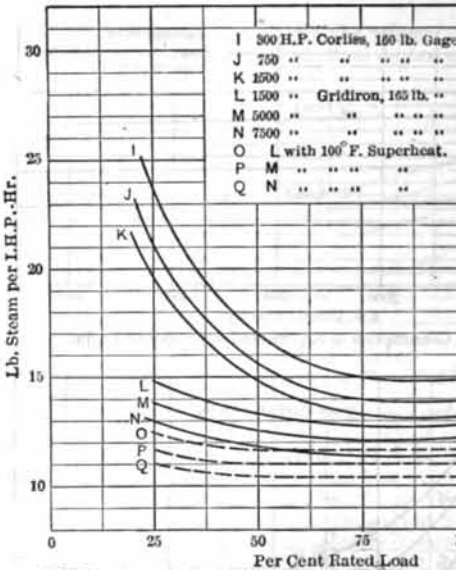


Fig. 15. Steam Consumption 4 Corliss and Grid-iron
Condensing Engines

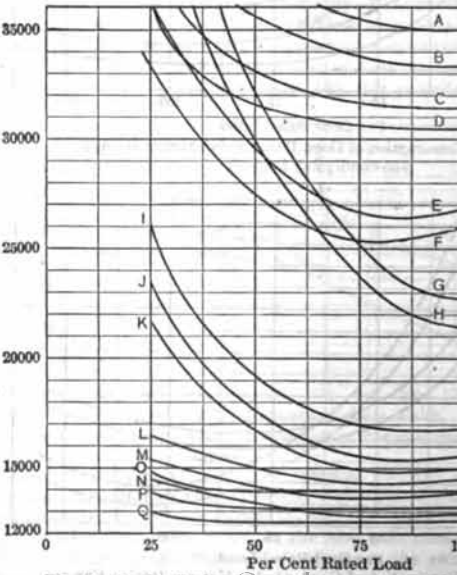


Fig. 16. Engine Performance in B.t.u. per Indicated

Variation of Economy with Load. — Other factors affecting the economy of engines are the size of the unit, the speed, the mode of governing and the uniformity of load. Stevens and Hobart give the relations between engine sizes, loads and economy shown in Fig. 12 as averages for compound piston engines. Simple engines as a rule show smaller variation in economy with partial loads than compound engines. Typical economy curves for simple and compound engines with saturated steam and compound engines with superheated steam are shown in Figs. 13 to 16. The curves in Fig. 16 correspond to like lettered curves in the other figures.

Economy of the Binary-vapor Engine. — With this type of engine there has been obtained an economy of only 8.36 pounds of steam per indicated horse-power-hour, corresponding to a heat consumption of 158.3 B.t.u. per minute. This was the best recorded performance in steam-engine practice at the time of the report (1907) and has not been noticeably exceeded since (1913).

DIMENSIONS AND WEIGHT OF ENGINES depend so largely upon the type, speed, etc., that it is impossible to give representative figures in the space available. The following table from the *Elec. World*, (*Sept., 1902*), gives the dimensions of some very large engines in New York City.

DIMENSIONS OF SOME LARGE RECIPROCATING ENGINES

Name of station.....	Metropolitan	Manhattan	Kingsbridge	Rapid Transit	Edison
Type of engine.....	Vert. cross-comp.	Double 2 hor. 2 vert. cyls.	Vert. cross-comp.	Double, 2 hor. 2 vert. cyls.	3-cyl. vert.
Rated horse-power.....	4500	8000	4500	8900	5200
Cylinders, all 60-in. stroke, in.....	46, 86	44, 88	46, 86	42, 86	43½, 2–75½
Piston rods, diam., in.....	9, 10	8	9, 10	8, 10	9
Crank pins, in.....	14×14	18×18	14×14	20×18	22 & 16×14
Wrist pins, in.....	14×14	12×12	14×14	12×12	14×14
Shaft length	27 ft. 4 in.	25 ft. 3 in.	27 ft.	25 ft. 3 in.	35 ft.
max. diam.....	37 in.	37 in.	39 in.	37 in.	29⅝ in.
bearings, in.....	34×60	34×60	34×60	34×60	26×60

The shafts are hollow, with a 16-inch hole, except the Edison which have a 10-inch hole. The speed of all the engines is 75 revolutions per minute, or 750 feet per minute. The crank pins of the Manhattan and Rapid Transit engines are each attached to two connecting rods, side by side, horizontal and vertical, each rod having a bearing 9 inches long on the pin. The crank pins of the Edison engine are 16 inches in diameter for the side cranks, and 22 inches for the center crank.

TESTING OF STEAM ENGINES. — The actual work done by an engine may be tested by a brake or friction dynamometer, or in the case of engines driving electric generators by measuring the electric energy delivered, correction being made for the efficiency of the generator. The work done in the cylinder is obtained by taking numerous indicator diagrams and calculating

from them the mean effective pressure and the horse-power. The steam consumption is tested by condensing all the steam discharged by the engine and weighing the water of condensation. When a condenser is not available the feed water delivered to the boilers may be weighed instead, precautions being taken to insure that all of the steam made by the boiler is used by the engine. For directions for making steam-engine tests see A.S.M.E. Codes.

Plant Tests. — In the introduction to the report above referred to the Committee says:

The heat consumption of a steam-engine plant is ascertained by measuring the quantity of steam consumed by the plant, calculating the total heat of the entire quantity, and crediting this total with that portion of the heat rejected by the plant which is utilized and returned to the boiler. The term "engine plant" as here used should include the entire equipment of the steam plant which is concerned in the production of the power, embracing the main cylinder or cylinders; the jackets and reheaters; the air, circulating, and boiler-feed pumps, if steam driven; and any other steam-driven mechanism or auxiliaries necessary to the working of the engine. It is obligatory to thus charge the engine with the steam used by necessary auxiliaries in determining the plant economy, for the reason that it is itself finally benefited, or should be so benefited, by the heat which they return, it being generally agreed that exhaust steam from such auxiliaries should be passed through a feed-water heater, and the heat thereby carried back to the boiler and saved.

SPECIFICATIONS. — (*See also article on Specifications.*) In obtaining bids for steam engines the prospective purchaser or his engineer usually furnishes only general specifications, stating the kind of work to be done by the engine, such as driving a cotton mill, or an electric power plant, and the following requirements: (1) Indicated horse-power required, (*a*) Maximum, (*b*) Average; (2) Steam pressure available at engine; (3) Maximum absolute back pressure; (4) Number of revolutions; (5) Required steam consumption.

The bidders then furnish with their bids complete detailed specifications with guarantees of the engines they propose to supply, with drawings, when these are required. The bidders are usually prepared to contract for the installation, erection and starting of the engine, especially if it is of a large size.

FOUNDATIONS FOR STEAM ENGINES. — Engine foundations may be built of brick or concrete; the latter is more commonly employed in modern practice. The concrete is made with proportions of one barrel of Portland cement, three of sand, and five of crushed stone.

If the foundation is to be of concrete a wooden box is built in the ground, the inside of the box being the shape of the foundation. Over the top of this box are a number of pieces of joist, from which the anchor bolts or holding-down bolts are hung. Most engine builders furnish drawings giving location of foundation bolts and size of foundation required. The nuts at the top of these bolts are blocked up to the height they are to be when the engine is in place.

The heads of the bolts are at the bottom. A cast-iron plate eight inches by eight inches by one inch, with a square recess for the bolt head, is at the bottom of each rod. Around each bolt a piece of four-inch galvanized-iron gutter pipe is placed, and the top end of the pipe stuffed with waste to keep the mason from dropping cement into the space between the pipe and the bolt. The concrete is now dumped in and tamped down. After it has set, the wooden joists holding the bolts may be taken away.

The engine is next put over the foundation and supported on iron bars one-half inch square or perhaps larger, these bars being placed near the bolts. By means of wedges, etc., the engine is leveled; the main shaft is placed parallel

shafting which it is to drive. The bolts are next tightened fairly
s it is impossible to core the holes in the engine bed exactly as called
e drawing, the leeway given by the space between the bolts and the
surrounding it takes care of variations of from an inch to an inch and

f putty, sand, or cement about one inch high is built about one inch
ngine bed. A thin, neat Portland cement, mixed to the consistency
cream, is poured under the engine bed and serves to fill the space
e bolts and to give the bottom of the bed a perfect bearing over the
ndation. Before the cement becomes hard, the edge may be trimmed
by means of a trowel; the bolts are then tightened again.
es type metal instead of cement is poured under the engine bed.

ATION. — Full directions for setting the valves of a steam engine
nd in a little book by M. C. Myers, entitled *Types of Modern Engines*
Valve Setting (Boston, 1910). Other useful data on the operation
mance of steam engines will be found in a book published by the
eam Gauge and Valve Co., entitled *Steam Engine Indicator*. See
ore elaborate treatises listed in the bibliography below.

Control. — The speed of an engine can always be controlled by
he opening of the throttle valve, but this method is usually wasteful.
icient method is to change the point of cut-off. This can be done
engine is running by using a suitable link motion (*see above*), or by
he setting of the governor spring if the governor is of the "automatic"
engines driving alternators in parallel this is usually accomplished
an electric motor arranged to act directly on the governor spring so
nsion of the spring may be controlled from the switch-board.

ng Variable Load by Storing Heat in Hot Water. — There is
tory method for equalizing the load on the engines and boilers in
t stations. Storage batteries have been used, but they are expensive
, repairs and attention. Mr. Halpin, of London, proposes to store
g the day in specially constructed reservoirs. As the water in the
ised to 250 pounds pressure, it is conducted to cylindrical reservoirs
English horizontal boilers, and stored there for use when wanted.
a comparatively small boiler-plant can be used for heating the water
nds pressure all through the twenty-four hours of the day, and the
r may be drawn on at any time, according to the magnitude of the
The steam engines are to be worked by the steam generated by the
ressure from this water, and the valves are to be arranged in such a
he steam shall work at 130 pounds pressure. A reservoir 8 feet in
nd 30 feet long, containing 84,000 pounds of heated water at 250
ssure, would supply 5150 pounds of steam at 130 pounds pressure.
consumption of 18 pounds per horse-power-hour, such a reservoir
ly 286 effective horse-power-hours.

OF STEAM ENGINES (Pre-war figures). — The price of steam
ies not only with their size and weight, but also with their style,
workmanship. When builders are asked to submit bids for the
power of engine, with the same steam pressure and number of revo-
of the same general type, such as cross-compound condensing, it is
non to receive prices of which the highest is double that of the lowest.
eing say from $10 to $20 per horse-power for an engine of 500 horse-
r specially designed engines requiring new patterns to be made the
e considerably above $20. The price also varies with the condition
ket, discounts from regular prices of as much as 20 per cent being

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sometimes quoted in periods of dull business. The
usually give the weights of standard sizes of engines and
to the probable price may be made by taking it at from 5.
the lower price being for engines with heavy bed-plates
forms.

From a number of tables and sets of curves kindly fur
Whitham, Consulting Engineer, Philadelphia, containi
has received for different sizes and styles of engines, the
expressions have been deduced, where P is the rated hors

Type of Engine	Co
Corliss engines:	
Single cylinder, noncondensing	
Single cylinder, condensing	
Compound, noncondensing	
Compound, condensing	
Compound slide-valve engine:	
Portable (locomotive) boiler, noncondensing engine and stack	

The cost of condensing engines is exclusive of condenser.

Professor Wickenden gives the following values for
electric generators, these values being based on the actu
ber of installations.

Type of Engine	C
Simple high-speed engines and settings	
Compound high-speed engines and settings	
Simple low-speed engines and settings	
Compound low-speed engines and settings	

Cost of Operation. — See articles on *Power Station*

BIBLIOGRAPHY. — Richardson, J., *Modern Steam*
Steam Engine Theory and Practice; Sennett and Oran,
Rankine, *Steam Engine and Other Prime Movers;* Whitha
Design; Stumpf, J., *Una-flow Steam Engines;* Kent's
Pocket-Book; Marks, *Mechanical Engineers' Handbook;*
Power Plant Engineering; Low, F. R., *The Compound E*

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STEAM TURBINES. — (*See also Condensers, Steam; Power Stations; Steam; Steam Engines.*) Steam turbines may be classified as impulse, reaction, and composite; single-stage and multi-stage; nozzle expansion and blade expansion; vertical and horizontal. A set of nozzles or stationary guide blades and the rotating vanes through which the steam passes immediately upon leaving the nozzles or stationary blades constitute a single "stage." If there are several sets of stationary nozzles or guide blades and rotating vanes through which the steam passes successively, the turbine is called a "multi-stage" turbine.

APPLICATIONS OF STEAM TURBINES. — The steam turbine, when designed to use steam economically, is characterized by extremely high speed of rotation. The special field of application of the steam turbine is therefore the driving of electric generators, centrifugal blowers and pumps, and other machinery in which a high speed of the motor shaft is desirable. When lower speeds are desired in the motor shaft a reduction gear of some kind is placed between it and the turbine shaft. See also articles on *Generators; Power Stations; Pumps.*

RATING OF STEAM TURBINES. — Turbine ratings are usually based on maximum sustained load. Momentary overload capacity is very large and moderate overloads of considerable duration can be carried but may require the admission of high-pressure steam to low-pressure stages by means of a secondary valve. Small turbines for driving pumps, blowers, etc., are rated in horse-power. Turbines used to drive electric generators are usually rated in connection with the generator, the combined unit or turbo-generator being rated in kilowatts. Turbo-alternators of 20,000 kilowatts capacity each are in use (1913), and still larger units are considered practicable.

DESIGN AND CONSTRUCTION OF STEAM TURBINES. — Below are noted briefly some of the chief features in the design and construction of steam turbines. For further details see the treatises by Stevens and Hobart, Moyer, Stodola, Foster, Thomas, etc.

Impulse Turbines. — An impulse steam turbine of the simplest form is a wheel similar to a water wheel, which is moved by a jet of steam impinging at high velocity on its blades. By expansion of the steam its pressure energy is converted into kinetic energy, and the wheel is propelled by the impact of the steam moving at high velocity.

De Laval Turbine. — The distinguishing features of this turbine are the diverging nozzles, in which the steam expands down to the atmospheric pressure in non-condensing, and to the vacuum pressure in condensing wheels; a single forged-steel disk carrying the blades on its periphery; a slender, flexible shaft on which the wheel is mounted and which rotates about its center of gravity; and a set of reducing gears, usually 10 to 1 reduction, to change the very high speed of the turbine to a moderate speed for driving machinery.

The number and size of nozzles vary with the size of the turbine. The nozzles are provided with valves, so that for light loads some of them may be closed, and a relatively high efficiency is obtained at light loads. The taper of the nozzles differs for condensing and noncondensing turbines. Some turbines are provided with two sets of nozzles, one for condensing and the other for non-condensing operation.

Zolley or Rateau Turbine. — The Zolley or Rateau turbines are developments of the De Laval and consist of a number of De Laval elements in series, each succeeding element utilizing the exhaust steam from the preceding. The steam is partly expanded in the first row of nozzles, strikes the first row of

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buckets and leaves them with practically zero velocity. expanded through the second row of nozzles, strikes a s buckets and again leaves them with zero velocity. Thi until the steam is completely expanded.

Curtis Turbine, made by the General Electric Co wheel of several stages. Steam is expanded in nozzles three or more blades, at least one of which is stationary non-expanding, and the pressure is practically the same on of blades. In smaller sizes of turbines, only one set of sta blades is used, but in large sizes there are from two to five pressure stage, separated by diaphragms containing addi The smaller sizes and the more recent (1914) larger shafts. Earlier large sizes have vertical shafts support supplied with oil or water under a pressure sufficient weight of the shaft and its attached rotating disks.

Reaction and Composite Turbines.— In a simple re expanding through a set of blades or nozzles capable of axis, produces a reacting force and drives the rotating direction to the motion of the steam. Hero's engine is the tion turbine. The term "reaction" turbine, however, as to a turbine in which the reaction principle is combined ciple, i.e., to turbines in which jets of steam striking blad in the rim of a wheel give it a forward impulse, and escapi direction react upon it.

Parsons Turbine. — This is a reaction turbine large number of rows of blades, mounted on a rotor or tween each pair of rows there is a row of stationary blade ing, which take the place of nozzles. A set of stationary ing set of moving blades constitute what is known as a pands and loses pressure in both sets. The speed of ro speed of the blades and the velocity of the steam throug much lower than in the De Laval turbine. The rotor, o moving blades are carried, is usually made in three secti eters, the smallest at the high-pressure end, where steam largest at the exhaust end. In each section the radial len also their width increase from one end to the other, to increased volume of steam. The Parsons turbine is built by the Westinghouse Machine Co. and by the Allis-Chalm

The Westinghouse Double-flow Turbine. — F law. a turbine is built in which the impulse and reaction It has a set of non-expanding nozzles, an impulse wh stages (that is, two wheels with a set of stationary non- tween), one intermediate section and two low-pressure blading. After steam has passed through the impulse mediate section, it is divided into two parts, one going to th to the left-hand low-pressure section. There is an exhau In this turbine, the end thrust, which has to be balanced of the usual type, is almost entirely avoided. Other adva tion in size and weight, due to higher permissible speed; not exposed to high temperatures; reduction of size of length of shaft; avoidance of large balance pistons.

Comparison of Impulse and Reaction Turbines. following comparison of impulse and reaction turbines:

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Impulse	*Reaction*
tages.	1. Many stages.
ısion in nozzles.	2. No nozzles.
drop in pressure in a stage.	3. Small drop in pressure in a stage.
l steam velocities 1000 to o feet per second.	4. All steam velocities low, 300 to 600 feet per second.
velocities 400 to 1200 feet second.	5. Blade velocities 150 to 400 feet per second.
fficiency when the blade ve- ty is nearly half the initial ocity of steam.	6. Best efficiency when the blade velocity is nearly equal to the highest velocity of the steam.

ence has not made manifest any marked and consistent difference in and reliability between the impulse and reaction types.

al Versus Horizontal Turbines. —There is also no marked difference ny and reliability of the vertical and horizontal types. The former economical of floor space, especially when the base type of condenser yed, but requires more head room, as sufficient overhead space must ed to permit the lifting clear, and removal of, the shaft from the casing.

ction Gear for Steam Turbines. — Double spiral reduction gears, f a ratio of 1 to 10, are used with the De Laval turbine to obtain a of rotation suitable for dynamos, centrifugal pumps, etc. G. W. and J. H. McAlpine have designed a similar gear, with the pinion car- floating frame supported at a single point between the bearings to the strain on the gear teeth, for reducing the speed of large horizontal to suitable speeds for marine propellers. A 6000-horse-power gear uction from 1500 to 300 revolutions per minute has been tested, giving ncy of 98.5 per cent (*Eng'g, Sept. 17; Eng. News, Oct. 21 and Dec. 30,*

INES VERSUS RECIPROCATING ENGINES. — The inherent ges of the turbine are: (1) The perfect continuity and uniformity This permits the working parts to be made light and gives the uni- ular velocity which is desired for the parallel running of alternators. high velocity of rotation and of steam flow. This tends to great com- permits light weights, provides for the full expansion to high vacuum enormous volume of expansive space, cheapens the cost of turbine and r, and is favorable to the efficiency of the latter. The effect of items (2) on weights, sizes and costs may be best appreciated by comparing and gas-engine sets of equal maximum capacity. (3) The reduction nimum of condensation, radiation and leakage. (4) The absence of cation from the steam space. Difficulties of lubrication with high t are thus obviated and the condensed steam is free from oil. (5) The nce of good economy over a wide range of fractional loads. great momentary overload capacity obtained from the high inertia pidly rotating parts. To match this advantage in slow-speed ting engines requires very heavy working parts and the addition pensive flywheel. The reciprocating engine can be built to equal ine in economy over a wide range of loads but the refinements to this end are costly. For equal heat consumption the costs of gine-alternator units are from 35 to 50 per cent greater than those of cts.

nes versus Engines in Units of Small Capacity. — Under this title, Barstow presented the following summary before the A.S.M.E. in er, 1915, for units of less than 500 horse-power capacity.

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Applicability of Turbines. — 1. Direct-connected units, operating condensing. 60-cycle generators in all sizes, also 25-cycle generators above 1000 kw. capacity. (This paper is, however, not intended to deal with units of this size.) Direct-current generators in sizes up to 1000 kw. capacity, including exciter units of all sizes.

Centrifugal pumping machinery operating under substantially constant head and quantity conditions, and at moderately high head, say from 100 feet up, depending upon the size of the unit.

Fans and blowers for delivering air at pressures from 1½ inch water column to 30 pounds per square inch.

2. Direct-connected units, operating non-condensing for all the above purposes, in those cases wherein steam economy is not the prime factor or where the exhaust steam can be completely utilized, and, in the latter case, particularly where oil-free exhaust steam is desirable or essential.

3. Geared units, operating either condensing or non-condensing for all the above-mentioned applications, and in addition, many others which would otherwise fall in the category of the steam engine, on account of the relatively low speed of the apparatus to be driven.

Applicability of Engines. — 1. Non-condensing units, direct-connected or belted and used for driving: Electric generators of all classes excepting exciter sets of small capacity, unless belted from the main engine.

Centrifugal pumping machinery, operating under variable head and quality conditions and at relatively low heads, say up to 100 feet, depending on the capacity of the unit. Pumps and compressors for delivering water or gases in relatively small quantities and at relatively high pressures in the case of pumps at pressures above 100 pounds per square inch, and in the case of compressors at pressures from 1 pound per square inch and above.

Fans and blowers (including induced draft fans) for handling air in variable quantities and at relatively low pressures, say not over 5 inches water column. Line shaft of mills, where the driven apparatus is closely grouped and the load factor is good.

All apparatus requiring reversal in direction of rotation, as in hoisting engines and engines for traction purposes.

2. Condensing units direct-connected or belted, for all the above purposes particularly where the condensing water supply is limited, and where the water must be recooled and recirculated.

Low-pressure Turbines compounded with high-pressure reciprocating engines are coming into extensive use where it is necessary to increase the capacity or improve the efficiency of existing engine plants. By combining the superior efficiency of the engine in the pressure range above the atmosphere with that of the turbine below the atmospheric range a resultant superior to the efficiency of either single type may be secured. Standard piston engines are able to sustain full-rated load when run non-condensing and often will carry from 25 to 50 per cent above rated load without danger or excessive wear. Under such conditions the water rate per kilowatt-hour is high but all the heat rejected in the exhaust is available to a low-pressure turbine; hence the net economy of the combined engine and turbine may be considerably superior to that of the engine when run condensing. By proportioning the turbine to efficiently utilize the exhaust steam and by connecting to it a high-vacuum condenser, the initial capacity of the unit may be doubled or even trebled, and if the engine is in good condition, the resultant efficiency may be superior to that obtainable from a new complete-expansion turbine of equal capacity.

Structurally, the low-pressure turbine is similar to the full-pressure type with the high-pressure stages omitted. It is, therefore, somewhat shorter but

n spaces are necessarily greater than in a full-pressure type of equal It is highly desirable that an efficient separator be installed between e and the turbine as the presence of moisture in the steam adds greatly ction against the turbine blades. When the exhaust is to be returned oiler it is also necessary to extract the oil from the steam as it leaves e.

CIENCY AND LOSSES. — The maximum theoretical efficiency of a rbine is the efficiency of the Rankine ideal engine between the tem- of admission and exhaust (*see Steam Engines*).

veral losses which tend to reduce the efficiency of turbines below the al maximum are: (1) residual velocity, or the kinetic energy due to ity of the steam escaping from the turbine; (2) friction and imperfect in the nozzles; (3) windage, or friction due to rotation of the wheel ; (4) friction of the steam traveling through the blades; (5) shocks, eddies, etc., due to imperfect shape or roughness of blades; (6) leak- nd the ends of the blades or through clearance spaces; (7) shaft fric- radiation. The sum of all these losses amounts to about 25 per cent ailable energy in the largest and best designs and to 50 per cent or more izes or poor designs.

nsation, leakage and radiation are of small magnitude. Windage and re especially marked in the high-pressure stages and the turbine is cient in its low-pressure stages, in direct contrast to the piston engine. hanical friction is relatively small, due to the small loads on wearing nd the effectiveness with which they may be lubricated. Steam fric- dage and condensation are much increased by moisture in the steam. ted steam is particularly advantageous in turbines because of its low luctivity, dryness and high fluidity.

M ECONOMY OF TURBINES. — Like all heat engines the effi- the turbine depends on the range of expansion and the reduction of Increasing the ex- ange by raising the n pressure affords a small gain in ef- The chief advant- ing from high initial is in the decreased e turbine of a given The relation of essure to the steam consumption per output varies some- th the individual ut the general rela- fixed conditions of and superheat is Fig. 1.

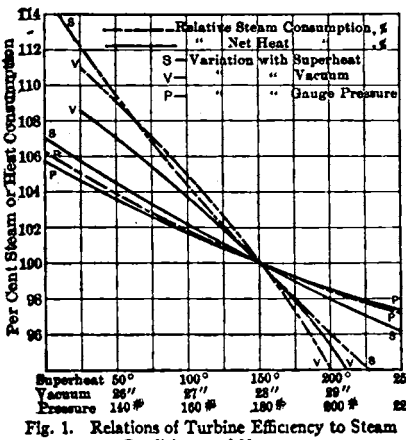


Fig. 1. Relations of Turbine Efficiency to Steam Conditions and Vacuum

lvantage gained by g the range of ex- at the lower end xceeds that gained ual pressure incre- he upper end of the cycle. tly surpasses the engine. fficiency for typical units.

In the utilization of high vacua the tur- Fig. 1 shows the relation of vacuum to This relation depends to a marked degree

on the design of the particular turbine and is therefore not identical in all units of a given general type.

Effect of Vacuum on Economy.— The economical limit of vacuum in turbines is much higher than in engines. The attainment of very high vacua involves a very heavy investment in condensers and auxiliaries and a considerable consumption of heat for their operation. The ultimate effect on plant economy is therefore decidedly less than the percentage gain indicated in Fig. 1. Factors unfavorable to high vacuum are a poor load factor for the unit; costly, warm or corrosive cooling water; the necessity of artificially cooling condensing water when the supply is limited; and very cheap fuel.

The question of the most economical vacuum must be determined by care-

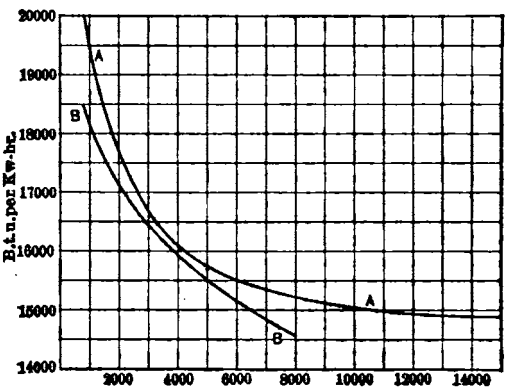


Fig. 2. Average Full-load Net Heat Consumption of Turbines

A. American types, mean values from guarantees and tests
B. Results of 50 European Tests

fully weighing against each other the annual charges on the condenser system (interest, depreciation, attendance, repairs, and the net cost of water for its operation included, and, on the other hand, the annual saving in total fuel consumed plus the saving on boiler-plant fixed charges and operation. Such an analysis takes due account of the heat consumed in driving the auxiliaries. Where an abundant supply of cold condensing water is available, experience indicates that the highest vacuum attainable is a good investment in connection with large units operated at load factors of 60 per cent, or above. With ordinary central-station conditions vacua of from 27 to 28 inches are most advantageous.

Effect of Superheat on Economy. — Superheat of almost any practicable degree improves turbine efficiency, though the net saving is much less than that indicated by the water rate, due to the extra heat content of superheated steam of high temperature. On account of the influence of superheat on the first cost and maintenance expense of piping, valves and fittings, also because of the difficulties in providing for expansion of turbine parts at very high temperatures, the tendency of American practice is to exceed a steam temperature of 500° F only in very large units, though the tendency in Europe is toward a higher limit. Fig. 1 shows the effect of superheat on steam consumption and net heat consumption of steam turbines, the relation being practically uniform for all types

of Size and Type on . — The efficiency of the ike that of the engine, as the size of the unit see Fig. 2. Large units ely cheaper than small, l better economy in pip- ensing equipment, space, e and maintenance. -generator is rated as a t. The momentary and overload capacity of roper is very large, but tor is much restricted by to dissipate the heat in its parts. The usual based either upon maxi- ained capacity (*M* in Fig. n normal sustained capa- an allowable overload of for a two-hour period (*N*

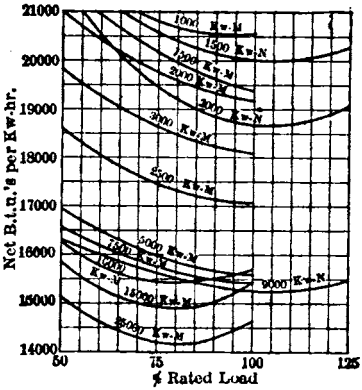
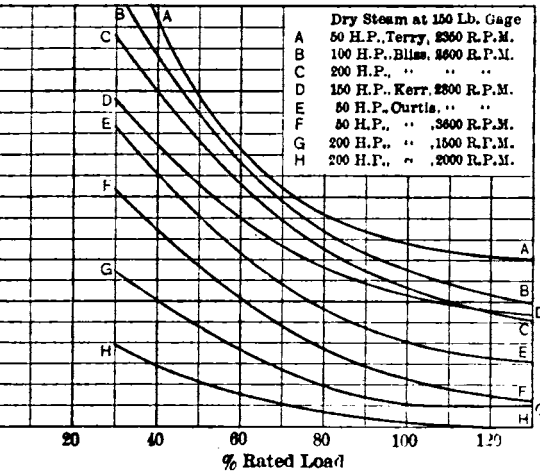


Fig. 3. Net Heat Consumption of Modern Turbines

M. Maximum Rating. N. "Normal" Rating

ace has not made manifest any marked or consistent differences in nd reliability between the several commercial types. The vertical t well suited to the highest speeds, but is especially economical of in connection with the base type of condenser. It requires greater than the horizontal type. Fig. 4 shows the steam consumption of of small non-condensing turbines (*see paper by G. A. Orrok, Trans. 1909*). All curves are test results.



. 4. Steam Consumption of Small Non-condensing Steam Turbines

OMY OF COMBINED TURBINE AND ENGINE UNIT. — ing is reported by H. G. Stott and R. J. S. Pigott in *Jour. A.S.M.E.*,

Mar., 1910. The steam-engine is one of the 7500-kilowatt Manhattan type engines at the 59th St. Station of the Rapid Transit Co., New York, with two 42-inch horizontal high-pressure and two 86-inch vertical low-pressure cylinders, and the turbine, also 7500 kilowatt, is of the vertical three-stage impulse type. The principal results are summarized as follows: An increase of 100 per cent in the maximum capacity and 146 per cent in the economical capacity of the plant; a saving of about 85 per cent of the condensed steam for return to the boilers [it was previously wasted]; an average improvement in economy of 55 per cent over the best high-pressure turbine results and of 2.5 per cent (between 7500 and 15,000 kilowatts) over the results obtained by the engine alone; an average thermal efficiency between 6500 and 15,500 kilowatts of 20.6 per cent. [This efficiency is not quite equal to that reached by triple-expansion pumping engines.]

TESTING OF STEAM TURBINES. — Turbines are tested in the same way as reciprocating steam engines, measuring the power by a Prony brake or by an electric generator whose efficiency at different loads is known and the steam consumption by weighing the water discharged from the condenser.

SPECIFICATIONS. — See *Specifications* in article on *Steam Engines*.

OPERATION. — Several important features are noted below. For additional information see article on *Power Stations*.

Oil-pressure System for Step Bearing of Vertical Turbine. — When running the end of the shaft is lifted slightly from its seat and supported by a forced circulation of water or oil under a pressure of from 500 to 1200 pounds per square inch. This pressure is produced by a special step bearing pump which may be of the steam-driven, direct-acting type or of the motor-driven, triplex type, and is reinforced by a heavily weighted plunger accumulator. When a double pump equipment is installed the second may serve as a reserve and, if of the motor-driven type, may readily be arranged to automatically take up the load if the accumulator falls to a certain point, due to the failure or inadequacy of the primary pump. The horizontal-shaft type is subject to an end thrust, which must be neutralized by dividing the turbine into two sections through which the steam flows in opposite directions or by the use of pressure rings opposed to the thrust on the turbine.

Speed Control. — Turbines having nozzle expansion are most efficiently governed by varying the number of active nozzles. Reaction turbines are governed by the intermittent throttling of steam at the admission valve. The governor is usually of the shaft or flywheel type (*see Steam Engines*). In both types, when used for driving alternators in parallel, a small motor is attached to the governor spring so that the tension may be controlled at the switchboard. This affords a convenient control of speed for synchronizing and adjusting the loads taken by the several machines.

Speed Control of Combined Turbine and Reciprocating Engine Unit. — In central-station service the two elements are so adjusted that the turbine takes all the steam from the engine, the load on the two is varied simultaneously and the two are electrically coupled by being connected to the same bus bars. This arrangement simplifies the problem of governing and the division of load. It has not been found advantageous to place a governor on the turbine under such conditions. The turbine operates under variable admission pressure, depending on the load. The turbine should be equipped with a speed-limiting relay, which opens the atmospheric exhaust from the engine should the speed of the turbine become unsafe.

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T OF STEAM TURBINES (Pre-war figures). — Small turbines for pumps, blowers, etc., cost from $20 to $40 per horsepower.
. 5 are given the total costs of various turbo-generator sets in 1912. sts include both the turbine and generator but do not include condensers liaries. The curves were kindly supplied by Prof. W. E. Wickenden esent the average of the actual costs of a number of units of various

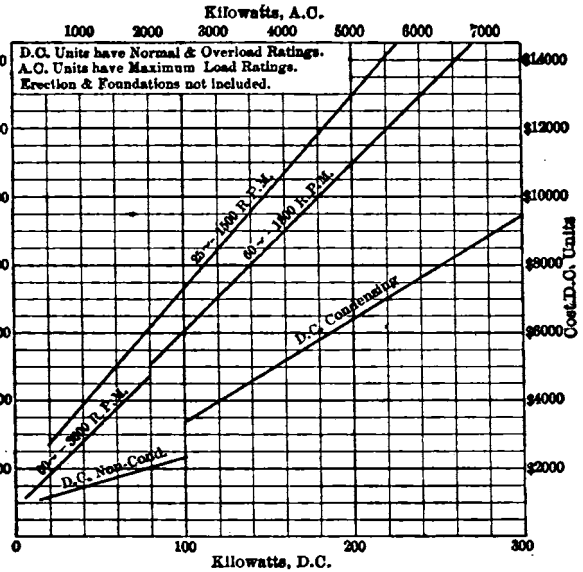


Fig. 5. Approximate Cost of Turbo-generator Sets

s. Impulse and reaction turbines cost approximately the same. Tur- s are subject to considerable variation, the tendency being a decided in the cost per kilowatt from year to year. The costs given in the hould therefore be checked against actual quotations, even when used inary estimates.

OGRAPHY. — Neilson, R. M., *Steam Turbine;* Thomas, C. C., *urbine;* Stodola, A., *Steam Turbines;* Moyer, J. A., *Steam Turbine;* C. H., *Steam Engines and Turbines;* French, L. G., *Steam Turbines;* t, G. F., *Steam Power Plant Engineering;* Stott and Finley *Report iciency Test of a 30,000 kw. Cross-Compound Steam Turbine,* A.S.M.E. 8, p. 655; Fernald and Orrok, *Engineering of Power Plants;* Kent's *al Engineers' Pocket-Book;* Marks, *Mechanical Engineers' Handbook.*

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STEEL. — (*See also Iron, Pig and Cast; Castings, Iron and Steel; Rails, Tra and Third.*) Carbon steel (the ordinary commercial steel) may be defined a an alloy of iron and carbon produced by any one of the methods described in the following article. It differs from wrought iron in not being slag bearing and from cast iron in being malleable at certain temperatures.

Slag is the substance which collects on the surface of molten iron or ste in the blast furnace, converter or open-hearth furnace. Its constitution vari with the process but it includes oxides of the various impurities found in th iron such as silicon, aluminum, phosphorus, calcium and magnesium. It m also include some oxide of iron. The slag from blast furnaces is often very ri in calcium owing to the amount of limestone added to the charge as a flu The manufacture of Portland cement from blast-furnace slag is an importa industry. The process of puddling used in making wrought iron involves th mixing of some of the slag with the iron, thus making it an integral part of th finished product as explained in the article on *Iron, Wrought.*

METALLURGY. — The various processes by which steel is at present manu factured are described in the following paragraphs:

Bessemer Process. — This process consists of the burning out of most of th impurities and carbon contained in molten iron by the aid of a blast of unheat air, and subsequent recarburization of the mass by the addition of spiegel-eise or ferro-manganese. The molten material is placed in a pear-shaped vess called a converter and the blast is introduced through openings in the bottom After the process has continued long enough to convert the iron into ste the molten material is either poured into iron molds forming ingots which ar later rolled or hammered into commercial shapes, or else cast into *steel castin*

Two processes are in use, the acid and the basic; in the former the converter lining is of refractory acid materials composed principally of silica, so that the phosphorus and sulphur in the charge are unreduced; in the latter, the con verter is lined with burnt dolomite, and lime is added to the charge to reduce the phosphorus and sulphur. The heat necessary for the process is obtained from the combustion of silicon in the acid process and of phosphorus in the ba process. The acid process alone is in use in the United States owing to the prevalence of low phosphorus and sulphur ores. Steel of fair quality is pro duced by this process at low cost and with great rapidity, but Bessemer steel is gradually being replaced for important structures by the more reliable open hearth steel.

Open-hearth Process. — This process consists of the reduction of the carbon and other impurities contained in a mixture of pig iron, scrap iron or scrap steel and iron ore by exposure for seven or eight hours to an intense heat obtained from a mixture of producer gas and air, the process being stopped when the bath is found to have the right proportions as determined by physical and chemical analyses. The steel is then withdrawn from the furnace and either poured into ingots or cast into usable forms. Steel of excellent quality for structural purposes is thus produced in large quantities, a single furnace often having a capacity of 50 tons.

Duplex Process. — This process consists of a combination of the Bessemer and open hearth; pig iron is first blown into the converter to remove the silicon and a portion of the carbon; it is then transferred to the open hearth, where it is dephosphorized and the carbon reduced to the proper percentage. The process permits the use of a poorer grade of material than the Bessemer, and gives a higher grade of finished product, while the speed of production is superior to that of the open hearth.

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Crucible Process. — This process consists of melting down, in covered clay or graphite crucibles, wrought iron (sometimes diluted with steel scraps) with charcoal, ferro-manganese and various so-called physics, such as salt, oxide of manganese, etc. The crucibles hold from 50 to 100 lb. each. Crucible steel is high in carbon and low in sulphur and phosphorus. It is superior to Bessemer and open-hearth steel and is used for tool making.

Cementation Process. — This process consists of converting wrought iron into steel by piling iron bars and charcoal together, bringing to a yellow heat and keeping in this condition for a period extending from ten days to two weeks. The steel thus obtained is known as blister steel. If the blister steel is cut, piled, heated and forged, *shear* steel is produced; if the operation is repeated on shear steel, *double shear* steel is obtained. Blister steel is frequently melted in the crucible to free from slag; the resulting product is of the highest quality and is used in making the finest grades of cutting tools, such as razors. Case hardening is a special form of cementation by which the outer surfaces of articles forged from wrought iron or steel are hardened. Harveyizing of armor plate is also a cementation process.

MECHANICAL TREATMENT. — (*See also Steel Mills, Electric Drive of.*) Steel made by any of the preceding processes may be put into usable form either by casting, or by forging while hot under the hammer, or usually by rolling while hot between heavy grooved rollers, the latter process being used for rods, plates, rails, and structural shapes such as angles, channels and I-beams. The rolling process is usually divided into two parts: (*a*) the reduction of the ingot into *blooms* or *billets* by the *blooming mill;* and (*b*) the reduction of the blooms or billets into commercial shapes by the *shaping mill.*

The blooming mill consists of a pair of horizontal grooved rollers, one above the other, between which the ingot is passed back and forth, the rolls being gradually forced closer together. These rolls are actuated by a reversing engine. This process reduces the ingot from a block of steel perhaps 16 inches square by 6 feet in length to a bar of small cross-section, usually rectangular and of considerable length. This is then cut into sections several feet in length which are called blooms if the cross-section contains more than 36 square inches and billets if less. In England this mill is called a cogging mill.

The shaping mill is similar to the blooming mill, but there are usually three non-reversing rolls in a vertical plane, the bloom passing forward between the lower and middle rolls, and returning between the middle and upper roll.

HEAT TREATMENT; CRITICAL TEMPERATURE. — When iron or steel cools from a high temperature, say 1000° C., the rate of cooling is not uniform, but is marked by certain periods of retardation accompanied by spontaneous evolution of heat, the opposite phenomena occurring when the temperature is increased. There are in general three of these critical points which are designated by metallurgists by the letters A_1, A_2 and A_3, A_1 being at the lowest temperature. Owing to *lag* the changes occur at slightly lower temperatures on cooling than on heating, and to distinguish between them, the cooling points are designated Ar_1, Ar_2 and Ar_3, and the heating points Ac_1, Ac_2 and Ac_3. These points vary with the percentage of carbon, and for certain grades of steel the three cooling points may be merged into one and also the three heating points. With favorable conditions when the temperature Ar_1 is reached an increase in temperature of the metal may be detected by its change of color. This point is called the point of recalescence. At this temperature also a softening of the metal occurs. An interesting feature of the point A_2 is that at a higher temperature steel is *non-magnetic*, but in passing through Ar_2 it becomes suddenly *magnetic*. *See Magnetic Properties of Iron and Other Metals.*

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The approximate values of these critical points in degr
by Sauveur are shown in the following table:

CRITICAL TEMPERATURES IN DEGREES

Grade of steel	Low carbon	Medium-high carbon
Carbon content, per cent	0.1	0.45
Ar_1	675	650 to 700
Ar_2	750	725
Ar_3	850	725
Ac_1	700	...
Ac_2	750	...
Ac_3	875	...

ANNEALING. — Steel with a coarse structure due t
improved in grain by heating to a temperature varying
tent and cooling slowly. The accompanying table giv
peratures which are commonly specified for this purpose.

Range of carbon content, per cent	Range of annealing tem	
	°C.	
Less than 0.12	875 to 925	1607
0.12 to 0.29	840 to 870	1544
0.30 to 0.49	815 to 840	1499
0.50 to 1.00	790 to 815	1454

The object should be kept at the annealing temperat
sure a uniform temperature throughout and then co
carbon, or the greater the ductility and softness require
the cooling. It is usually sufficient to remove the objec
to allow it to cool in air protected from rain, snow and d
more than 0.50 per cent carbon should cool more slowly
before removing from the furnace; it may then be rem
To remove the effects of cold working the object shou
775° C. and cooled with a slowness depending upon the
For detailed specifications see *Amer. Soc. for Test. Ma*

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CARBON STEEL. — The alloy of carbon and iron of which ordinary carbon steel is composed is divided into the five following groups by Sauveur:

Grade of steel	Hardness	Carbon content, per cent
Very low carbon	Very soft	Not over 0.10
Low carbon	Soft	Not over 0.25
Medium-high carbon	Half hard	0.26 to 0.60
High carbon	Hard	Over 0.60
Very high carbon	Hard, extra hard	Over 1.25

The properties of these different groups when made under normal conditions depend upon the relative amounts of the following constituents:

Ferrite, or iron free from carbon, this being the same as the ferrite in wrought iron (q.v.).

Pearlite, consisting of a mixture of iron carbide and ferrite.

Cementite, or iron carbide, with the formula Fe_3C, combined with a varying amount of carbide of manganese.

Austenite and Martensite. — Steel that is suddenly cooled from a high temperature contains also certain other compounds of iron and carbon, the two of most importance being known as *austenite* and *martensite*. The former is generally considered as a solid solution of carbon, or of the carbide Fe_3C, in iron in the allotropic condition in which the latter exists at a high temperature (above 875° C.). It is not a constituent of constant composition, and is seldom found in ordinary steels since it is rapidly transformed in cooling into an aggregate of ferrite and cementite. To obtain it highly carburized steel may be suddenly cooled from a temperature of 1000° C. or more by a bath such as ice cold water. It may also be obtained by slow cooling if the steel contains a considerable portion of manganese or nickel. Martensite is generally believed to be an early stage in the transformation of austenite.

Phosphorus and Sulphur. — The common injurious impurities in carbon steel are phosphorus and sulphur, both of which cause brittleness and should be allowed only in small quantities. Specifications (*see section below on this topic*) frequently forbid more than 0.05 per cent of sulphur and 0.04 per cent of phosphorus. Other impurities commonly occuring in small quantities in steel are silicon and manganese, which in small quantities help to reduce blow holes by their deoxidizing action. These elements while often present in higher percentages than the carbon have comparatively little influence upon the strength of ordinary carbon steel.

Composition of Low-carbon Steel. — Low-carbon steel consists chiefly of a mass of ferrite with pearlite occuring at the junction of the grains of ferrite, the percentage of the former decreasing in medium and hard steels until in steel having 0.8 per cent to 0.9 per cent carbon, it disappears entirely, the steel then consisting exclusively of pearlite. In still higher carbon steels some of the pearlite is replaced by free cementite, the substance which gives steel its hardening property.

Strength and Weight of Carbon Steel. — The tensile strength of steel varies with its composition. For ordinary carbon structural steel the working values given in the following table may be adopted with safety:

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Nature of stress	Working strength, pounds per square inch
Tension on net section, and extreme fiber stress in bending	16,000
Compression in columns*	$16{,}000 - \frac{70\,l}{r}$, with a maximum of 14,000
Shear on net section of plate-girder webs and on machine-driven shop rivets	12,000
Bending on extreme fiber of pins	24,000
Bearing on pins and shop-driven rivets	24,000
Bearing on hand-driven rivets	18,000
Shear on hand-driven rivets	9,000
Modulus of elasticity	28,000,000 lb. per sq. in.

* In the expression for compression in columns, $\frac{l}{r}$ = maximum value of ratio of the unsupported length of column to radius of gyration, both values being expressed in inches. This ratio should be restricted by the form of the column so that it will not exceed 100 for main members and 120 for lateral and other secondary members.

Steel weighs approximately 490 lb. per cu. ft., or 2 per cent more than wrought iron.

CHEMICAL COMPOSITION

Elements considered	Structural steel	Rivet steel	Steel castings	
			Class A	Class B
Carbon, max. per cent	.....	.....	0.30	.....
Phosphorus, max., per cent:				
Acid	0.06	0.04	0.07	0.06
Basic	0.04	0.04	0.06	0.05
Sulphur, max., per cent	0.05	0.045	.....	0.06

TENSILE PROPERTIES

Properties considered	Structural steel	Rivet steel	Steel castings, Class B, medium
Tensile strength, pound per square inch	55,000 to 65,000	46,000 to 56,000	70,000
Yield point, min.	0.5 Ten. str.	0.5 Ten. str.	0.45 Ten. str.
Elongation in 8 in., min., per cent	$\frac{1{,}500{,}000}{\text{Tensile strength}}$	$\frac{1{,}500{,}000}{\text{Tensile strength}}$	.....
Elongation in 2 in., min., per cent	22	.....	18
Reduction of area	.....	.....	25

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ifications for Structural Steel and Steel Castings. — The American for Testing Materials has adopted standard specifications for steel to in various classes of structures. (*See A.S.T.M. Standards.*) Among s covered are the chemical and physical properties of the material, the ns and methods of tensile and bend tests and the permissible variation t and gauge. The preceding tables give the requirements as to chemical ion and tensile properties as given in the Society's specifications for al steel for bridges and ordinary steel castings (*A.S.T.M. Standards,*

CIAL OR ALLOY STEELS. — The more usual forms of special d their uses, composition and general characteristics are as follows:

el Steel. — Steel containing a considerable percentage of nickel, but not more than 3½ per cent, is called nickel steel. This steel has a strength and a higher elastic limit than carbon steel, and practically the odulus of elasticity; it is more ductile in proportion to its strength and at harder than carbon steel of like properties, it is more expensive be- the cost of the nickel, and the additional cost of working. Nickel steel used considerably in recent years for bridges of large size, for steamer utomobile parts, etc.

Steel. — This is a nickel steel containing about 36 per cent of nickel. icient of expansion is practically zero. It is used in making steel tapes line measurements in geodetic surveying.

ganese Steel. — The steel commonly known as manganese steel con- m 12 per cent to 13 per cent of manganese and generally from 1.25 per 2.00 per cent of carbon for castings; for forgings or rolled steel, less s used. It is austenitic in composition and is very hard without brittle- king it well fitted for railroad frogs, railroad rails or curves and burglar- fes. It is adapted principally to parts that can be cast, since working ools is practically impossible and forging is difficult. It is not used for al work as its elastic limit is so low as to offset the advantage of its rength. Like nickel, the manganese interferes with the transformation nite to pearlite during cooling. It is often called "Hadfield" steel from e of its inventor.

ne Steels. — Steels containing from 1 per cent to 2 per cent of chromium hard and have a high elastic limit. They are well adapted for armor- projectiles, steel balls, files and automobile gears. Krupp armor plate contain 3.25 per cent nickel, 1.5 per cent chromium and 0.25 per cent

dium Steels. — The addition to steel of a small amount of vanadium, less than 0.3 per cent, adds greatly to the elastic limit, ductility and e. Vanadium is especially advantageous in increasing strength, tough- l temper of nickel and chromium steels. This steel is particularly use- springs, axles and automobile parts.

on Steels. — The only silicon steels in use contain less than 5 per cent n. The alloy recommended by Hadfield, its patentor, contains 2.75 per con with the smallest possible amounts of carbon, manganese and other es. Such steel has a greater magnetic permeability than the purest d also a high electrical resistance. Its magnetic hysteresis is low. It uable material for use in electromagnetic and in electrical generating ry. See *Magnetic Properties of Iron.*

sten Steels. — These steels have the property of becoming martensitic eating to a high temperature and air cooling and are said to be "self-

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hardening." Such steels are used for springs, magnets and with manganese added for self-hardening tools. See also *High-speed Steels and Magnetic Steels, below.*

Self-hardening Steels. — Steel which is hard without tempering and cannot be annealed by known processes is called self-hardening steel. All such steels are non-magnetic. Any steel which is in an austenitic condition at atmospheric temperature is self-hardening. (*See Mushet Steel, below.*)

Ternary and Quartenary Steels. — These are steels consisting of three or four essential components, viz., iron, carbon and one or two alloys. Some of the more important ternary steels are nickel steel, manganese steel, chrome steel, tungsten steel and silicon steel. Among quartenary steels are nickel-chromium, nickel-manganese, nickel-vanadium, tungsten-chromium, etc. The effect of these various alloys upon carbon steels is very striking and the possibilities are very great.

Chrome-nickel Steel. — The chrome-nickel steels in use are pearlitic and contain moderate amounts of carbon, nickel and chromium. Such steel has a high elastic limit combined with high ductility and has greater hardness, resilience and wearing power than carbon steels. It is used in automobile construction and for the manufacture of armor plate.

Chrome-tungsten Steel. — Tungsten and chromium have the property of producing a finely martensitic structure in steel when heated to a high temperature and cooled in air. The martensite in this case is so stable that the steel may be heated to a red heat without losing hardness. Such steels are known as "high speed steels" (q.v.).

High-speed Steels. — These steels have a finely martensitic structure which is stable up to red heat. They may contain from 0.25 per cent to 1.00 per cent of carbon, from 5 per cent to 25 per cent tungsten, 2 per cent to 10 per cent of chromium and seldom over 0.40 per cent of manganese. Tungsten may be replaced wholly or in part by molybdenum. Steels of this character are of great importance in machine work as tools made from them can be driven without injury until the cutting edge is red hot.

Mushet Steel. — This steel contains both tungsten and manganese. It is a self-hardening steel and has been used for many years for tools which make very heavy or deep cuts such as is required for armor plates. The speed allowable is a little greater than for carbon steel, but it lasts a long time without grinding.

Magnetic Steels. — Steels containing 4 per cent to 5 per cent of tungsten and from 0.5 per cent to 0.7 per cent of carbon if heated to red heat and quenched in water will retain their magnetism better than carbon steel. The addition of chromium increases the permanency but decreases the magnetic force.

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STEEL MILLS, ELECTRIC DRIVE OF.—(*See also Flywheels for Load Equalization; Motors, Industrial Applications of.*) The application of electric motors to steel mill service may be divided in two general classes; 1. that dealing with the application of motor drive to the main rolls, that is to those rolls in which the ingot or billet is reduced in section, and 2. that dealing with the problems of electrifying the numerous other auxiliary machines and devices, such as tables, screw-downs, charging machines, etc.

MAIN-ROLL APPLICATION.—The term "mill" is sometimes used to designate a single stand or group of stands, and sometimes to include the main rolls and all auxiliaries involved in the production of a given class of materials. The stands are generally classified according to the arrangement of rolls and method of operation, that is two-high or three-high, the two-high being either reversing or non-reversing, see Fig. 1.

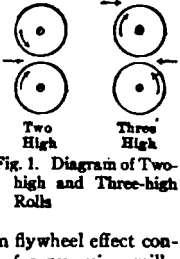


Fig. 1. Diagram of Two-high and Three-high Rolls

Reversing and Non-reversing Mills.—The great majority of rolling mills in this country are of the non-reversing type where the rolls run continuously in one direction. Flywheels are used to equalize the input to the motor. The ideal combination would be to use a motor of sufficient capacity to carry the average load and a flywheel which would take care of all the peaks. Such a wheel would be too large and a compromise between the motor and flywheel must generally be made. As opposed to the heavy flywheel effect required by the two-high or three-high non-reversing mill, the minimum flywheel effect consistent with the necessary speed and torque is desirable for reversing mills. In order to avoid the reflection of peak loads of these motors back upon the system, it is customary to interpose a flywheel motor-generator set with one or more generators between the power station and the mill. In order to minimize the flywheel effect of the reversing motor, two or more direct-current motors are often mounted on the same shaft and their armatures connected in series. This arrangement renders possible the use of smaller armature diameters with consequent reduction of acceleration losses and also permits the use of a high-voltage generator on the flywheel set. The mill motor is separately excited and perfect speed control is obtained by varying the excitation of the generator on the flywheel set. Direct-current generators can be designed for 2400 volts to give excellent results when operating two 1200-volt motors in series.

Power Required.—Rolling mill loads are irregular in the extreme due to the intermittent character of the process. For any particular ingot the motor load consists of periods of heavy duty increasing in length with the length of the metal in the pass, interspersed with periods of friction load only. With a given mill the load varies widely with the difference in the section rolled, differences in temperatures of metal, personal equation of the operator, etc. The practical determination of the power required to roll steel is a matter of elaborate and extensive tests under widely varying conditions. For methods and results see papers in *Bibliography*. The information for predetermining the sizes of motor and flywheel for an installation must cover the following points:

Type of mill; rail, plate, etc.	Time between passes.
Diameter and speed of rolls.	Elongation in each pass and total.
Weight of ingot.	Initial length.
Initial and final section.	Average and maximum rate of rolling.
Number of passes.	Temperature of metal.

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Load Curves. — From these data and a thorough understanding of the many variable factors encountered in steel-mill practice, it is possible to lay out load curves similar to the ones shown in Figs. 2, 3 and 4. From such curves it is then possible to determine the proper size of the motor and the flywheel.

The typical curve shown in Fig. 2 represents a load curve calculated for a two-high single-stand reversing blooming mill in which a 3000-pound ingot is reduced from initial to final section in eleven consecutive passes occurring at 5-second intervals. This curve is characteristic of blooming mills, roughing mills, etc., which in general give the lowest load factor. The work done in horse-power seconds is indicated by the area under the curve. Fig. 3 is representative of a large and mixed class with medium load factor, such as small merchant mills, bar mills, sheet mills, etc. Fig. 4 shows a load factor so high as to be scarcely approximated except in merchant mills with a large number of stands working at full capacity.

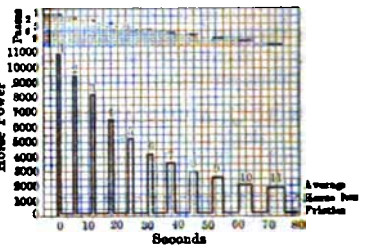


Fig. 2.

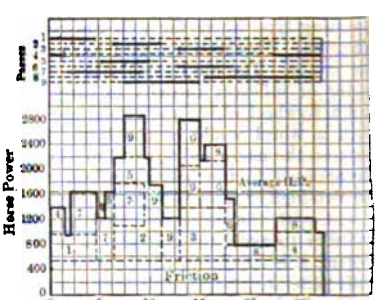


Fig. 3.



Fig. 4.

In determining the most suitable size of motor for the work indicated by the load curve full consideration must be given to the fact that excessive loads may be encountered at times due to the low temperatures of the metal in the pass, too heavy draft or other causes, and ample margin allowed. Assuming for the moment that by properly combining simultaneous passes on the several stands and the application of a suitable flywheel the load curve has been flattened out as much as appears possible, the question of continuity of service and duration of peaks must be considered to determine whether the limiting feature will be maximum torque or heating. With rolling-mill motors the limiting feature of design is usually torque rather than heating. The motor rating is determined by a consideration of the root-mean-square value of the current for a single cycle, and the frequency and duration of successive cycles.

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Induction Motors. — The choice of alternating- or direct-current
main rolls must be determined by a careful consideration of several
ief of which are the capacity of individual units, constant, variable or
speeds, reversing or non-reversing, transmission distance, existing
ion equipment, etc.

eneral conceded that for large units and constant speed, constant-load
luction motors with phase-wound rotors possess many advantages over
ent motors. This is due to the ruggedness of construction and
of operation of the induction motor, and to the facility with which
current may be stepped up to any desired voltage, thus rendering the
f economic power distribution relatively simple.

se main-roll drives where it is essential that close regulation be main-
a large number of speeds, each constant under varying loads, a direct-
otor with shunt characteristics has until recently been practically
It is now possible to obtain these characteristics by using standard
motors with phase-wound rotors and speed regulating sets.

thod of obtaining speed control consists in replacing the non-inductive
esistance by a compensated commutator machine which may be
either on the shaft of the main motor, or more commonly as one
f a two-unit motor-generator set, in which latter case, the second
s a squirrel-cage induction motor. The speed of the motor driving
ay be varied both above and below synchronism. When operating
chronism, the commutator machine acts as a motor and drives the
machine slightly above synchronism, thus returning to the line energy
al to the slip of the main motor minus the losses in the regulating set
hen the main motor is operated above synchronism, the induction
cts as a motor and drives the commutator machine as a generator
vers power to the slip-ring circuit of the mill motor.

Equipment for Induction Motors. — The control for large steel
s is important because of the size of the apparatus involved and the
mportance of continuous operation. Most motors for main-roll drive
l up at the beginning of a shift, immediately brought up to full speed,
nning until the end of the shift. Provision must be made for running
ne at reduced speed when desired, for making adjustments to the mill,
versing, in order to back out ingots which have stuck in the mill. If
is used, there should also be provision for quick stopping, so that if a
broken, the motor can be brought to rest quickly and a new spindle
d without delay. Current-limiting relays are desirable in order to
re fluctuations in input during starting and to maintain an approxi-
en torque without depending upon the intelligence of the operator,
service magnetically-operated contactors are necessary. It is always
to have some device by which the motor can be shut down from a
int in case of accident.

sistors for Starting Rheostats. — The resistance should be liberal,
he control may often be held on the first point for some time when
nts are being made and the starting torque may sometimes be heavy,
ly when an ingot has stuck in the rolls. Also, where a flywheel is
acceleration is necessarily slow, and some mills, particularly cold rolls,
very heavy torque during starting and until they have warmed up.
es should always be furnished having at least enough capacity to pro-
ll-load torque for two minutes. In special cases more will be required.

ntactors and Oil Switches. — Where 440- or 550-volt alternating
used, contactors can be employed for both primary and secondary,
te control is an easy matter. 2200- or 6600-volt motors require oil

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switches in the primary, which cannot be operated read
ing current. They can be operated with direct curre
the system and makes the operation of the alternating-
upon the direct-current supply. As remote control is
majority of cases, hand-operated oil switches can be us

Control Systems. — Figs. 5 and 6 show two
grams of double-range speed-regulating equipments. T
show the main mill motor when used with a speed regulating set. This set consists of an induction machine and a polyphase, commutator regulating machine with shunt-field excitation. The slip rings of the main induction motor are connected to the shunt winding of this regulating machine so that its counter electromotive force opposes the voltage of the main motor. The slip-ring voltage of the induction motor follows the variation in counter electromotive force of the regulating machine produced by changes in its shunt excitation. The shunt characteristics of the regulating machine are reflected in the speed-torque characteristics of the induction motor which is similar to that of the well-known shunt direct-current motor. The slip energy o conserved by converting it through the induction g power and returning it to the power lines. Another arr the diagram) consists of mounting the polyphase reg main-roll shaft and thus convert this slip energy into m

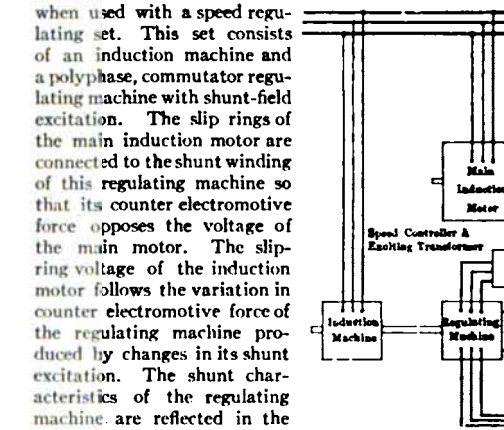


Fig. 5. Double-range Sp

In addition to the regulating set there is required a sm ohmic-drop exciter. Its armature is mounted on the m its speed is always the same as that of the main moto this ohmic-drop exciter to supply the ohmic-drop comp of the regulating machine when operating at or near sy field of the regulating machine also received excitation former. This transformer supplies the necessary reactiv of which is greatest at speeds remote from synchronism of excitation has made possible the development of a the main motor that retains all the desirable characterist tion motor operated with short-circuited slip rings, not ably below synchronism but equally well at speeds ne chronism and above synchronism.

Fig. 6 shows the arrangement in the synchronous c the slip energy is converted into direct current throu and in turn, into mechanical power by a direct-current main motor shaft. The arrangement shown in Fig. 5 over the rotary converter method, such as greater stabi motor is operating near synchronism, higher efficiency,

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l cases) and ability to operate non-regulating at an intermediate speed, tically at synchronism.

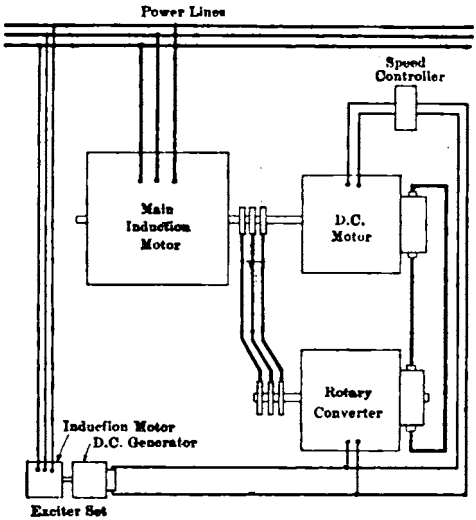


Fig. 6. Rotary Converter Speed Regulating Equipment.

-current Motors are used only on low-voltage circuits, usually 250 d can be handled by contactors. Quick stops can be accomplished . motors by dynamic braking, by which the armature is disconnected line and connected across a resistance so that the motor becomes a . Where flywheels are used, compound motors are necessary in order tomatic reduction in speed as the load increases.

cteristics of Gary Equipment. — The characteristics of the main- r equipment for the rail, billet, and sheet-bar mills of the Indiana npany, Gary, Indiana, are given in the table on page 1508.

IARY MOTOR APPLICATIONS.—The application of electric or auxiliary steel-mill machinery has been used for a long time. re of this service is unusually severe and has led to the development l-type motor for both d-c. and a-c. service. These motors are de- withstand heavy overloads and abnormally rapid acceleration, and truction is such that various parts are interchangeable, which greatly repairs and minimizes the delays incident to the same.

C. versus Mixed System. — Whether a-c. or d-c. motors should be driving the auxiliary machinery in a steel mill is a problem which has seriously discussed, and has led to the use of two recognized systems. known as the all a-c. system, where no direct current is used, and the tem, where both a-c. and d-c. motors are used.

many factors must be considered in comparing the two systems. In lace, it is to be assumed that power will primarily be alternating cur- e transmission distances ordinarily preclude the use of direct-current

CHARACTERISTICS OF MAIN ROLL

Rail mill

No. of motors*	H.P.	R.p.m.	Flywheel effect†
2	2000	214	4,312,000
1	6000	83	11,600,000
1	2000	68	8,950,000
1	6000	88	11,600,000
1	6000	75	14,100,000
	Billet mill		
2	2000	214	4,312,000
3	6000	83	11,600,000
	Sheet-bar Mill		
1	6000	83	11,600,000

* All motors 25 cycles, 6600 volts.
† Weight of flywheel in pounds times square of radius o

generators. It would therefore seem to be simplest and down to a suitable voltage through static transformer current motors. On the other hand, with certain of t screw-downs, live-roll tables, etc., the advantages in favo great that they are almost universally adopted. The additional expense for motor-generator sets and entai loss due to the low efficiency of conversion. On the oth motors are lower in first cost than induction motors and is maintained on the entire system where they are used. increase in power factor is effected by eliminating the induction motors, and, in addition, the motor-generator with synchronous motors which will take a leading curr offset part of the lagging current on the rest of the sys power factor enables a reduction to be made in the size a and generators, and also increases their efficiency due to th they are required to handle and to the decreased excit generators.

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ERS, MECHANICAL. — (*See also Boilers.*) Mechanical stokers wofold purpose: they make possible a more uniform and a more combustion of the fuel and thereby prevent the formation of smoke, and reduce the amount of labor required in handling and firing the fuel. e the prevention of smoke a fire-brick arch should also be used over part of the furnace.

S OF STOKERS. — There are three general types of mechanical lthough there are several which cannot be conveniently placed in any ese classes.

-grate Stoker. — The first is the chain-grate stoker consisting of an hain placed in the furnace of the boiler with its top side revolving om the front of the furnace toward the back. The coal is fed onto this rate in front and is burned as it passes toward the bridge wall, where, grate is moving at its proper speed, the coal will have been completely ash which will drop down into the ashpit below.

e great advantage of the chain-grate stoker over most of the others is suitable for burning with natural draft bituminous coals of very high ontent. In plants where the load is reasonably steady and where eaks are not thrown upon the boilers this stoker makes a first-class on.

d Overfeed Type. — The second type of stoker is the inclined type. These stokers consist of movable bars forming an inclined a mechanism for moving these bars in such a manner as to cause the h is fed in at the top to be pushed gradually down the grates until it e dumping grate at the bottom, at which point it should be completely

feed Type. — The third type is the underfeed. In these stokers the onto the grate or up under the grate in such a manner that the fresh ways close to the grate while the coal which is being burned is at the air is also introduced at the bottom and while passing up through f coal is heated and thoroughly mixed with the volatile gases distilled coal and when passing through the incandescent layer at the top s temperature of combustion, so that generally no arches are neces-

Types. — There are several other stokers which are used to a greater extent and work on somewhat different principles, perhaps the most ing the so-called "finger" stoker, which has several oscillating paddles k up the coal and throw it into the furnace. There is another stoker of this order in which the coal is mechanically shovelled into the These stokers, however, have not reached any extensive application in general are only applicable to particular conditions.

G BY USE OF MECHANICAL STOKERS. — The difference ood and bad firing may easily amount to from 5 to 20 per cent of the fuel fired; hence, there is no investment around a steam plant which etter than the extra amount paid to secure good boiler practice.

tic stokers are now developed to a remarkable degree of perfection, suited to the fuel, have an advantage over hand-firing in that under ons they are reliable, can be adjusted to the minimum of the air and ium of load, and can be depended upon to operate continuously with ium amount of skilled labor. The economic saving will depend on f comparison and the method of operation. Compared with an ordi- or fireman, they should show a large saving. Whether a stoker will

save labor in the fire room depends upon the size of
mechanical stokers are not labor-saving devices in pla
six to eight boilers (1500 to 4800 h.p.).

One man can handle the coal and ashes, fire the bo
water level of 200 h.p. of boilers equipped with the com
With shaking or dumping grates 300 h.p. may be contro
large boilers equipped with dumping grates one man wil
h.p., when using the steam sizes of anthracite coal, but th
in front of the boiler and a water tender is usually provi
With soft coal about 700 boiler h.p. may be fired by on
cumstances. In a large plant containing twelve 650 B.
with stokers, a water tender, one fireman and one helpe
for their efficient operation. In stations of this size
basement, and the change from hand to stoker firing w
in their number.

One authority states that stokers save 30 to 40 per
in plants using over 200 tons of coal per week; 20 to 30
from 50 to 200 tons of coal per week, and no saving in

It should be remembered that unless the type of sto
of fuel obtainable, the maintenance of the stoker plant
high, running in some cases twice or three times as
under hand-fired conditions.

COST OF MECHANICAL STOKERS (Pre-wa
mechanical stokers cost from $3.50 to $6.50 per boiler
depends more on the width of the stoker than on the
Chain-grate stokers cost in the neighborhood of from
width. Inclined-grate stokers from $140 to $225 per
feed stokers from $200 to $300 per foot of width. Th
usually standard and depends on the type of coal to b
differ considerably with the amount of auxiliary mat
stoker, such as fronts, air boxes, coking arches, stoker
ing devices, but are based on labor and material cos
prior to the European war.

R. J. S. Pigott (*Proceedings Am. Elec. Ry Assoc.*,
data for mechanical stokers:

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AVERAGE DATA FOR STOKERS

Type of stoker	Step and slope overfeed	V overfeed	Chain overfeed	Gravity underfeed	Horizontal retort underfeed
Average price per rated b.h.p....	$3.60	$3.60	$3.50–$6.55	$5.65	$4.44
Normal forcing ability in per cent of rating...	190	175	260	300–350	300
Price per max. h.p. developable	$1.90	$2.06	$2.52	$1.62–$1.88	$1.48
Maintenance per ton coal fired, in cents.....	10–12	11–14	6–10	2.5–4	4–6
Attendance in man-hours per active hour....	0.45	0.45–0.50	0.20–0.30	0.08–0.10	0.30–0.40
Pounds coal per sq. ft. grate surface (max.)..	35–38	35–42	45–48	60–75	50–65

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STRENGTH AND ELASTICITY. — (*See also Buildings, Allowable Unit Stresses in; Mechanics, Principles of; Structures, Simple.*) When opposing external forces are applied to a body the latter is in general deformed more or less, and, in the case of solids, when the applied forces are increased sufficiently the body ruptures.

STRESSES. — A stress is the internal resisting force set up within a body opposing the external forces which tend to deform it. When the external forces cause a stretching of the body the stress is called a tension; when the external forces compress the body the stress is called a compression; when the external forces cause a relative slipping of the particles in two contiguous parallel planes in the body the stress is called a shear.

Unit Stress. — By unit stress is meant the stress per unit area; in the case of tension or compression the area is taken perpendicular to the line of action of the forces producing the stress; in the case of shear the area is taken parallel to the forces producing the stress. Unless otherwise stated the stress is assumed uniformly distributed over the area upon which it acts.

Ultimate Stress or Ultimate Strength. — The ultimate stress which a body will stand, or the ultimate strength of the body, is the greatest stress which can be produced in the body without rupturing it. Ultimate strength for tension and compression are usually quite different; the former is usually called tensile strength and the latter compressional strength. The ultimate strength of materials is usually specified in terms of the stress per unit area; see *Units and Conversion Factors*.

DEFORMATIONS OR STRAINS. — The deformation accompanying any stress is usually called a strain. The strain corresponding to a tension is called an elongation, the strain corresponding to a compression is a shortening, the strain corresponding to a shear is called a detrusion. An elongation is usually specified as the ratio (or percentage) of the increase in length to the original length of the specimen. For example, if a rod 10 feet long is stretched by an applied force to a length of 10.2 feet, the elongation is $(10.2-10)/10 = 0.02$ or 2 per cent. The term elongation is frequently used to designate specifically the *maximum* elongation just before rupture.

Hooke's Law. — Experiment shows that when the unit stress in a body does not exceed a certain value it bears a constant ratio to the resulting unit strain (ratio of change in size to original size). This fact is known as Hooke's Law. In the case of a tension the change in size is usually taken as the change in length, no attention being paid to the decrease in cross-section, which is usually negligible, except just before rupture.

ELASTICITY. — A body deformed under stress will return to its original shape when the stress is removed, provided it has not been strained beyond the point at which the proportionality between stress and strain ceases. This ability to return to its original form after deformation is called elasticity.

Elastic Limit. — The stress per unit area corresponding to the point at which the proportionality between stress and strain ceases is called the elastic limit of the material.

Permanent Set. — When a body is stressed beyond its elastic limit, the deformation per unit increase in stress becomes greater than it was before this point was reached, and the material takes a permanent "set," i.e., when the stress is removed the body does not return to exactly its original form. As a measure of the "set" is taken the ratio of the permanent change in size (after the stress is removed) to the original size.

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Modulus of Elasticity. — Let ΔF denote the change in the total tension producing a change Δl in a rod of length l and cross section A; then the quotient of the increase in the unit stress by the increase in the elongation per unit length, is called the modulus of elasticity (Young's modulus) of the material, and may be designated by the symbol M, i.e.,

$$M = \frac{\Delta F}{\Delta l} \cdot \frac{l}{A}.$$

This modulus has the dimensions of pounds per square inch.

VALUES OF TENSILE STRENGTH AND MODULUS OF ELASTICITY. — Values of these properties given by different authorities are extremely variable, since the measured values depend largely upon the chemical composition, heat treatment, age, size and shape of the test specimen.

Alloys, Miscellaneous. — See articles on *Alloys* and *Wires, Resistance.*

Aluminum. — See article on *Aluminum.*

Belting. — Tensile strength, in pounds per square inch: Cotton, 4500 to 8900; Single leather, 3200 to 5900; Double leather, 2200 to 5400. See also article on *Belts and Belting.*

Brass Wire. — Tensile strength ranges from about 50,000 to 150,000 pounds per square inch; modulus of elasticity is about 14×10^6 pounds per square inch.

Brick. — See article on *Bricks and Brick Masonry.*

Bronze Wire. — The tensile strength of phosphor-bronze wire ranges from about 44,000 to 140,000 pounds per square inch; of silicon-bronze wire, from 95,000 to 115,000 pounds per square inch.

Cement. — See article on *Cement.*

Concrete. — See article on *Concrete.*

Copper. — See articles on *Copper* and *Wires and Cables, Bare.*

Earth. — See *Soils*, below.

Glass. — Tensile strength of common green or of flint glass ranges from about 2500 to 5000 pounds per square inch. Modulus of elasticity ranges from about 8.5×10^6 to 11.5×10^6.

The crushing or compressive strength of glass ranges from about 13,000 to 40,000 pounds per square inch.

Granite. — Crushing or compressive strength ranges from about 9700 to 34,000 pounds per square inch.

Iron. — See articles on *Iron, Pig and Cast*, and *Iron, Wrought.*

Lead. — Tensile strength ranges from about 2600 to 3300 pounds per square inch.

Limestone. — Crushing or compressive strength ranges from about 6000 to 25,000 pounds per square inch.

Marble. — Crushing or compressive strength ranges from about 7500 to 21,000 pounds per square inch.

Nickel. — Tensile strength of cast nickel ranges from about 40,000 to 85,000 pounds per square inch, and tensile strength of annealed nickel ranges from about 70,000 to 95,000 pounds per square inch. Modulus of elasticity ranges from about 24×10^6 to 27×10^6 pounds per square inch.

Rope. — See *Ropes and Rope Drive.*

Soils. — See articles on *Power Stations, Hydroelectric*, and *Buildings, Allowable Unit Stresses in.*

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Steel. — Tensile strength in pounds per square inch:

Bessemer: 56,000 to 74,000, Open-hearth: 50,00
Cast: 67,000 to 106,000, Wire: 50,00

Modulus of elasticity of various kinds of steels usually
and 35×10^6 pounds per square inch. See also articles
Cables, Bare.

Timber. — See articles on *Timber* and *Poles for Overh*

Tin. — Tensile strength ranges from about 4000 to
inch; modulus of elasticity from about 2.5×10^6 to $6 \times$
inch.

Zinc. — Tensile strength ranges from about 7000
square inch; modulus of elasticity is about 12×10^6 pou

Wood. — See *Timber*, above.

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TURES, SIMPLE. — (*See also Building Laws; Cement; Concrete; hanics, Principles of; Steel; Timber; Towers for Transmission Lines.*)
re in the sense used by engineers is a member or combination of onstructed to hold forces in equilibrium. The common structures are lers, columns and trusses.
outline of the contents of this article is as follows:

ions and Fundamental Relations..... p. 1515
tles of Plane Sections..... 1518
of Structural Shapes..... 1523
nces for Impact..... 1529
ation of Reactions..... 1531
ation of Shear..... 1532
ation of Bending Moment..... 1535
, Formulas and Costs..... 1537
Girders, Formulas and Costs..... 1538
ns, Formulas and Costs..... 1539
s, Design of..... 1550
uous Girders, Beams, Slabs and Trusses..... 1555

ITIONS AND FUNDAMENTAL RELATIONS. — The more erms used in the treatment of structures are defined below.

of Gravity; Moment of Inertia; Radius of Gyration; Stress and See *Mechanics, Principles of.*

Axis. — The neutral axis of the cross-section of a stressed bar is of those points in the plane of the cross-section at which the direct equals zero. If the bar is of homogeneous material and subjected (*see Bending Moment, below*) only, the neutral axis passes through of gravity of the cross-section, and if the loads causing flexure are the plane of one of the principal axes, the neutral axis coincides with principal axis. This is the condition commonly occurring in wooden eams. Table I which follows gives the location of the neutral axis for only. If the cross-section is subjected to combined flexure and direct neutral axis will not pass through its center of gravity, but will deviate an amount depending upon the ratio of bending moment to direct hing infinity when the stress is direct tension or compression only, se of a tie rod or column centrally loaded.
eam is of unhomogeneous material the position of the neutral axis termined by calculation. The reinforced concrete beam is the only xample of such a case. For formulas for this case, see *Concrete,*

Modulus. — If c is the normal distance from the neutral axis of a surface to the most remote portion of its perimeter, and I the mo- rtia of the surface about its neutral axis the expression I/c is called the dulus. For symmetrical beams exposed to pure flexure only, c = one- th of the beam. Tabular values of this quantity for plane surfaces of apes are given in Table I and for the ordinary structural steel beams II to VI, which follow.

of Resistance. — If s is the allowable unit stress per square inch treme fiber of a beam or girder, the expression $\frac{sI}{c}$ is called the moment since its value equals the maximum bending moment which the mem- rry without causing a stress greater than the allowable unit stress.

Moment. — The statical moment of a plane surface about a given the plane is the summation of the products of each elementary area,

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dA, of which the surface is composed, times the distanc from the given axis, distances above the axis being c below negative. It may be expressed mathematically follows: (See Fig. 1.)

Let Q = statical moment of a given area about an a Y-Y lying in the plane of the area,
dA = an elementary area,
y = distance of center of gravity of the area from the axis,

then $Q = \int y dA$.

The statical moment of an area about an axis of syn zero since the positive lever arm of any elementary are corresponding negative lever arm.

Equations of Equilibrium. — (*See also Mechanic* following laws apply to a structure lying in a plane an lying in the same plane:

1st. The algebraic sum of the components of all th to any axis in the plane of the forces must equ
2nd. The algebraic sum of the moments of all the f right angles to the plane of the forces must equ

If we resolve the applied forces into components par axes, OX and OY, and let ΣX and ΣY equal the alge parallel respectively to OX and OY, and ΣM the algebr about any axis, normal to the plane of the forces, thes comprehended by the three equations:

$$\Sigma X = 0,\ \Sigma Y = 0,\ \Sigma M = 0.$$

If OX and OY are respectively horizontal and vertical generally used form:

$$\Sigma H = 0,\ \Sigma V = 0,\ \Sigma M = 0.$$

Unless a structure satisfies all these conditions it can

Reactions. — The forces which the abutments or pie such as beams, girders or trusses, are called the reactio in general, have three unknown factors, viz., directio of application. In order to simplify computations it is trusses to eliminate three of these unknowns by the meth in end-supported trusses and long girders, the ends are u of comparatively small diameter thereby fixing the poin reactions. Moreover, the pin at one end is in turn sup thereby making that reaction normal, or nearly so, to its fixing the direction of one of the reactions. These refin applied to short girders the ends of which are supporte ings. Even in such cases, however, the point of ap comparatively small limits, and the base plate at on thus making the reaction at that end approximately n surface. For ordinary beams no special provision is reaction conditions but each reaction is assumed to be n surface and to act at its center.

When the unknown reaction factors are thus reduc may be determined by the three equations of equilibriu being the usual procedure in the case of beams on tw later. For beams supported at more than two points, tion (*see below*) may be applied.

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Moment Equation. — This is an equation connecting the moments adjoining points of support of a continuous structure. It is strictly le only to structures having a constant moment of inertia and on level but is applied approximately to structures the moment of inertia of not constant.

ormula for concentrated loads is as follows:

M_c = moment at any support,
M_a = moment at adjoining support on left,
M_b = moment at adjoining support on right,
L_1 = length of span to left of support at which M_c acts,
L_2 = length of span to right of support at which M_c acts,
P_1 = any load in span L_1 and k_1L_1 its distance from left support,
P_2 = any load in span L_2 and k_2L_2 its distance from support at left of that span.

$$M_a L_1 + 2 M_c(L_1 + L_2) + M_b L_2 = \Sigma P_1 L_1^2(k_1^3 - k_1) + \Sigma P_2 L_2^2 (3 k_2^2 - k_2^3 - 2 k_2).$$

iform load of w_1 lb. per ft. over span L_1 and w_2 lb. per ft. over span L_2 ding formula becomes

$$M_a L_1 + 2 M_c(L_1 + L_2) + M_b L_2 = -\frac{1}{4} w_1 L_1^3 - \frac{1}{4} w_2 L_2^3.$$

pplication of these formulas to successive series of spans enables the at all supports to be computed and from these the reactions and shears be determined, and the structure completely solved; see section below *s, Design of.*

. — The shearing force or shear at any section of a body is the force nds to produce slipping along the given section. Shearing failure ue either to transverse fracture or to slipping of the fibers on each other. rdinary structural materials wood is the only one of fibrous character ring failure in this material frequently occurs on planes parallel to the

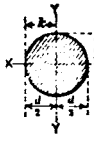
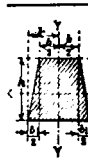
ng Moment; Flexure. — The bending moment at any section of a e to a set of coplanar forces is the resultant moment about an axis hrough the center of gravity of the section of all the forces on either e section, it being understood that the section and the axis are perpen- o the plane of the forces. Fractures due to excessive bending moment rough longitudinal failure of the fibers either by tension or crushing. ling which results from the application of a bending moment is termed

and Live Loads. — The loads acting upon a given structure may be nto two distinct types: viz., quiescent loads which are known as *dead* l moving or intermittent loads which are known as *live loads*. The includes all loads which are fixed in magnitude and position such as nt of the structure itself and such superimposed loads as the floor of g or bridge; the second class includes such loads as crowds of people, dise, snow, wind and vehicles of all sorts. The live load through its and irregularity of application is more injurious in its effect than the d, hence in a structure subjected to live loads, either the value of the should be increased as explained below under *Allowances for Impact*, lowable unit stress in the material should be reduced. The former eems to be more logical and is commonly adopted at the present time g structural engineers.

(*Text continued on p. 1522.*)

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TABLE I.—PROPERTIES

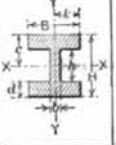
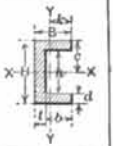
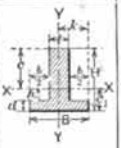
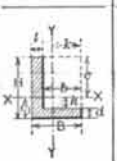
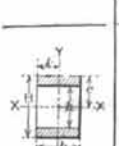
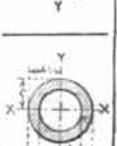
Section. Axes X–X and Y–Y pass through center of gravity	Distance from X–X to extreme edge of section	Moment of inertia with respect to axis X–X	Section modulus with respect to axis X–X	Radius of gyration with respect to axis X–X
	c	I_x	$\frac{I_x}{c}$	ρ_x
	$\frac{h}{2}$	$\frac{1}{12}bh^3$	$\frac{1}{6}bh^2$	$\frac{h}{\sqrt{12}}=0.289h$
	$\frac{2}{3}h$	$\frac{1}{36}bh^3$	$\frac{1}{24}bh^2$	$\frac{h}{\sqrt{18}}=0.236h$
	$\frac{d}{2}$	$\frac{\pi d^4}{64}=0.0491d^4$	$\frac{\pi d^3}{32}=0.0982d^3$	$\frac{d}{4}$
	$\frac{h}{3}\left(\frac{3b+2b_1}{2b+b_1}\right)$	$\frac{h^3}{36}\left(\frac{6b^2+6bb_1+b_1^2}{2b+b_1}\right)$	$\frac{h^2}{12}\left(\frac{6b^2+6bb_1+b_1^2}{3b+2b_1}\right)$	$\frac{h}{2b+b_1}\sqrt{\frac{6b^2+6bb_1+}{18}}$
	$\frac{b}{\sqrt{2}}=0.707b$	$\frac{b^4}{12}$	$\frac{\sqrt{2}}{12}b^3=0.118b^3$	$\frac{b}{\sqrt{12}}=0.289b$
	$\frac{H}{2}$	$\frac{BH^3-bh^3}{12}$	$\frac{BH^3-bh^3}{6H}$	$\sqrt{\frac{BH^3-bh^3}{12(BH-bh)}}$

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Moment of inertia with respect to axis $Y-Y$	Section modulus with respect to axis $Y-Y$	Radius of gyration with respect to axis $Y-Y$
I_y	$\frac{I_y}{k}$	ρ_y
$\frac{1}{12}hb^3$	$\frac{1}{6}hb^3$	$\frac{b}{\sqrt{12}}=0.289b$
$\frac{1}{48}hb^3$	$\frac{1}{24}hb^3$	$\frac{b}{\sqrt{24}}=0.204b$
$\frac{\pi d^4}{64}=0.0491d^4$	$\frac{\pi d^3}{32}=0.0982d^3$	$\frac{d}{4}$
$\frac{hb_1^3}{48}+\frac{bb_1h(3b+2b_1)}{24}$	$\frac{\frac{hb^3}{6}+\frac{hb_1^3}{24}+\frac{bb_1h(3b+2b_1)}{12}}{b+b_1}$	$\frac{1}{12}\sqrt{\frac{24b^3+6b_1^3+12bb_1(3b+2b_1)}{2b+b_1}}$
$\frac{b^4}{12}$	$\frac{\sqrt{2}}{12}b^3=0.118b^3$	$\frac{b}{\sqrt{12}}=0.289b$
$\frac{HB^3-hb^3}{12}$	$\frac{HB^3-hb^3}{6B}$	$\sqrt{\frac{HB^3-hb^3}{12(BH-bh)}}$

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TABL

Section. Axes X–X and Y–Y pass through center of gravity	Distance from X–X to extreme edge of section	Moment of inertia with respect to axis X–X	Section mo lus with respect to a X–X
	c	I_x	$\frac{I_x}{c}$
	$\frac{H}{2}$	$\frac{BH^3-h^3(B-b)}{12}$	$\frac{BH^3-h^3(B}{6H}$
	$\frac{H}{2}$	$\frac{BH^3-h^3b}{12}$	$\frac{BH^3-h}{6H}$
	$H-\frac{1}{2}\left(\frac{tH^2+bd^2}{tH+bd}\right)$	$\frac{1}{3}(Bc_1^3-bh^3+tc^3)$	$\frac{\frac{1}{3}Bc_1^3-bh^3}{H-\frac{1}{2}\left(\frac{tH^2}{tH}\right.}$
	$H-\frac{1}{2}\left(\frac{tH^2+bd^2}{tH+bd}\right)$	$\frac{1}{3}(Bc_1^3-bh^3+tc^3)$	$\frac{1}{3}\left(\frac{Bc_1^3-bh^3}{H-\frac{1}{2}\frac{tH^2}{tH}}\right.$
	$\frac{H}{2}$	$\frac{b}{12}(H^3-h^3)$	$\frac{b}{6}\frac{H^3-h}{H}$
	$\frac{D}{2}$	$\frac{\pi}{64}(D^4-d^4)$	$\frac{\pi}{32}\frac{D^4-}{D}$

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TIONS — (*Continued*)

	Moment of inertia with respect to axis $Y-Y$	Section modulus with respect to axis $Y-Y$	Radius of gyration with respect to axis $Y-Y$
	I_y	$\frac{I_y}{k}$	ρ_y
	$\frac{2dB^3+hb^3}{12}$	$\frac{2dB^3+hb^3}{6B}$	$\sqrt{\frac{2dB^3+hb^3}{12(2dB+hb)}}$
	$\frac{H\beta+2db^3}{3}$ $-(Ht+2db)(b-k)^2$	$\frac{H\beta+2db^3}{3k}$ $-\frac{(Ht+2db)(b-k)^2}{k}$	$\sqrt{\frac{H\beta+2db^3}{3(Ht+2db)}-(b-k)^2}$
	$\frac{(H-d)\beta+dB^3}{12}$	$\frac{(H-d)\beta+dB^3}{6B}$	$\sqrt{\frac{(H-d)\beta+dB^3}{12(H-d)t+12dB}}$
	$\frac{H\beta+db^3}{3}$ $-(Ht+db)(b-k)^2$	$\frac{H\beta+db^3}{3k}$ $-\frac{(Ht+db)(b-k)^2}{k}$	$\sqrt{\frac{H\beta+db^3}{3(Ht+db)}-(b-k)^2}$
	$\frac{(H-h)b^3}{12}$	$\frac{(H-h)b^2}{6}$	$\frac{b}{\sqrt{12}}=0.289b$
	$\frac{\pi}{64}(D^4-d^4)$	$\frac{\pi}{32}\frac{(D^4-d^4)}{D}$	$\frac{1}{4}\sqrt{D^2+d^2}$

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Impact is the name given to the dynamic force which is added to the forces due to live and dead loads to obtain the true forces acting upon structures; see section below on *Allowances for Impact*.

Beam or Girder. — A beam is a bar of wood, metal, concrete or other stress-resisting substance supported at certain definite points along its length and loaded transversely to its longitudinal axis, which is usually but not always placed in a horizontal position. The name girder is commonly applied to large beams built up of structural members; for example, a plate girder is a steel or iron structure made up of plates and angles, or other structural shapes, riveted together.

Floor Beam; Panel.—Frequently girders and trusses receive all their live load and much of their dead load through other members called floor beams. Fig. 1 illustrates such construction. The distance between adjacent floor beams is the panel length.

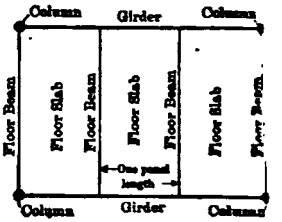


Fig. 2.

Column. — A column is a member intended primarily to resist direct compression, although it may also be subjected to bending stresses due either to transverse loads or to eccentric application of the direct loads.

Truss. — A truss is a structure consisting of separate bars constructed to carry either direct tension or direct compression. These bars are connected at their ends and occasionally at intermediate points, the points of connection being called joints. The connections are sometimes made by riveting the bars directly together and sometimes by riveting them to a common steel plate, the truss in either case being called a *riveted truss*. The connections may also be made by fastening together with a large steel pin all the members meeting at a joint; such a truss is called a *pin truss*. The outer forces should be applied at the joints only, since the members are not intended to carry bending. This is accomplished by the use of floor beams in a bridge and purlins in a roof.

PROPERTIES OF PLANE SECTIONS. — In Table I are given the location of the center of gravity, and values of the moment of inertia, section modulus and radii of gyration of the more common plane sections.

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ES OF STRUCTURAL SHAPES. — Tables II to VI give the
ns and properties of the commonly used shapes of structural steel;
sheared plates, angles with either equal or unequal legs, I-beams, and
For information upon other metallic structural material see the
ons of the various steel manufacturing companies,

TABLE II.—SHEARED PLATES *

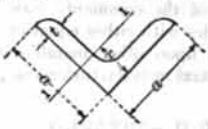
Thickness in inches																			
3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1	1 1/8	1 1/4	1 1/2	1 3/4	2
Maximum length in inches																			
00	525	575	600	600	600	600	600	....	....	....	....	....	....	....	....	....	....	....	....
75	525	500	600	600	625	625	625	....	....	....	....	....	....	....	....	....	....	....	....
75	475	525	550	550	575	575	575	575	550	525	500	475	475	450	425	400	375	350
50	525	550	575	610	600	600	600	575	575	525	500	500	500	475	425	400	375	350
00	525	575	600	600	600	600	600	600	575	550	550	525	525	500	450	400	375	350
00	525	550	600	600	625	625	625	600	575	550	550	525	525	500	450	400	375	350
00	525	550	600	600	625	625	625	600	575	550	550	525	525	475	425	400	375	325
00	475	500	575	575	600	600	600	600	575	550	550	525	525	475	425	375	350	325
50	450	500	540	550	575	575	575	575	575	550	525	500	500	475	425	375	350	300
..	425	475	440	540	540	540	540	540	525	500	475	450	450	425	375	325	300	280
..	400	475	440	540	540	540	540	540	500	450	450	425	425	375	350	325	300	280
..	350	375	400	450	450	450	450	450	425	400	400	375	375	350	325	280	270	260
..	300	325	350	400	400	400	400	400	400	375	375	350	325	300	275	260	260	250
..	275	300	325	375	375	375	375	375	375	350	350	325	300	275	250	250	240	240
..	250	275	300	350	350	350	350	350	350	325	325	300	275	250	250	180	175	160
..	175	200	225	275	275	275	300	300	300	275	275	250	250	225	200	175	160	150
..	....	175	200	250	250	250	250	250	275	250	250	225	225	200	200	175	160	150
..	....	....	180	180	180	180	180	180	180	200	200	175	175	160	160	150	144	144
15	124	127	127	127	127	127	127	127	127	126	126	126	126	126	125	125	125	125
Minimum diameter of heads = 30 inches.																			

Cambria Steel, George E. Thackray, Engineer, (1919).

med by shearing. Narrower plates are rolled to dimensions and
in practically any width; even inches should be used.

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TABLE III. — STANDARD ANGLES WITH



Dimensions	Thickness	Weight per foot	Area of section	Distance of center of gravity from back of leg
$a \times a$	t		A	x
Inches	Inch	Pounds	Sq. in.	Inches
1½×1½	⅛	1.23	0.36	0.42
"	3/16	1.80	0.53	0.44
"	¼	2.34	0.69	0.47
"	5/16	2.86	0.84	0.49
"	⅜	3.35	0.98	0.51
2 ×2	⅛	1.65	0.48	0.55
"	3/16	2.44	0.72	0.57
"	¼	3.19	0.94	0.59
"	5/16	3.92	1.15	0.61
"	⅜	4.7	1.36	0.64
"	7/16	5.3	1.56	0.66
"	½	6.0	1.75	0.68
2½×2½	⅛	2.08	0.61	0.67
"	3/16	3.07	0.90	0.69
"	¼	4.1	1.19	0.72
"	5/16	5.0	1.47	0.74
"	⅜	5.9	1.73	0.76
"	7/16	6.8	2.00	0.78
"	½	7.7	2.25	0.81
3 ×3	¼	4.9	1.44	0.84
"	5/16	6.1	1.78	0.87
"	⅜	7.2	2.11	0.89
"	7/16	8.3	2.43	0.91
"	½	9.4	2.75	0.93
"	9/16	10.4	3.06	0.95
3½×3½	¼	5.8	1.69	0.97
"	5/16	7.2	2.09	0.99
"	⅜	8.5	2.48	1.01
"	7/16	9.8	2.87	1.04
"	½	11.1	3.25	1.06
"	9/16	12.4	3.62	1.08
"	⅝	13.6	3.98	1.10
"	11/16	14.8	4.34	1.12

From *Cambria Steel*, George E. Thackray, En

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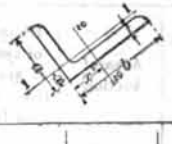
E III.—STANDARD ANGLES WITH EQUAL LEGS—(*Continued*)

Thickness	Weight per foot	Area of section	Distance of center of gravity from back of leg	Moment of inertia axis 1–1	Section modulus axis 1–1 $= \frac{I}{a-x}$
t		A	x	I	S
Inch	Pounds	Sq. in.	Inches	Inches^4	Inches^3
3/4	16.0	4.69	1.15	4.96	2.11
13/16	17.1	5.03	1.17	5.25	2.25
7/8	18.3	5.36	1.19	5.53	2.39
5/16	8.2	2.40	1.12	3.71	1.29
3/8	9.8	2.86	1.14	4.36	1.52
7/16	11.3	3.31	1.16	4.97	1.75
1/2	12.8	3.75	1.18	5.56	1.97
9/16	14.3	4.18	1.21	6.12	2.19
5/8	15.7	4.61	1.23	6.66	2.40
11/16	17.1	5.03	1.25	7.17	2.61
3/4	18.5	5.44	1.27	7.66	2.81
13/16	19.9	5.84	1.29	8.14	3.01
7/8	21.2	6.23	1.31	8.59	3.20
5/8	14.9	4.36	1.64	15.39	3.53
7/16	17.2	5.06	1.66	17.68	4.07
1/2	19.6	5.75	1.68	19.91	4.61
9/16	21.9	6.43	1.71	22.07	5.14
5/8	24.2	7.11	1.73	24.16	5.66
11/16	26.5	7.78	1.75	26.19	6.17
3/4	28.7	8.44	1.78	28.15	6.66
13/16	31.0	9.09	1.80	30.06	7.15
7/8	33.1	9.73	1.82	31.92	7.63
15/16	35.3	10.37	1.84	33.72	8.11
	37.4	11.00	1.86	35.46	8.57
2	26.4	7.75	2.19	48.65	8.37
16	29.6	8.68	2.21	54.09	9.34
4	32.7	9.61	2.23	59.43	10.30
1/16	35.8	10.53	2.25	64.64	11.25
8	38.9	11.44	2.28	69.74	12.18
1/16	42.0	12.34	2.30	74.72	13.11
	45.0	13.23	2.32	79.58	14.02
16	48.1	14.12	2.34	84.34	14.91
	51.0	15.00	2.37	88.98	15.80
16	54.0	15.87	2.39	93.53	16.67
8	56.9	16.73	2.41	97.97	17.53

Cambria Steel, George E. Thackray, Engineer, 1919.

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TABLE IV.—STANDARD ANGLES WITH U



Dimensions	Thickness	Weight per foot	Area of section	Distance of center of gravity from back of longer leg	Moment of inertia axis
$b \times a$	t		A	x	I
Inches	Inch	Pounds	Sq. in.	Inch	Inches
2½×2	5/16	2.75	0.81	0.51	0.2
"	¼	3.62	1.06	0.54	0.3
"	5/16	4.5	1.31	0.56	0.4
"	3/8	5.3	1.55	0.58	0.5
"	7/16	6.1	1.78	0.60	0.5
"	½	6.8	2.00	0.63	0.6
3 ×2½	¼	4.5	1.31	0.66	0.7
"	5/16	5.6	1.62	0.68	0.9
"	3/8	6.6	1.92	0.71	1.0
"	7/16	7.6	2.22	0.73	1.1
"	½	8.5	2.50	0.75	1.3
"	9/16	9.5	2.78	0.77	1.4
3½×2½	¼	4.9	1.44	0.61	0.7
"	5/16	6.1	1.78	0.64	0.9
"	3/8	7.2	2.11	0.66	1.0
"	7/16	8.3	2.43	0.68	1.2
"	½	9.4	2.75	0.70	1.3
"	9/16	10.4	3.06	0.73	1.4
3½×3	¼	5.4	1.56	0.79	1.3
"	5/16	6.6	1.93	0.81	1.5
"	3/8	7.9	2.30	0.83	1.8
"	7/16	9.1	2.65	0.85	2.0
"	½	10.2	3.00	0.88	2.3
"	9/16	11.4	3.34	0.90	2.5
"	5/8	12.5	3.67	0.92	2.7
"	11/16	13.6	4.00	0.94	2.9
"	¾	14.7	4.31	0.96	3.1
"	13/16	15.8	4.62	0.98	3.3
"	⅞	16.8	4.92	1.00	3.5
4 ×3	5/16	7.2	2.09	0.76	1.6
"	3/8	8.5	2.48	0.78	1.9
"	7/16	9.8	2.87	0.80	2.1
"	½	11.1	3.25	0.83	2.4
"	9/16	12.4	3.62	0.85	2.6

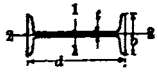
From *Cambria Steel*, George E. Thackray, E

ABLE IV.—STANDARD ANGLES WITH UNEQUAL LEGS—(Continued)

Dimensions	Thickness	Weight per foot	Area of section	Distance of center of gravity from back of longer leg	Moment of inertia axis 1–1	Distance of center of gravity from back of shorter leg	Moment of inertia axis 2–2
$b \times a$	t		A	x	I	x'	I'
Inches	Inch	Pounds	Sq. in.	Inches	Inches ^{4}	Inches	Inches ^{4}
4 ×3	⅝	13.6	3.98	0.87	2.87	1.37	6.03
"	11/16	14.8	4.34	0.89	3.08	1.39	6.49
"	¾	16.0	4.69	0.92	3.28	1.42	6.93
"	13/16	17.1	5.03	0.94	3.47	1.44	7.35
"	⅞	18.3	5.36	0.96	3.66	1.46	7.75
5 ×3	5/16	8.2	2.40	0.68	1.75	1.68	6.26
"	⅜	9.8	2.86	0.70	2.04	1.70	7.37
"	7/16	11.3	3.31	0.73	2.32	1.73	8.43
"	½	12.8	3.75	0.75	2.58	1.75	9.45
"	9/16	14.3	4.18	0.77	2.83	1.77	10.43
"	⅝	15.7	4.61	0.80	3.06	1.80	11.37
"	11/16	17.1	5.03	0.82	3.29	1.82	12.28
"	¾	18.5	5.44	0.84	3.51	1.84	13.15
"	13/16	19.9	5.84	0.86	3.71	1.86	13.98
"	⅞	21.2	6.23	0.88	3.91	1.88	14.78
5 ×3½	5/16	8.7	2.56	0.84	2.72	1.59	6.60
"	⅜	10.4	3.05	0.86	3.18	1.61	7.78
"	7/16	12.0	3.53	0.88	3.63	1.63	8.90
"	½	13.6	4.00	0.91	4.05	1.66	9.99
"	9/16	15.2	4.47	0.93	4.45	1.68	11.03
"	⅝	16.8	4.92	0.95	4.83	1.70	12.03
"	11/16	18.3	5.37	0.97	5.20	1.72	12.99
"	¾	19.8	5.81	1.00	5.55	1.75	13.92
"	13/16	21.3	6.25	1.02	5.89	1.77	14.81
"	⅞	22.7	6.67	1.04	6.21	1.79	15.67
"	15/16	24.2	7.09	1.06	6.52	1.81	16.49
6 ×3½	⅝	11.7	3.42	0.79	3.34	2.04	12.86
"	½	15.3	4.50	0.83	4.25	2.08	16.59
"	⅝	18.9	5.55	0.88	5.08	2.13	20.08
"	¾	22.4	6.56	0.93	5.84	2.18	23.34
"	⅞	25.7	7.55	0.97	6.55	2.22	26.39
"	15/16	27.3	8.03	0.99	6.88	2.24	27.84
"	1	28.9	8.50	1.01	7.21	2.26	29.15
6 ×4	⅝	12.3	3.61	0.94	4.90	1.94	13.47
"	½	16.2	4.75	0.99	6.27	1.99	17.40
"	⅝	20.0	5.86	1.03	7.52	2.03	21.07
"	¾	23.6	6.94	1.08	8.68	2.08	24.51
"	⅞	27.2	7.98	1.12	9.75	2.12	27.73
"	15/16	28.9	8.50	1.14	10.26	2.14	29.26
"	1	30.6	9.00	1.17	10.75	2.17	30.75

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TABLE V. — STANDARD I-BEAMS



Depth of beam	Weight per foot	Area of section	Thickness of web	Width of flange	Moment of inertia axis 1-1	Section modulus axis 1-1	Radius of gyration axis 1-1	Moment of inertia axis 2-2	Radius of gyration axis 2-2	Coefficient of strength*
d	(a)	*A*	*t*	*b*	*I*	*S*	*r*	*I'*	*r'*	
In.	Lb.	Sq.in.	In.	In.	In.⁴	In.³	In.	In.⁴	In.	
3	5.70	1.63	0.17	2.33	2.5	1.7	1.23	0.46	0.53	17,650
3	6.50	1.91	0.26	2.42	2.7	1.8	1.19	0.53	0.52	19,140
3	7.50	2.21	0.36	2.52	2.9	1.9	1.15	0.60	0.52	20,710
4	7.7	2.21	0.19	2.66	6.0	3.0	1.64	0.77	0.59	31,810
4	8.50	2.50	0.26	2.73	6.4	3.2	1.59	0.85	0.58	33,890
4	9.50	2.79	0.34	2.81	6.7	3.4	1.54	0.93	0.58	35,960
4	10.50	3.09	0.41	2.88	7.1	3.6	1.52	1.01	0.57	38,070
5	10.00	2.87	0.21	3.00	12.1	4.8	2.05	1.23	0.65	51,580
5	12.25	3.60	0.36	3.15	13.6	5.4	1.94	1.45	0.63	58,100
5	14.75	4.34	0.50	3.29	15.1	6.1	1.87	1.70	0.63	64,630
6	12.50	3.61	0.23	3.33	21.8	7.3	2.46	1.85	0.72	77,460
6	14.75	4.34	0.35	3.45	24.0	8.0	2.35	2.09	0.69	85,270
6	17.25	5.07	0.47	3.57	26.2	8.7	2.27	2.36	0.68	93,110
7	15.30	4.42	0.25	3.66	36.2	10.4	2.86	2.69	0.78	110,420
7	17.50	5.15	0.35	3.76	39.2	11.2	2.76	2.94	0.76	119,400
7	20.00	5.88	0.46	3.87	42.2	12.1	2.68	3.24	0.74	128,360
8	18.4	5.33	0.27	4.00	56.9	14.2	3.27	3.78	0.84	151,660
8	20.25	5.96	0.35	4.08	60.2	15.0	3.18	4.04	0.82	160,510
8	22.75	6.69	0.44	4.17	64.1	16.0	3.10	4.36	0.81	170,970
8	25.25	7.43	0.53	4.26	68.0	17.0	3.03	4.71	0.80	181,430
9	21.8	6.31	0.29	4.33	84.9	18.9	3.67	5.16	0.90	201,300
9	25.00	7.35	0.41	4.45	91.9	20.4	3.54	5.65	0.88	217,930
9	30.00	8.82	0.57	4.61	101.9	22.6	3.40	6.42	0.85	241,460
9	35.00	10.29	0.73	4.77	111.8	24.8	3.30	7.31	0.84	264,990

From *Cambria Steel*, George E. Thackray, Engineer, 1919.

* Divide by span in feet to determine total allowable dead load in pounds, including weight of beam, uniformly distributed over length of beam. Table is based upon a fiber stress of 16,000 lb. per sq. in. For allowable live and dead load reduce load as determined from table by amount of impact. Compression flange should be supported laterally at intervals not greater than 20 times its width. If this cannot be done reduce coefficients to one-half of above value where unsupported length divided by width = 70, and proportionally for intermediate values between 20 and 70.

(a) Weights revised Sept. 1, 1920.

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BLE V. — STANDARD I-BEAMS — (*Continued*)

Area of section	Thickness of web	Width of flange	Moment of inertia axis 1–1	Section modulus axis 1–1	Radius of gyration axis 1–1	Moment of inertia axis 2–2	Radius of gyration axis 2–2	Coefficient of strength*
A	*t*	*b*	*I*	*S*	*r*	*I'*	*r'*	
.in.	In.	In.	In.⁴	In.³	In.	In.⁴	In.	
.37	0.31	4.66	122.1	24.4	4.07	6.89	0.97	260,470
.82	0.45	4.80	134.2	26.8	3.90	7.65	0.93	286,250
.29	0.60	4.95	146.4	29.3	3.77	8.52	0.91	312,390
.76	0.75	5.10	158.7	31.7	3.67	9.50	0.90	338,530
.26	0.35	5.00	215.8	36.0	4.83	9.50	1.01	383,670
.29	0.44	5.09	228.3	38.0	4.71	10.07	0.99	405,800
.76	0.56	5.21	245.9	41.0	4.57	10.95	0.96	437,170
.48	0.41	5.50	441.8	58.9	5.95	14.62	1.08	628,270
.24	0.46	5.55	455.8	60.8	5.87	15.09	1.07	648,310
.71	0.56	5.65	483.4	64.5	5.73	16.04	1.04	687,530
.18	0.66	5.75	511.0	68.1	5.62	17.06	1.03	726,740
.65	0.75	5.84	538.6	71.8	5.52	18.17	1.01	765,960
.93	0.46	6.00	795.6	88.4	7.07	21.19	1.15	942,880
.65	0.56	6.10	841.8	93.5	6.91	22.38	1.13	997,680
.12	0.64	6.18	881.5	97.9	6.79	23.47	1.11	1,044,740
.59	0.72	6.26	921.2	102.4	6.69	24.62	1.09	1,091,800
.08	0.50	6.25	1169.5	117.0	7.83	27.86	1.21	1,247,490
.59	0.58	6.33	1219.8	122.0	7.70	29.04	1.19	1,301,110
.06	0.65	6.40	1268.8	126.9	7.58	30.25	1.17	1,353,400
.32	0.50	7.00	2087.2	173.9	9.46	42.86	1.36	1,855,310
.00	0.57	7.07	2167.8	180.7	9.31	44.35	1.33	1,926,950
.47	0.63	7.13	2238.4	186.5	9.20	45.70	1.31	1,989,700
.94	0.69	7.19	2309.0	192.4	9.09	47.10	1.30	2,052,440
.41	0.75	7.25	2379.6	198.3	8.99	48.55	1.28	2,115,190

From *Cambria Steel*, George E. Thackray, Engineer.

an in feet to determine total allowable dead load in pounds, including uniformly distributed over length of beam. Table is based upon a 000 lb. per sq. in. For allowable live and dead load reduce load as able by amount of impact. Compression flange should be supported ls not greater than 20 times its width. If this cannot be done re- to one-half of above value where unsupported length divided by roportionally for intermediate values between 20 and 70.
vised Sept. 1, 1920.

ES FOR IMPACT. — The force applied to a structure by a n as a locomotive or electric car is a function of its weight and cation. The value of the former can usually be determined e degree of accuracy; the effect of the latter cannot in general

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TABLE VI. — STANDARD CHAN



Depth of Channel	Weight per foot (a)	Area of section	Thickness of web	Width of flange	Moment of inertia axis 1-1	Section modulus axis 1-1	Radius of gyration axis 1-1	Moment of inertia
d		*A*	*t*	*b*	*I*	*S*	*r*	*I*
In.	Lb.	Sq. in.	In.	In.	In.^{4}	In.^{3}	In.	In.
5	6.70	1.95	0.19	1.75	7.4	3.0	1.95	0
5	9.00	2.65	0.33	1.89	8.9	3.5	1.83	0
5	11.50	3.38	0.48	2.04	10.4	4.2	1.75	0
6	8.20	2.38	0.20	1.92	13.0	4.3	2.34	0
6	10.50	3.09	0.32	2.04	15.1	5.0	2.21	0
6	13.00	3.82	0.44	2.16	17.3	5.8	2.13	1
6	15.50	4.56	0.56	2.28	19.5	6.5	2.07	1
7	9.80	2.85	0.21	2.09	21.1	6.0	2.72	0
7	12.25	3.60	0.32	2.20	24.2	6.9	2.59	1
7	14.75	4.34	0.42	2.30	27.2	7.8	2.50	1
7	17.25	5.07	0.53	2.41	30.2	8.6	2.44	1
7	19.75	5.81	0.63	2.51	33.2	9.5	2.39	1
8	11.50	3.35	0.22	2.26	32.3	8.1	3.10	1
8	13.75	4.04	0.31	2.35	36.0	9.0	2.98	1
8	16.25	4.78	0.40	2.44	39.9	10.0	2.89	1
8	18.75	5.51	0.49	2.53	43.8	11.0	2.82	2
8	21.25	6.25	0.58	2.62	47.8	11.9	2.76	2
9	13.40	3.89	0.23	2.43	47.3	10.5	3.49	1
9	15.00	4.41	0.29	2.49	50.9	11.3	3.40	1
9	20.00	5.88	0.45	2.65	60.8	13.5	3.21	2
9	25.00	7.35	0.61	2.81	70.7	15.7	3.10	2
10	15.30	4.46	0.24	2.60	66.9	13.4	3.87	2
10	20.00	5.88	0.38	2.74	78.7	15.7	3.66	2
10	25.00	7.35	0.53	2.89	91.0	18.2	3.52	3
10	30.00	8.82	0.68	3.04	103.2	20.6	3.42	3
10	35.00	10.29	0.82	3.18	115.5	23.1	3.35	4
12	20.70	6.03	0.28	2.94	128.1	21.4	4.61	3
12	25.00	7.35	0.39	3.05	144.0	24.0	4.43	4
12	30.00	8.82	0.51	3.17	161.6	26.9	4.28	5
12	35.00	10.29	0.64	3.30	179.3	29.9	4.17	5
12	40.00	11.76	0.76	3.42	196.9	32.8	4.09	6
15	33.90	9.90	0.40	3.40	312.6	41.7	5.62	8
15	35.00	10.29	0.43	3.43	319.9	42.7	5.57	8
15	40.00	11.76	0.52	3.52	347.5	46.3	5.44	9
15	45.00	13.24	0.62	3.62	375.1	50.0	5.32	10
15	50.00	14.71	0.72	3.72	402.7	53.7	5.23	11
15	55.00	16.18	0.82	3.82	430.2	57.4	5.16	12

From *Cambria Steel*, George E. Thackray, E

(a) Weights revised Sept. 1, 1920.

rmined since it depends upon such uncertain factors as rapidity of ap- irregularity of track, improper counterbalancing of locomotive driving raying action of crowds of people and similar causes. The allowance t (so-called) ranges from 0 to 100 per cent of the live load and is d by empirical rules as indicated in the formulas below. An excep- is rule is made in the case of timber structures where the effect of commonly allowed for by using a low unit stress. (*See Timber.*)

on Buildings. — No allowance is generally made for impact on except with special loadings such as moving machinery, swinging ., for which the designer should use his judgment. The building laws er cities fix arbitrary loads and unit stresses by which the designer overned; see article on *Buildings, Allowable Unit Stresses in.*

on Highway Bridges Carrying Electric Railways. — The fol- ract from the *Specifications for Bridges Carrying Electric Railways* the Massachusetts Public Service Commission (revised March, 1915), fely used for such cases:

tal maximum stress in any piece shall be computed by adding together nd live stresses, the live loads being placed in the most unfavorable ogether with a percentage of the live stress to allow for impact and This added percentage shall be as follows:

truck.

ringers, floor beams hangers and truss members receiv- their whole load from one panel point only ..... 50 per cent

ther live loads:

ood flooring and wood stringers..... no impact
or beams and stringers..... 25 per cent
or beam hangers..... 40 per cent
l counters..... 40 per cent

members in trusses, and for main girders, the percentage shall be one-twelfth the loaded length in feet with a maximum of 25 and a f 10 per cent."

on Steam Railroad Bridges. — The following rule of the American ngineering and Maintenance of Way Association is commonly used ed States:

namic increment of the live load shall be added to the maximum com- oad strains* and shall be determined by the formula $I = S\frac{300}{L+300}$,

ere I = impact or dynamic increment to be added to live-load strains,
S = computed maximum live-load strain,
L = loaded length of track in feet producing the maximum strain in the member.

es carrying more than one track, the *aggregate length of all tracks* he strain shall be used. Impact shall not be added to strains pro- ngitudinal, centrifugal and lateral or wind forces."

ATION OF REACTIONS. — The reactions upon a truss, girder ng in a plane and acted upon by forces lying in the same plane may ed by the application of the equations of equilibrium (*see preceding* vided there are but two reactions which together have three unknown ; such a structure is said to be statically determined. If more than wn reaction components exist the reactions cannot be computed by the structure, although stable, is statically undetermined; if less than

* as here used means stresses in the more modern meaning of the words.

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three exist the structure is unstable. If the structure is supported at more than two points it cannot be made statically determined except by the insertion in the structure of special devices, such as hinged joints. The tower shown in Fig. 3 is statically determined with respect to the outer forces since the points of application of the reactions at *a* and *b* are fixed in position, and the reaction at *b* is also fixed in direction. If neither of the reactions were fixed in direction the structure would be indeterminate; if both of the reactions were fixed in direction the tower would be unstable, e.g., if both ends were on rollers and neither end bolted to the masonry.

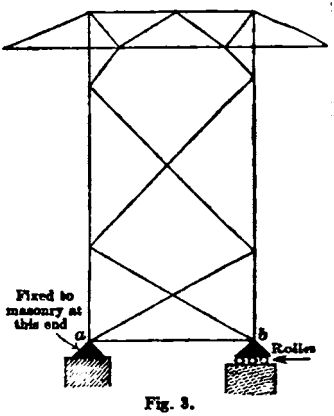


Fig. 3.

Such towers when used for transmission lines are seldom built with rollers or even planed plates, and frequently the bottoms of the columns are imbedded in a concrete base, the latter condition making it impossible to accurately compute the reactions. Similar towers for railroad and highway bridges are usually made determinate.

Method of Computation. — The following example illustrates the analytical method of computing reactions on statically determinate structures. The method may be applied equally well to uniformly distributed loads provided the resultants of such loads are used in place of concentrated loads.

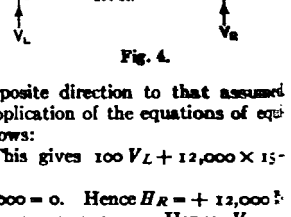


Fig. 4.

To Compute the Reactions on Truss Shown in Fig. 4. — Let V_L = left reaction, and V_R and H_R = the components of the right reaction, the direction of which is unknown. V_L will be vertical since it is supported on rollers bearing on a horizontal surface. V_R and V_H may be assumed to act in either direction. A negative sign in the final result indicates that the force acts in the opposite direction to that assumed. The determination of the reactions by the application of the equations of equilibrium (*see above*) may be carried out as follows:

1st. Apply $\Sigma M = 0$ about right end. This gives $100\,V_L + 12{,}000 \times 15 - 20{,}000 \times 75 = 0$. Hence $V_L = 13{,}200$ lb.

2nd. Apply $\Sigma H = 0$. This gives $H_R - 12{,}000 = 0$. Hence $H_R = +12{,}000$ lb.

3rd. Apply $\Sigma V = 0$. This gives $V_R + 13{,}200 - 20{,}000 = 0$. Hence $V_R = -6800$ lb.

In these results a positive sign shows that the reaction acts as indicated in Fig. 4.

Reactions on Continuous Girders. — See sections which follow on *Continuous Girders, Beams, Slabs* and *Trusses*.

CALCULATION OF SHEAR. — The nomenclature used in the discussion of shear is as follows:

V = the total external shear on any section in pounds,

P = magnitude of a single concentrated load in pounds,

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= a uniform load in pounds per foot,
= span of beam in feet (distance center to center of supports),
= length of a panel in feet,
= distance in feet from a given section to one of the points of support,
= total number of equal panels into which a girder is divided,
= number of panels between a given panel and the more remote abutment.

of Computation. — The magnitude of the shear at any section of to a set of coplanar forces may be readily computed in the following Resolve each force into nents, parallel and per- respectively to the on; the algebraic sum ponents parallel to the all the forces on either he section equals the he shear is generally positive when the re- ce is *upward* on the *left* on.

of Shear. — A curve a line the ordinate to any point equals the the given body at the here the ordinate is Fig. 5 shows typical his sort.

m Shear with Single Uniform Load. — In a supported beam, girder oncentrated load causes shear at a given section d an infinitesimal dis- the section on the side more distant point of he magnitude of this ls that of the nearer A concentrated load aximum shear on the placed an infinitesimal one side of either point this shear equals the of the load itself. A distributed live load imum shear at a given n placed over the entire om the section to the t point of support; its s that of the nearer re- s given by the equation . Its maximum value equals $wL/2$ at either end of the beam when fully loaded.

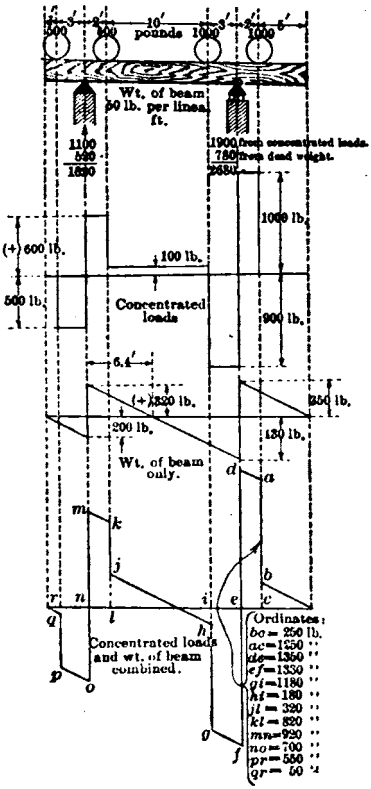


Fig. 5. Curves of Shear. Positive results are shown above the axis. Curve shown by full line

-supported Girders or Trusses with Loads Applied by Floor- A concentrated load causes maximum shear in any panel when

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placed at the end of the panel nearer the more remote reaction. The value is equal panels is given by the equation $V = Ps/n$. The maximum shear occurs in the end panel and its value for equal panels is $V = P\ (n-1)/n$.

Maximum positive shear in any panel due to uniform load occurs when all panel points to the right are assumed to be loaded with full panel loads, and all panel points to the left are unloaded; its value equals the left reaction. This method is approximate but is on the safe side and is commonly used.

The maximum positive shear occurs in the left panel and for girders with equal panels is given by the formula:

$$V = \frac{wp}{2}(n-1).$$

The same rules are applicable for the maximum negative shear by interchanging left and right in the discussion.

Computation of Maximum Shear for System of Concentrated Loads. — The shear at any section of a beam, girder or truss, due to a system of concentrated loads such as wheel loads of a moving crane, electric car or electric locomotive, equals the algebraic sum of either reaction and the loads lying between that reaction and the given section. In case the girder is divided into panels and the shear in a given panel is to be computed, only that portion of the load acting in the panel under consideration which is carried by the floor-beam at the end of the panel nearer the selected reaction should be deducted from the reaction. To determine the position in which a system of concentrated loads should lie to give maximum shear it is often necessary to proceed by trial. The use of the following simple rules may be helpful.

(*a*) The maximum shear at a given section of a simple beam always occurs with one of the loads at an infinitesimal distance to one side of the section. This load should usually, but not always, be one of the heavier loads of the system; e.g. one of the driving wheels of a locomotive. The proper load may be determined by starting with the first load just to the left of the section and moving the loads to the left until $\sum \frac{Pa}{L} \leq P'$. In this expression P = any load which may be on the span during the process of moving the loads, and a is the distance which it is moved. P' = the load which passes to the left of the section as the loads are moved from one position to another.

(*b*) The maximum shear in a given panel of a girder always occurs with one of the loads directly over one of the adjoining floor-beams. This load should usually, but not always, be one of the heavier loads.

(*c*) The position of the loads for maximum positive shear in an intermediate panel may be determined as follows. Place the first load of the system at the right end of the panel and move the system to the left until $\sum \frac{Pa}{L} \leq \sum \frac{P_1 a_1}{p}$. Apply the same criterion to the second load and following loads until the position giving maximum shear is reached. In the above expression, P and a are as before, P_1 = any load which may be at any time in the panel under consideration during the process of moving the loads, and a_1 = the distance which P_1 may move in the panel.

If no load comes on or goes off the span and if no load passes out of the panel, $a = a_1$ and we may write

$$\sum \frac{P}{L} \leq \sum \frac{P_1}{p}.$$

It follows that for this case the first load should lie at the panel point unless the average load per foot on the entire span is greater than the first load divided by a panel length, in which case the second load should be tried at the panel point and so on until the position for maximum shear is determined.

e maximum shear in the end panel of a girder equals the maximum
at the first panel point divided by the length of the panel. (*See section
g Moment, below.*)

JLATION OF BENDING MOMENT. — The nomenclature used
scussion of bending moment is as follows:

= external bending moment at any section in foot pounds,
= magnitude of a single concentrated load in pounds,
= a uniform load in pounds per foot,
= span of beam in feet (distance center to center of support),
= length of a panel in feet,
= distance in feet from a given section to one of the supports,
= total number of equal panels into which a given girder is divided.

termine the magni-
he bending moment
n section it is neces-
btain the algebraic
e products of every
ts distance from the
is of the section. A
ommonly made is the
onsider all the forces,
y horizontal forces.
nt is considered posi-
clockwise on the *left*
ion; it follows that
nt is also positive if
ter-clockwise on the
e section.

of Moments. — A
moments is a line
inate at any point
e moment on the
y at the section
ordinate is meas-
. 6 shows a typical
ent curves.

**um Moment with
oad or Uniform**
or simple end-sup-
ams, girders and
single concentrated
maximum moment
section when placed
on. The following
es its value:

$$\frac{P\,(L-x)}{L}\,x.$$

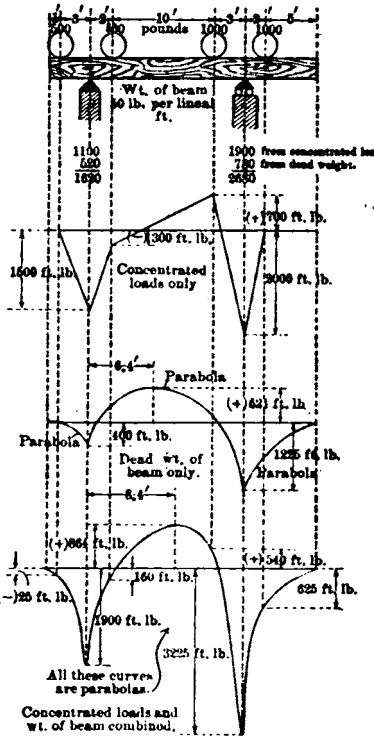


Fig. 6. Curves of Moments

um possible moment occurs when $x = L/2$ and has the value

e end-supported structures a uniform load causes maximum moment
on when it covers the entire beam. Its value at any section is

$$M = \frac{wx}{2}\,(L-x).$$

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The maximum possible moment occurs at the center of the span and equa $wL^2/8$.

End-supported Girders or Trusses with Loads Applied by Floor-Beams. — Moments at panel points are exactly the same as moments at co responding points on simple girders. It is seldom necessary to consider moment between panel points for concentrated loads. For a uniform load the mom between floor-beams varies uniformly; i.e., the moment due to that portion the load applied through the floor-beams.

The maximum moment due to a concentrated load occurs at the panel poi nearest the center with the load at that point. Its value is given by the follo ing equations:

For even number of equal panels, $M = \frac{Pp_n}{4}$.

For odd number of equal panels, $M = \frac{Pp}{4n}(n^2-1)$.

The maximum moment due to a uniform load occurs at the panel point near the center with load over entire span. Its value is:

For even number of equal panels, $M = wL^2/8$.

For odd number of equal panels, $M = \frac{1}{8}\left[wL^2\left(1-\frac{1}{n^2}\right)\right]$.

Computation of Moment for System of Concentrated Loads. — Th moment at any section due to a system of concentrated loads, such as whe loads of a moving crane, electric car or electric locomotive equals the algebra sum of the moments of either reaction and the loads lying between it and th given section, the lever arm for each load being its distance from the sectio In case the girder is divided into panels and the section under consideratio is at some intermediate point in a panel only that portion of the load applied in this panel which is transmitted to the girder by the floor-beams between it and the reaction used should be considered.

Determination of Maximum Moment at a Given Section. — Th maximum moment at any section of a simple beam or at any panel point of a girder loaded through floor-beams always occurs with some load at the sectio (usually one of the heavier loads). This load should be one which when locate just to the right of the section makes the average load per foot of all the loa on the span to the right of the section greater than the corresponding averag load per foot on the left of the section, and which reverses this condition whe placed just to the left of the section. Such loads may be selected by trial; i more than one satisfies this criterion the largest moment must be determine by actual computation.

Determination of Position of Maximum Moment on a Beam. — Previous articles deal with maximum moment at a given section. The maxi mum moment on a beam caused by a system of concentrated loads usua occurs near the center but not at it. The following method may be used t determine the location of the section at which the maximum moment occu

(*a*) Select, by inspection, one of the heavier loads which would probably b located at the center to give the maximum moment at the center.

(*b*) Determine by inspection the loads which would be on the span when th load is near the center and compute the position of their resultant.

(*c*) Place the loads on the beam in a position such that the center of the spa lies half way between this resultant and the assumed load. If the loads on the span in this position correspond to those assumed under *b*, the moment at the load should be computed; otherwise, another trial may be made. If more

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an one set of loads corresponds to this condition the moment at the load ould be computed for both sets of loads.

(*d*) Apply the same method to any other load which would possibly give aximum moment at the center.

Since the maximum moment at any section always occurs with some load at e section this method if applied to enough loads will give the absolute maximum oment. It is often unnecessary to try more than one load, and seldom more an two. It should be noted that with two equal loads such a distance apart at with one at the center the other will not be on the span, but that with the nter of the span midway between the resultant and one of the loads both will on the span, the maximum moment may possibly occur with either condition, th of which should be investigated.

BEAMS; FORMULAS AND COSTS. — The effect of the external forces on any cross-section of a simple beam is to cause bending moment and ear, the former usually being the predominant factor in determining the size the beam. If the beam is subjected to axial forces as well as transverse rces, it becomes a combination of beam and column, or beam and tie, and n no longer be considered as a simple beam. If a beam has an end which

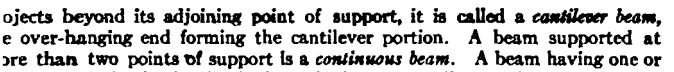


Fig. 7.

ojects beyond its adjoining point of support, it is called a *cantilever beam*, e over-hanging end forming the cantilever portion. A beam supported at ore than two points of support is a *continuous beam*. A beam having one or th ends rigidly fixed either by being built into a wall, or by being fastened to other member is called a *fixed ended beam*. Fig. 7 represents all of these types.

Beam Formulas for Ordinary Cases. — As a preliminary step in the design beams, it is necessary to determine the maximum value of the external bend- g moments, shears and reactions on the beam by the methods given in the ctions above which deal with these subjects inclusive. With these items de- rmined, the following formulas of mechanics (*see Mechanics of Materials, erriman, 10th Edition, Arts. 41 and 108*) may be employed for the design of ams of *symmetrical section* and *homogeneous material* loaded with *transverse loads* plied in the *plane* of one of the *principal axes*. For the treatment of beams unhomogeneous material (reinforced concrete) see article on *Concrete*.

Let M = maximum external bending moment on beam in inch-pounds,
I = moment of inertia in (inches)^4 about the neutral axis lying perpendicular to the plane of the external loads. (This axis in a symmetrical beam lies at mid-height.)
c = distance in inches from neutral axis to extreme fiber, equals one-half the depth for symmetrical beams,
s = allowable value of fiber stress (working value),
Q = statical moment about the neutral axis of that portion of the cross-section lying above the neutral axis,
v = allowable intensity of longitudinal shear in lb. per sq. inch,
V = maximum external shear on beam in pounds,
b = thickness of beam at neutral axis.

Then, $$M = \frac{sI}{c} \qquad \frac{I}{c} = \frac{M}{s},$$

nd $$v = \frac{VQ}{bI} \qquad \frac{Q}{bI} = \frac{v}{V},$$

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Steel Beams. — Such beams are made in the shape of the letter I in order to obtain maximum strength for a given amount of material. They are rolled to desired shape and size while hot. For dimensions, allowable loads and properties of the standard sizes made in the United States see Table V above. In addition to the I-beams listed in the table of standard I-beams which are manufactured by all the leading structural steel makers, the Bethlehem Steel Co. manufacture certain special beams of the same general shape but either of greater depth or with wider flange, and the Carnegie Steel Co. also manufacture certain special types of beams. These beams may often be used to great advantage.

Cost of Steel Beams (Pre-war prices). — The cost of steel beams in place depends upon the cost of transportation, punching, riveting and other necessary shop work and the cost of erection and painting. The base price at the mills is quoted each week in the *Iron Age;* the figures which follow are from the issue of June 19, 1913, and are representative of average prices prior to the European war.

I-beams under 15 in., 1.45¢ to 1.50¢ per lb.
I-beams over 15 in., 1.55¢ to 1.60¢ per lb.
H-beams over 18 in., 1.55¢ to 1.60¢ per lb.
For cutting to length, under 3 ft. to 2 ft. inclusive, 0.25¢ per lb.
For cutting to length, under 2 ft. to 1 ft. inclusive, 0.50¢ per lb.
For cutting to length, under 1 ft., 1.55¢ per lb.
No charge for cutting to lengths 3 ft. and over.

For total cost in place an estimate of 3 cents per pound is ordinarily safe.

PLATE GIRDERS; FORMULAS AND COSTS. — A typical plate girder with the various parts is shown in Fig. 8. Plate girders are used for openings

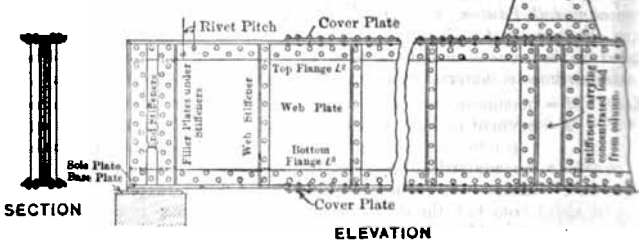


Fig. 8. Typical Plate Girder

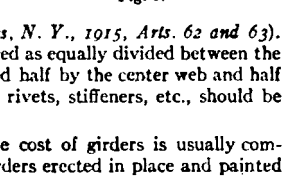
where either the load to be carried is too heavy or the clear span too great to be spanned with safety by rolled beams. The maximum length and depth are limited by the possibility of transportation. Probably the largest girder yet made was designed for the Boston & Albany Railroad for use at Worcester, Mass. It is 122 feet 6 inches long, 10 feet 11½ inches deep, and weighs 172 tons. The ordinary and economical depth of plate girders is from ⅛ to 1/12 the span; ⅛ the span is a common value. The maximum depth is usually restricted to 10 feet 6 inches or less.

al Points in Plate-Girder Design are as follows:
letermination of area of web required to carry the maximum external

etermination of area of flange required to resist the maximum external oment.
letermination of the flange rivet spacing necessary to transmit the ss from web to flange.
letermination of spacing and size of stiffeners required to prevent the from buckling sidewise, and of size of stiffeners at all points of appli- oncentrated loads together with number of rivets required therein.
etermination of length of flange cover plates.
esign of splices for web, angles and cover plates.
esign of bearing plates to transmit end reactions into masonry.

possible to give in the limited space available here the necessary nd data for the design of plate girders. For further information see *Theory of Structures*, N. Y., 1915.

of Box Girders. — Box girders resemble plate girders, but have two ebs as indicated in Fig. 9. They are used where conditions require irder of great strength. The rules to plate girders appiy in general ders, but owing to their shallow is usually advisable to determine gth against bending by the general ula $M = \frac{sI}{c}$, the moment of inertia nputed with due allowance for (*see Spofford's Theory of Structures, N. Y., 1915, Arts. 62 and 63*). in a two-web girder may be considered as equally divided between the and in a three-web girder as carried half by the center web and half o side webs combined. The flange rivets, stiffeners, etc., should be on the same basis.


Fig. 9.

Girders (Pre-war prices). — The cost of girders is usually com- cent-per-pound basis. Price of girders erected in place and painted nges in the Eastern states from 2½ to 4 cents per pound, depending state of the market, location, amount and complexity of the work, specifications and inspection, cost of maintaining traffic (in railroad The price of 3½ cents per pound may be considered a fair average or approximate estimates. In the West this figure should be mate- ased to cover the additional freight rate from Pittsburgh or Chicago. c prices of material see below under *Price of Structural Material*. rates to various points from Pittsburgh, see below under *Freight*

INS; FORMULAS AND COSTS. — Steel columns may be made lled sections such as I-beams or channels, or of compound sec- sting of single sections riveted together. A typical steel column n Fig. 10. Single sections of steel columns should be limited in convenience in erection and economy in shipment to 60 feet over all . Lengths up to 120 feet may, however, be shipped in one piece if

columns are made by pouring liquid iron into molds. They may be shapes, but are always of comparatively short lengths seldom ex- or 20 feet. Common shapes are shown in Fig. 11. To obtain free- itial stresses due to unequal rates of cooling and from stresses due to

eccentricity with centrally applied loads, the shells of hollow cast-iron columns should be of uniform thickness throughout. This result may best be secured by pouring the column in an upright position; if cast in a horizontal position the core must be carefully restrained against flotation.



Timber columns should consist of single sticks and may be either circular or rectangular in cross-section. Two lengths are sometimes connected by means of cast-iron caps which also furnish seats for beams.

Concrete columns are made by pouring concrete into wooden or metal molds; they may be made of any desired shape or length. Such columns are generally reinforced by longitudinal steel rods extending from end to end of the column and held in place at intervals by transverse steel rings. The transverse reinforcement may be made to add materially to the strength of the column by placing the rings at frequent intervals or by making it in the form of a spiral extending from end to end of the column, the column then being called a hooped column. The strengthening effect of the transverse reinforcement is due to its influence in preventing the bursting tendency of the concrete when subjected to compression.

Splices. — Steel columns are commonly spliced by bringing the abutting ends into close contact after first planing them at right angles to the axis. Splice plates are used on webs and flanges to hold the sections in line. If the column carries no bending moment the size of splice plates and number of rivets may be determined by the designer's judgment; if the column carries flexure as well as direct stress the splice must be sufficient to transmit the flexure.



Fig. 10

Changes of cross-sections in steel columns may be accomplished by changing the thickness of the material or by adding additional material. An advantageous location of a splice is at a section where the cross-section area is to be changed. If the column carries only direct compression and is loaded at intervals throughout its length such a section should be near the point of application of one of the loads and on that side of it in which the smaller stress occurs, e.g., in a high building column the section should be changed just *above* one of the floors. For columns carrying flexure as well as direct stress the splices should be located where the bending moment is small, as for example at a point of contraflexure. Cast-iron columns should

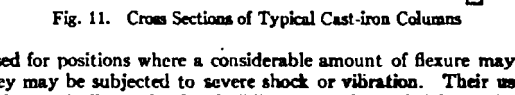


Fig. 11. Cross Sections of Typical Cast-iron Columns

not be used for positions where a considerable amount of flexure may occur or where they may be subjected to severe shock or vibration. Their use in construction is practically confined to buildings of moderate height. They may be spliced by bolting the flanges. In interior building columns the load is sometimes transferred from one section to another by means of a pintle extending between the beams which are supported on the cap of the lower column. Such a joint depends for its lateral rigidity upon the friction between the beams and column cap and can evidently transmit no bending moment.

Ratio of Unsupported Length of Column to Radius of Gyration. — The controlling factor in column formulas is the value of the ratio between the unsupported length of the column and the radius of gyration of its cross-section. If the column is of constant cross-section and restrained against lateral deflection at

nly, then l equals the total length of the column and r its least radius
n. If the column is held against lateral deflection in every direction
several intermediate points, the value of $\frac{l}{r}$ equals the largest value
tween any two adjoining lateral supports. If the column is held at
diate point in one direction only, the value of $\frac{l}{r}$ equals the maximum
by using for l the length of either section, or the total length of the
d for r in each case the corresponding least radius of gyration re-
ny axis about which the column is free to bend. If the column is of
oss-section the designer must use his judgment in determining the
to be used, but generally the value should be that at the middle of
orted length of the particular portion of the column that is under
on.

n of Ends.—It was formerly assumed that the strength of columns
actice depended very largely upon the condition of the ends. At
time, however, no difference is made between round-ended, pin-
square-ended columns as used in ordinary practice. For columns of
that Euler's formula should be applied, a distinction should be made
und-ended and square-ended columns (*see following section*). Col-
one free end should receive special consideration.

ended Formulas for Steel Columns.—

Columns of Ordinary Length:

$$\frac{P}{A} = 16{,}000 - 70\frac{l}{r}, \qquad (1)$$

l/r not to exceed 120 for principal members,
l/r not to exceed 150 for secondary members,
P/A not to exceed 14,000 lbs.

of symbols, see list following equation (4).

Long Columns having values of l/r greater than allowed in formula
mn may fail by collapsing rather than crushing; in this case the fol-
ulas should be used:

Fixed Ends $$\frac{P}{A} = \frac{4\pi^2 E}{c}\left(\frac{r}{l}\right)^2, \qquad (2)$$

Round Ends $$\frac{P}{A} = \frac{\pi^2 E}{c}\left(\frac{r}{l}\right)^2, \qquad (3)$$

One Free End $$\frac{P}{A} = \frac{\pi^2 E}{4c}\left(\frac{r}{l}\right)^2, \qquad (4)$$

total allowable centrally applied load on column in pounds includ-
ing proper allowance for impact,
minimum area of cross-section in square inches,

maximum ratio of length to radius of gyration for any laterally
unsupported section of column,
suitable factor of safety, usually 5 to 6,
modulus of elasticity in pounds per square inch.

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Recommended Formulas for Cast-iron Colum

$$\frac{P}{A} = 6100 - 32\frac{l}{d}, \qquad \frac{l}{d} \text{ not to exceed } 40,$$

where P = total allowable centrally applied load
cluding proper allowance for impact,
A = minimum area of cross-section in squa
d = diameter of circular column or shorter
in inches.

Recommended Formulas for Timber Column

For longleaf yellow pine, $\frac{P}{A} =$

For shortleaf pine and spruce, $\frac{P}{A} =$

where P = total allowable centrally applied load
regarding impact),
A = area of cross-section in square inches,
$\frac{l}{d}$ = unsupported length divided by least radi

The values in (6) and (6a) are for railroad bridges
crease these values by 25 per cent. For buildings
and reasonably free from impact, increase these va
other timbers, multiply value for longleaf yellow pin
compressive stress of timber in question and of long
section on Unit Stresses in article on Timber.)

Steel Column Details. — Columns composed o
so constructed that the various parts will resist buc
the strength of the column will be no greater than t
combined. As an illustration of this, the column sh
sidered. If the two channels are not connected, t
will be only double that of the two separate channels
will have the low value corresponding to a single ch
column composed of thin planks bolted loosely toget
strength than the same number of separate planks
together the ribs of a steel column, plates or diaphra
out its length, the plates forming a part of the
main or stress bearing cross-section, or plates
and lattice bars may be used as shown in
Fig. 10. The width of the lattice bars is usu-
ally taken as the minimum value allowable
for the rivets used. For columns consisting of
two channels, the minimum sizes of lattice bars
given in the accompanying table may be used.
In no case should single lattice bars have a
thickness less than $\frac{1}{40}$ the distance between
rivets connecting them to the channels; but for double
intersection the thickness may be $\frac{1}{60}$ of the distance

ch

For columns of unusual size, the lattice bars sho
(*See Spofford's Theory of Structures, N. Y., 1915, Art*

Rivet Pitch in Built Steel Columns. — F
stress only, the rivets should not be farther apart tha
thinnest plate connected and at each end or at ea
concentrated loads they should not be farther apart

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also sections below on *Design of Tension Members* and *Design of*
ts.

ally Loaded Columns. — If the resultant force acting at any cross-
column is not applied at its center of gravity the column is said to
ially loaded. The effect of an eccentric load is to subject the column
ation of direct stress and flexure, and thereby to increase the maxi-
ress over what it would otherwise be. A similar condition arises if
t force on the cross-section is the resultant of an axial force acting
of gravity of the section and a couple causing flexure at the section.
m fiber stress at such a section may be determined by the following
oximate formula for the usual case where the resultant force acts
of one of the principal axes and the neutral axis for flexure coin-
e other principal axis.

$$s = \frac{P}{A} + \frac{My}{I - \frac{Pl^2}{10E}}, \qquad (7)$$

maximum fiber stress at any section in pounds per square inch,
resultant axial force on section in pounds,
unsupported length of column in inches,
area of cross-section in square inches,
bending moment on section in inch-pounds,
moment of inertia of cross-section about neutral axis in (inches)^4,
modulus of elasticity in pounds = 29,000,000 for steel,
distance in inches from neutral axis to most remote fiber. (Neu-
tral axis as used in this formula is the neutral axis for flexure.)

e in a Building Column Carrying an Eccentric Load. — The
ding column supporting a track for a traveling crane is a common
rve of moments for such a case is shown by
ne in Fig. 12 in which P is the applied load
track at a distance x from the center of the
maximum bending moment always occurs
d depends upon the height of application of
ts maximum value is Px and occurs when
the top of the column.

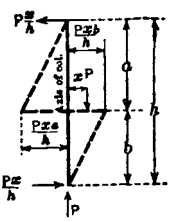


Fig. 12.

s of Columns. — The following specifications
ely followed:
ion members the metal shall be concentrated
ossible in webs and flanges. The thickness
shall be not less than one-thirtieth of the
een its connections to the flanges. Cover plates shall have a
ess than one-fortieth of the distance between rivet lines.
les of compression members shall be provided with lattice bars
tie plates as near each end as practicable. Tie plates shall be
ntermediate points where the lattice is interrupted. In main
nd tie plates shall have a length not less than the distance be-
of rivets connecting them to the flanges, and intermediate ones
ne-half this distance. Their thickness shall not be less than one-
ame distance.
nts in compression members when faced for bearing shall be
sides sufficiently to hold the connecting members accurately in
er joints in riveted work, whether in tension or compression, shall
plates are not in direct contact with the parts which they con-

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nect, rivets shall be used on each side of the joint in exc
cally required to the extent of one-third of the number

Column Caps, Bases and Brackets. — The proj
plied loads to the column, and the distribution of the
ing, is a matter of great importance. The three follow
in designing column caps:

a. Provide sufficient bearing area so that the crushi
or of the loading beam, girder or column will not be

b. Arrange connections to eliminate eccentric app
this is impossible to reduce the eccentricity to the

c. Arrange connections so that the stress-bearing
shall be directly under the stress-transmitting portio
e.g., if a column receives load from a girder, the ou
stiffeners on the girder should be located directly ove

Typical column bases are shown in Fig. 13. The
be observed in the design of column bases as in the de
advantage of a separate base is that it can be set up on the foundation and leveled to receive the column with less difficulty than would be the case with the finished column. Such bases should always be planed on top and the base of the column should also be planed. Steel columns to which cap and base plates are shop riveted should be planed at each end before these plates are riveted on, and the cap and base plates are also generally planed on top and bottom respectively.

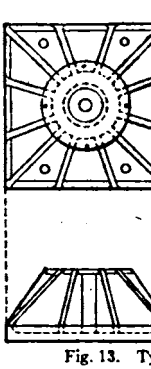


Fig. 13. T

It is important that brackets for connections of girders to columns should always be designed so as to throw the resultant beam reaction as near th
possible in order to reduce the eccentricity of loadi
occur. This is particularly important for cast-iro
the brackets should be slightly beveled downward
or girder cannot be supported at or near the edge of t

I-Beam Column Footings. — On poor soils it is of
heavy column loads over an area so large as to requi
may be economically constructed of steel beams, in con
not be closer together than 3 inches to permit con
between and around them. The method of design
the ordinary case, that of a column carrying direct
(1) Determine the number of square feet required in
the number of tiers of I-beams; (3) assume the ent
layer of beams (weight of over-lying footing courses
distributed equally over all the beams in that layer a
is uniformly loaded; (4) determine the maximum mo
will occur at the center and equal approximately

$$M = \frac{W}{8n}(l - h)$$

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oad on layer of beams under consideration, n = number of beams, of beam loaded from above, in feet, and l = length of beam loaded in feet; (5) determine in the usual manner the size of beam carry this bending moment; (6) test the web thicknesses of the ed to see if they are sufficient to transmit the applied load without plying formula (1).

ings. — If the ground is soft, piles may be necessary to provide ring area. For the allowable bearing value for these see Baker's *A Masonry Construction*, N. Y., 1909.

Columns and Footings. — Steel columns cost about the same as values for which are given in the section on *Cost of Girders*, above. ng the weight of columns it should be remembered that the details erially to the weight of the stress-bearing section, especially in the ed columns, where the excess may amount to as much as 50 per he cost of footings, the I-beams may be computed on a pound price e weekly quotations given in *The Iron Age* with a reasonable allow- sportation and delivery, or more accurate figures can be obtained dealer. For cost of cast-iron columns see section on *Cost* in article *and Cast*. For the cost of concrete and excavation, see articles on ive subjects.

r Steel Columns. — The allowable load for a number of simple s and the important properties of the columns are given in Tables To determine the allowable load for built-up columns not given in e radius of gyration may be interpolated for columns having the dimensions and the unit stress computed by substitution in the ula. The areas and other properties of the simple structural as beams, angle irons, and channels, are given in Tables II to VI

es are all based on the formula

$$\frac{P}{A} = 16{,}000 - 70\frac{l}{\rho}$$

ium value of 14,000 and are calculated for Cambria Steel Co.'s e load is assumed to be applied at the center of gravity of the o act parallel to its axis.

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TABLE VII. — STEEL I-BEAM COLUMNS



ρ_x = radius of gyration about axis X-X
ρ_y = " " " " " Y-Y

Depth of beam, in.	Width of flange, in.	Weight per foot, lb.	Thickness of web, in.	Area of column, sq. in.	Least radius of gyration ρ_x, in.	ρ_y, in.	Max. allowable load P in thousands of pounds for various values of $l \div \rho$. To determine strength of column use maximum possible value of $l \div \rho$. If column is unsupported laterally use for ρ the value ρ_x.										
							$\frac{l}{\rho}=10$	20	30	40	50	60	70	80	90	100	110	120
5	3.00	9.75	0.21	2.87	0.65	2.05	40.2	40.2	39.9	37.9	35.9	33.9	31.9	29.8	27.8	25.8	23.8	21.8
6	3.33	12.25	0.23	3.61	0.72	2.46	50.5	50.5	50.2	47.7	45.1	42.6	40.1	37.5	35.0	32.5	30.0	27.4
7	3.66	15.00	0.25	4.42	0.78	2.86	61.9	61.9	61.4	58.3	55.3	52.2	49.1	46.0	42.9	39.8	36.7	33.6
8	4.00	18.00	0.27	5.33	0.84	3.27	74.6	74.6	74.1	70.4	66.6	62.9	59.2	55.4	51.7	48.0	44.2	40.5
9	4.33	21.00	0.29	6.31	0.90	3.67	88.3	88.3	87.7	83.3	78.9	74.5	70.0	65.6	61.2	56.8	52.4	48.0
10	4.66	25.00	0.31	7.37	0.97	4.07	103.2	103.2	102.4	97.3	92.1	87.0	81.8	76.6	71.5	66.3	61.2	56.0
10	5.10	40.00	0.75	11.76	0.90	3.67	164.6	164.6	163.5	155.2	147.0	138.8	130.5	122.3	114.1	105.8	97.6	89.4
12	5.00	31.50	0.35	9.26	1.01	4.83	129.6	129.6	128.7	122.2	115.8	109.3	102.8	96.3	89.8	83.3	76.9	70.4
12	5.21	40.00	0.56	11.76	0.96	4.57	164.6	164.6	163.5	155.2	147.0	138.8	130.5	122.3	114.1	105.8	97.6	89.4

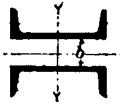
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Max. allowable load P in thousands of pounds for various values of $l \div \rho$. To determine strength of column use maximum possible value of $l \div R$. If column is unsupported laterally use for ρ the value ρ_x.

Depth base to base of angles, in.	Size of web, in.	Size of angle, in.	Width of flange, in.	Area of column, sq. in.	Weight per foot of column exclusive of details, lb.	Least radius of gyration ρ_x, in.	P_x, in.	$l \div \rho$ = 10	20	30	40	50	60	70	80	90	100	110	120
6½	6 by ¼	3 by 2½ by ¼	6¼	6.79	23.1	1.24	2.41	95.1	95.1	94.4	89.6	84.9	80.1	75.4	70.6	65.9	61.1	56.4	51.6
6½	6 by ⅝	3 by 2½ by ⅝	6⅝	15.94	54.4	1.43	2.29	223.2	223.2	221.6	210.4	199.3	188.1	176.9	165.8	154.6	143.5	134.3	121.1
7½	7 by ¼	3½ by 2½ by ¼	7¼	7.50	25.6	1.46	2.88	105.0	105.0	104.3	99.0	93.8	88.5	83.3	78.0	72.8	67.5	62.3	57.0
7½	7 by ⅜	3½ by 2½ by ⅝	7⅜	17.82	60.9	1.65	2.76	249.5	249.5	247.7	235.2	222.8	210.3	197.8	185.3	172.8	160.4	147.9	135.4
8½	8 by ¼	3 by 2½ by ¼	6¼	7.29	24.8	1.19	3.25	102.1	102.1	101.3	96.2	91.1	86.0	80.9	75.8	70.7	65.6	60.5	55.4
8½	8 by ⅜	4 by 3 by ⅝	8⅝	20.96	71.4	1.82	3.14	293.4	293.4	291.3	276.7	262.0	247.4	232.7	218.0	203.3	188.6	173.9	159.2
10½	10 by ¼	3 by 2½ by ¼	6¼	7.79	26.5	1.16	4.07	109.1	109.1	108.3	102.8	97.4	91.9	86.5	81.0	75.6	70.1	64.7	59.2
10½	10 by ⅝	4 by 3 by ⅝	8⅝	22.21	75.7	1.77	3.98	310.9	310.9	308.7	293.2	277.6	262.1	246.6	231.0	215.4	199.9	184.3	168.8
12½	12 by ¼	3 by 2½ by ¼	6¼	8.29	28.2	1.12	4.87	116.1	116.1	115.2	109.4	103.6	97.8	92.0	86.2	80.4	74.6	68.8	63.0
12½	12 by ⅝	6 by 3½ by ⅝	12⅝	29.69	101.1	2.68	4.93	415.7	415.7	412.7	391.9	371.1	350.4	329.6	308.8	288.0	267.2	246.4	225.6
14½	14 by 7/16	7 by 3½ by 7/16	14 7/16	23.76	80.8	3.05	5.92	332.6	332.6	330.2	313.6	297.0	280.4	263.8	247.1	230.5	213.8	197.2	180.6
14½	14 by ⅝	7 by 3½ by ⅝	14⅜	33.48	113.7	3.13	5.85	468.7	468.7	465.4	442.0	418.5	395.1	371.6	348.2	324.7	301.3	277.9	254.4
16¾	16 by ⅝	5 by 3½ by 5/16	10 5/16	15.23	51.8	1.94	6.59	213.2	213.2	211.7	201.0	190.4	179.7	169.1	158.4	147.7	137.1	126.4	115.7
16½	16 by ⅝	5 by 3½ by ⅝	10⅝	29.73	101.2	2.08	6.48	416.2	416.2	413.3	392.5	371.6	350.8	330.0	309.2	288.4	267.6	246.8	225.9
16¼	16 by 7/16	7 by 3½ by 7/16	14 7/16	24.65	83.8	3.00	6.75	345.1	345.1	342.7	325.4	308.1	290.9	273.6	256.4	239.1	221.8	204.6	187.3
16½	16 by ⅝	7 by 3½ by ⅝	14⅝	34.72	118.0	3.08	6.69	486.1	486.1	482.6	458.3	434.0	409.7	385.4	361.1	336.8	312.5	288.2	263.9

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TABLE IX. — STEEL LATTICED CHANNEL COLUMNS

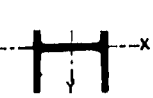


ρ_y = radius of gyration about axis Y-Y
b = minimum allowable distance apart of channels

Depth of channel, in.	Weight per foot of each channel, lb.	Width of flange, in.	Thickness of web, in.	Area of section, sq. in.	Weight per foot exclusive of details, lb.	Radius of gyration ρ_y, in.	b in.	Max. allowable load P in thousands of pounds for various values of $l + \rho$. To determine strength of column use maximum possible value of $l + \rho$. If column is unsupported laterally use for ρ the value ρ_y.										
								$\frac{l}{\rho}$ = 10	20	30	40	50	60	70	80	90	100	110	120
6	8.0	1.92	0.20	4.76	16.00	2.34	3.52	66.6	66.6	66.2	62.8	59.5	56.2	52.8	49.5	46.2	42.8	39.5	36.2
6	15.5	2.28	0.56	9.12	31.00	2.07	2.90	127.7	127.7	126.8	120.4	114.0	107.6	101.2	94.8	88.5	82.1	75.7	69.3
7	9.75	2.09	0.21	5.70	19.50	2.72	4.22	79.8	79.8	79.2	75.2	71.3	67.3	63.3	59.3	55.3	51.3	47.3	43.3
7	19.75	2.51	0.63	11.62	39.50	2.39	3.48	162.7	162.7	161.5	153.4	145.3	137.1	129.0	120.8	112.7	104.6	96.4	88.3
8	11.25	2.26	0.22	6.70	22.50	3.10	4.90	93.8	93.8	93.1	88.4	83.8	79.1	74.4	69.7	65.0	60.3	55.6	50.9
8	21.25	2.62	0.58	12.50	42.50	2.76	4.20	175.0	175.0	173.8	165.0	156.3	147.5	138.8	130.0	121.3	112.5	103.8	95.0
9	13.25	2.43	0.23	7.78	26.50	3.49	5.64	108.9	108.9	108.1	102.7	97.3	91.8	86.4	80.9	75.5	70.0	64.6	59.1
9	25.0	2.85	0.61	14.70	50.00	3.10	4.82	205.8	205.8	204.3	194.0	183.8	173.5	163.2	152.9	142.6	132.3	122.0	111.7
10	15.0	2.60	0.24	8.92	30.00	3.87	6.32	124.9	124.9	124.0	117.7	111.5	105.3	99.0	92.8	86.5	80.3	74.0	67.8
10	25.0	2.89	0.53	14.70	50.00	3.52	5.66	205.8	205.8	204.3	194.0	183.8	173.5	163.2	152.9	142.6	132.3	122.0	111.7
10	35.0	3.18	0.82	20.58	70.00	3.35	5.18	288.1	288.1	286.1	271.7	257.3	242.8	228.4	214.0	199.6	185.2	170.8	156.4
12	20.5	2.94	0.28	12.06	41.00	4.61	7.68	168.8	168.8	167.6	159.2	150.8	142.3	133.9	125.4	117.0	108.5	100.1	91.7
12	30.0	3.17	0.51	17.64	60.00	4.28	7.06	247.0	247.0	245.2	232.9	220.5	208.2	195.8	183.5	171.1	158.8	146.4	134.1
12	40.0	3.42	0.76	23.52	80.00	4.09	6.60	329.3	329.3	326.9	310.5	294.0	277.5	261.1	244.6	228.1	211.7	195.2	178.8
15	33.0	3.40	0.40	19.80	66.00	5.62	9.52	277.2	277.2	275.2	261.4	247.5	233.6	219.8	205.9	192.1	178.2	164.3	150.5
15	40.0	3.52	0.52	23.52	80.00	5.44	9.16	329.3	329.3	326.9	310.5	294.0	277.5	261.1	244.6	228.1	211.7	195.2	178.8
15	55.0	3.82	0.82	32.46	110.00	5.16	8.54	454.8	454.8	451.5	429.0	406.4	383.8	361.2	338.6	316.0	293.4	270.8	248.2

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TABLE X. — STEEL H-COLUMNS



ρ_x = radius of gyration about X-X
ρ_y = " " " " " Y-Y

Depth of column, in.	Width of flange, in.	Weight per foot, lb.	Thickness of web, in.	Area of section, sq. in.	Least radius of gyration, ρ_x in.	ρ_y, in.	Maximum allowable load P in thousands of pounds for various values of $l + \rho$. To determine strength of column use maximum possible value of $l + \rho$. If column is unsupported laterally use for ρ the value ρ_x.										
							$\frac{l}{\rho}$ = 10	20	30	40	50	60	70	80	90	100	110	120
8	8.00	34.5	0.31	10.17	2.01	3.46	142.4	142.4	141.4	134.2	127.1	120.0	112.9	105.8	98.6	91.5	84.4	77.3
8½	8.16	53.0	0.47	15.53	2.07	3.57	217.4	217.4	215.9	205.0	194.1	183.3	172.4	161.5	150.6	139.8	128.9	118.0
9	8.32	71.5	0.63	21.05	2.12	3.68	294.7	294.7	292.6	277.9	263.1	248.4	233.7	218.9	204.2	189.4	174.7	160.0
9½	8.47	90.5	0.78	26.64	2.17	3.80	373.0	373.0	370.3	351.7	333.0	314.4	295.7	277.1	258.4	239.8	221.1	202.5
10	10.00	54.0	0.39	15.91	2.51	4.32	222.7	222.7	221.1	210.0	198.9	187.7	176.6	165.5	154.3	143.2	132.1	120.9
10½	10.16	77.0	0.55	22.59	2.57	4.43	316.3	316.3	314.0	298.2	282.4	266.6	250.7	234.9	219.1	203.3	187.5	171.7
11	10.31	99.5	0.70	29.32	2.62	4.55	410.5	410.5	407.6	387.0	366.5	346.0	325.5	304.9	284.4	263.9	243.4	222.8
11½	10.47	123.5	0.86	36.32	2.67	4.67	508.5	508.5	504.8	479.4	454.0	428.6	403.2	377.7	352.3	326.9	301.4	276.0
12	12.00	78.0	0.47	22.94	3.01	5.18	321.2	321.2	318.9	302.8	286.8	270.7	254.6	238.6	222.5	206.5	190.4	174.2
12½	12.16	105.0	0.63	30.94	3.07	5.30	433.2	433.2	430.1	408.4	386.8	365.1	343.4	321.8	300.1	278.4	256.8	235.1
13	12.31	132.5	0.78	38.97	3.13	5.41	545.6	545.6	541.7	514.4	487.1	459.9	432.6	405.3	378.0	350.7	323.5	296.2
13½	12.47	161.0	0.94	47.28	3.18	5.53	661.9	661.9	657.2	624.1	591.0	557.9	524.8	491.7	458.6	425.5	392.4	359.3
14	14.00	99.0	0.51	29.06	3.56	6.07	406.8	406.8	403.9	383.6	363.3	342.9	322.6	302.2	281.9	261.5	241.2	220.9
14½	14.16	130.5	0.67	38.38	3.56	6.18	537.3	537.3	533.5	506.6	479.8	452.9	426.0	399.2	372.3	345.4	318.6	291.7
15	14.31	162.0	0.82	47.71	3.62	6.30	667.9	667.9	663.2	629.8	596.4	563.0	529.6	496.2	462.8	429.4	396.0	362.6
15½	14.47	195.0	0.98	57.35	3.67	6.41	802.9	802.9	797.2	757.0	716.9	676.7	636.6	596.4	556.3	516.2	476.0	435.9
16	14.62	227.5	1.13	66.98	3.73	6.53	937.7	937.7	931.0	884.1	837.2	790.4	743.5	696.6	649.7	602.8	555.9	509.0
16½	14.78	261.5	1.29	76.93	3.77	6.65	1077.0	1077.0	1069.3	1015.5	961.6	907.8	853.9	800.1	746.2	692.4	638.5	584.7

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TRUSSES, DESIGN OF. — All trusses may be c
classes based upon the methods necessary to determine
stresses can be determined by the application of the th
rium (*see paragraph on Equations of Equilibrium, above*
termined; otherwise they are statically undetermined.
a truss may be statically undetermined with respect to
reactions cannot be determined by statics; or it may be
with respect to the inner forces, i.e., the bar stresses c
statics.

Trusses that are statically indeterminate through ha
reactions are frequently constructed because of their
economy, but it is doubtful if such trusses are desirable

Statically determined trusses may be distinguished
mined trusses by comparing the number of unknown re

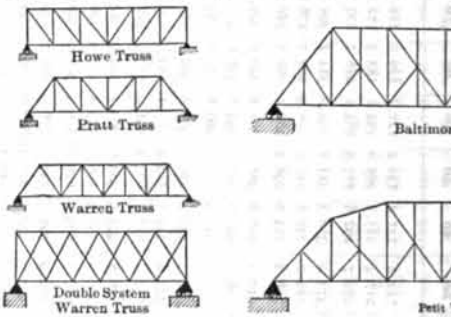


Fig. 14. Bridge Trusses

the number of bars with the number of joints. In ge
that any planar truss supported at two points will b
provided the number of bars equals $(2n-3)$,
where n is the number of joints. If the number
of unknown bars and reaction components com-
bined exceed twice the number of joints the
truss is statically indeterminate but may usually
be computed by methods based upon its elastic-
ity. If the number of unknowns is less than
twice the number of joints the truss is unstable
and may collapse; such structures should never
be constructed.

The preceding test should not be used alone
to determine whether a truss is or is not stable.
The framework should also be so put together as
to make it consist of a series of triangles.

Common Types. — All the trusses shown
in Figs. 14 and 15, except the double-system
Warren truss and the roof truss with monitor,
are statically determined; the former may
be made statically determined by omitting one
of the bars, say a diagonal; the latter by omitting o

Theory of Trusses. — The common theory of trusse
lowing assumption:

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he members are connected at the intersections of their center of nes by frictionless pins, and that in consequence the stresses in the embers are all direct stresses. The assumption of frictionless pins is ate particularly in the case of riveted trusses; however, the results by this method are sufficiently accurate for trusses of ordinary ns and are in common use. Great care should be used in design that center of gravity lines meet at the joints, otherwise the connec- be eccentric and the truss exposed to bending as well as direct

ethods of computing stresses in ordinary trusses involve only the pplication of the three equations of statics (*see section on Equations of m, above*). Three methods are in common use: viz., method of joints, f moments, and method of shear. All of these are methods of sections pplied by passing a section through the bar under consideration, cutting apart and applying the equations of equilibrium to the outer forces on ese sections and the stress in the bar under consideration. The first ese methods are described below.

d of Joints. — The method of joints is the most general of the three f computing the stresses in trusses; it may be applied either analyt- graphically.

alytical Method. — The mode of procedure for this method is as (1) Computation of reactions. (2) Selection of a joint at which only meet. (3) Application of the two equations of equilibrium, $\Sigma H = O$ O, to the outer forces and unknown bar stresses acting at this point. tresses should be assumed as tension, that is, as acting away from the negative result in any case would indicate compression. (4) Con- of any other joint at which only two unknown bars meet and deter- of the stresses in these bars in the same manner, treating known bar s outer forces.

raphical Method. — This method consists of drawing polygons for each joint in succession. e employed readily by drafts- others who are not familiar ss theories. It is also self- and reasonably rapid. It is ate than the analytical method, e diagrams are carefully con- t is accurate enough for ordinary s.

ode of procedure is: (1) A the structure is drawn to any scale and on it are shown all forces including reactions. (2) forces and bars are designated s so located that each force and will lie between two letters and , as illustrated by Fig. 16. (3) n of outer forces is drawn. This e drawn to a scale of sufficient ve the desired accuracy. The forces should be plotted in the order in ey are reached by going around the figure in a clockwise direction, and lettered at the ends by the letters in the order obtained by this clock- tion. This polygon should close if the reactions have been determined

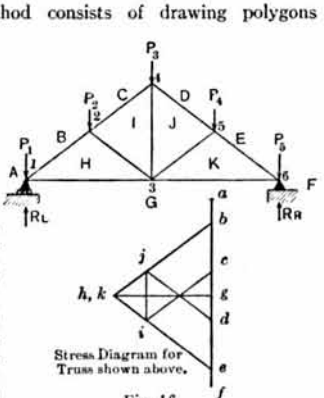


Fig. 16.

correctly. (4) A triangle of forces for each joint is drawn, beginning at a joint where an outer force and two bars only meet, and proceeding thence joint by joint, selecting the joints in such an order that at no joint will there be more than two undetermined forces to consider. The sides of these triangles representing the outer forces are the sides of the force polygon. The sides representing bar stresses should be lettered at the ends by the letters obtained by going around the joints in a clockwise direction. The diagram thus drawn should form a closed figure. (5) The magnitude and character of the bar stresses are determined from the diagram. The magnitude of the stress in any member equals the length of the line of the diagram parallel to the bar in question measured to the scale of the force polygon; its character is determined by the order in which the letters are reached in going about any joint in a clockwise direction. For example, to determine the character of the stress in bar *CI* of Fig. 16, note that *ci* in the stress diagram acts downward to the left, as determined by the order in which the letters are reached in going around joint 2; hence the stress in *CI* also acts downward to the left, or toward the joint, since the bar is above the joint, and is therefore compression. A similar result is obtained by considering joint 4. For this joint clockwise reading gives the designation of the bar as *IC*, and *ic* in the stress diagram acts upward to the right, that is toward joint 4, since the bar is below this joint.

Solutions by Graphical Method. — Fig. 16 shows a small truss drawn to scale and with all the outer forces represented in direction and point of application. The force polygon is *abcdefga;* this is a straight line, since all the forces are vertical. In it $ab = P_1$, $bc = P_2$, etc. The reactions R_L and R_R are represented by *ga* and *fg*. The triangle of forces for joint 1 is *gabkg* (*gb* is the resultant of R_L and P_1). Reading around joint 1 in a clockwise direction shows that the magnitude and direction of the stress in bar *BH* is determined by the length and direction of *bk* in the force polygon; as this acts downward to the left, it acts toward joint 1 and hence is compression. In the same manner the stress in *HG* is found to be tension. The stresses in the other bars may be determined similarly.

Fig. 17 shows a simple tower with wind forces acting on one side only. Ordinarily the wind forces on a tower would be equally divided between the two sides but they are all taken on one side here in order to more clearly illustrate the method. The only difference in the result would occur in the stresses in the horizontal members. In this case the diagonals in all panels are assumed to be tension members, only one of which in any one panel is in action under the forces shown. Inspection shows that in each case the bar shown dotted should be considered as out of action. The stress diagram and the scaled values of stresses in the bars are also shown in the figure.

Method of Moments. — This method of finding truss stresses is based upon the application of the equation $\Sigma M = 0$. It is very useful for determining stresses in individual bars of many trusses, but is not so general as the method of joints and is frequently inapplicable to some bars even in the simplest trusses. Like the method of joints, it is also a method of sections, the truss being considered as divided into two portions and the equilibrium of one of these portions under the influence of the outer forces and the stress in the cut bar being considered. The method can be used to determine the stress in a given bar when all the other bars cut by the section, or their prolongations, meet at a point not on the line of action of the given bar. This point should be selected as the origin of moments.

Design of Tension Members. — The design of tension members involves little more than the selection of bars with sufficient net area to carry the total stress without exceeding the allowable unit stress. Steel or iron tension

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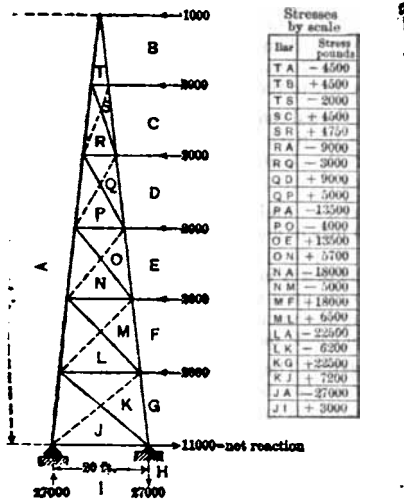


Fig. 17.

bers may be divided into two general types: viz., solid bars rectangular or lar in cross-section, and built-up members composed of structural shapes ed together. Solid bars are used generally in pin trusses for diagonals bottom chord members, and in Howe trusses for verticals. Built-up mem- are generally employed for tension members in riveted trusses and for the hangers in pin-trusses.

Solid Tension Pieces. — The eye bar shown in Fig. 18 is commonly l for the solid bar type of tension members. Such bars are made by most he large steel manufacturers and are fully described in their handbooks. heads of these bars are designed so that the bar if tested to destruction fail in the body rather than in the head, and the engineer should specify : full-sized tests should give this result and not attempt to proportion the ils. A good rule to observe in selecting bars is to keep the thickness between

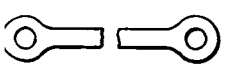


Fig. 18.



Fig. 19.

-sixth and one-third the width. Eye-bars are generally used in pairs, since odd number of bars would give a poor arrangement on the pin. For counters justable eye-bars, such as those shown in Fig. 19, may be used, the two parts ing connected by a turnbuckle or sleeve nut; iron rods with loops formed by lding may be used if the stresses are small. In proportioning adjustable embers allowance must be made for the decrease in section due to the screw reads. It is usually advisable to upset the screw end, so as to give sufficient ea at the root of the thread to make the bar as strong there as elsewhere. or short rods, however, the labor cost involved in this process may be greater an the saving of material would warrant.

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Riveted Tension Bars may be made of vari
nels, plates and angles, etc. Although these members c
plates to keep the separate parts from buckling, as in
connection between them should be used to make the c
The design of these details must be left to the judgm

Design of Riveted Joints.— A riveted connection
lowing ways: (*a*) by the shearing of the rivets, (*b*) by
or of one of the pieces upon which they bear, (*c*) by
through one of the connected pieces.

Shearing Strength of Rivet. — Under (*a*) i
allowable shearing value of the rivet may be found by m
area by the allowable shearing stress per square inc
⅞-inch rivet is 0.60 square inch, and of a ¾-inch rivet
signing rivets to resist shear the plane upon which t
must always be determined. If the maximum shear l
two planes the rivet is said to be in *double shear*.

Bearing Strength of Rivet. — The permis
strength of a rivet against a given plate is detern
allowable bearing strength per square inch by the dia
thickness of the plate in question.

Distance of Rivet from Edge of Member
noted under (*c*) the following empirical rule may be
spaced closer than three times the diameter, and th
the edge or end of a piece may not be less than 1¼ i
the edge in question be rolled or planed, or 1½ inch
where possible this distance should be at least twice
For other sizes of rivets proportional allowances shou
refer to the center of the rivet in each case.

Riveted Joints Carrying Torsion. — For c
as direct stress has to be transferred by rivets, as is
brackets carrying cranes are riveted to
the sides of columns or where girders are
riveted to columns, the conditions shown
by Figs. 20 and 21 may occur. For the
case shown in Fig. 20 the rivets carry tor-
sion only, and each rivet may be assumed to
offer a resistance to torsion proportional to
its distance from the center of gravity of the group.
of such a group is

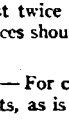


Fig.

$$R = \frac{rI}{d},$$

where r = the allowable working value of the most
I = summation of the squares of the distance
of gravity of the group of rivets to eac
d = distance in inches from center of gravity
most stressed rivet,
R = resistance to torsion of the group of rivet

In applying the formula to the case shown in Fig. 2
the rivets at a is r. For the case shown in Fig. 21 this
to allow for the effect of the vertical load. To mak
necessary to determine the allowable resistance to t
rivet also carrying its share of the vertical load.

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CONTINUOUS GIRDERS, BEAMS, SLABS AND TRUSSI

iese are structures which are continuous over several points of su
iey are statically indeterminate (*see section on Trusses, above*) with r
the outer forces and hence the moments and shears should be deter
the "three-moment equation" (*see above*). Continuous girders are
only used in reinforced-concrete construction, in which case the cont
allowed for by the following simple rules recommended by the Joint
ttee on Concrete and Reinforced Concrete. (*See article on Concrete.*)

(*a*) For floor-slabs, the bending moments at center and at support
taken at $\frac{wl^2}{12}$ for both dead and live loads, where w represents the lo
ear unit and l the span length.

(*b*) For beams, the bending moment at center and at support for i
ans should be taken at $\frac{wl^2}{12}$ and for end spans it should be taken at
iter and interior support, for both dead and live loads.

(*c*) In the case of beams and slabs continuous for two spans only, with
ds restrained, the bending moment both at the central support and ne
ddle of the span should be taken as $\frac{wl^2}{10}$.

(*d*) At the ends of continuous beams, the amount of negative moment
ll be developed in the beam will depend on the condition of restraint o
ss, and this will depend on the form of construction used. In the or
ses a moment of $\frac{wl^2}{16}$ may be taken; for small beams running into
umns this should be increased, but not to exceed $\frac{wl^2}{12}$.

For spans of unusual length, or for spans of materially unequal length
uct calculations should be made. Special consideration is also requi
e case of concentrated loads.

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Eccentric Riveted Loads; Catalogues of manufacturers of structura
ıpes.

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SUBSTATIONS, LIGHTING.—(*See also Batt of; Bus-bars and Bus-bar Structures; Circuit Breakers Distribution Lines; Distribution Systems; Lighting Regulators; Relays; Substations, Railway; Switchboa for Power Stations; Transformers.*) Three types of s lighting systems viz.:

Substations for Voltage Conversion and Regula These substations receive power from high-tension tra feeders designed for economical cross section of condu voltage drop. The standard equipment of such sub and oil circuit breakers for high-tension lines, step bars, oil switches and voltage regulators for delivery constant-current transformers serving local series st construction of bus-bar and switch structures is simil for the control of circuits of equal power. Transfo blast type, and are usually grouped in banks of thre constant-current transformers supplying d-c. arc ci mercury-arc rectifiers. The equipment is usually arr path through the substation as short and direct as line has its individual equipment of voltage regulato

Substations for the Conversion of Frequency usually combined with the conversion of voltage. power from 3-phase, 25-cycle primary feeders, conver form its voltage for the supply of local 60-cycle ligh frequency-changer most used is a pair of synchrono frequency ratio running on a common shaft. When cal-shaft type is generally used. By proper regulati the motor element it is possible to control the power of the primary feeders to the most advantageous val

Substations for the Conversion of Alternating rent. — The alternating current is received from hig feeders, and is converted to low-voltage direct curr d-c. lighting circuits. Substations of this type are with the 3-wire lighting networks in large cities. Th prises bus-bars and oil switches for incoming lines, e verters associated with lowering transformers and vol or (2) motor-generators, and direct-current switchb many cases the above equipment is supplemented battery to insure the continuity of service in case of must be associated with step-down transformers whil motor-generator may be wound for voltages up to 20, ment is somewhat more efficient and in most cases s motor-generator equipment affords the greater rang sation.

For methods of voltage control see *Converters, Syn*

In converter substations the step-down transforme three single-phase units. Transformer banks supp and are not connected in parallel on the low-tension s and higher are usually wound 6-phase. The neutra 3-wire system may be derived from the neutral of t storage battery arrangements see *Batteries, Storage,*

BIBLIOGRAPHY. — See articles on *Power Stati*

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ATIONS, RAILWAY. — (*See also Converters, Synchronous; Rail-ergy Requirements for; Switchboards; Switchgear Equipment; Trans-*

Substations are used for electric railways when the length of the road t that the whole road cannot be supplied with one power station at ge required by the motors without either an excessive drop in voltage ibitive amount of copper or both. Practically all electric railways eloped to such an extent that substations are required for successful

OMIC CONSIDERATIONS. — The location, capacity and num-bstations is a matter for careful study and calculation, involving not cost of the copper required for distribution and the cost of the sub-but also the distribution of traffic and special local conditions. The tal economics of the subject are expressed by the general theorem cost of operating the substations plus the cost of interest and fixed n investment in substations and line copper shall be a minimum. plained by the fact that if to any given arrangement an additional be added with the proper rearrangement of the spacing, the amount used in the distributing system may be considerably decreased on f the lesser distance between substations. If the saving in interest lue of the copper is greater than the cost of operation of this new plus the interest and fixed charges on the first cost of the substation, e is warranted.

ble Voltage Drop. — The distance between substations depends on the allowable loss in voltage, the amount of copper in the trolley ely as the load. The allowable loss of voltage is a matter of the nditions of each road. Roads may be logically divided into two sses: City and Interurban. In City roads a drop in voltage of 8 per average load and 15 per cent with maximum load is frequently In Interurban roads a drop of 12 per cent with average load and t with maximum load is customary.

o conditions which determine the allowable drop in voltage are the he lights and the effect on the control circuit of the car, each of which quires a lesser drop in voltage than the actual operating character-ne motors.

ce between Substations. — For the service usually found in prac-llowing tabulation shows the average or customary distance between s.

he length of track receives its power from only one direction the distance for a given drop in voltage is one-quarter the distance allow-en substations.

y Required. — The capacity of the substation depends upon the the size of the cars, since if there are many cars operating it is prob-only a few will be starting simultaneously and it is during starting ars demand the maximum amount of power. It is, therefore, neces-termine the number of cars which will be located on the section of plied by one substation and the frequency of starting. In inter-rice the number of cars on a given section is given by the formula:

$$X = \frac{2 \times (\text{length of section}) \times (\text{number of cars per hour})}{\text{schedule speed in miles per hour}}$$

ge load on the substation is equal to the average power demand of imes the number of cars on the section divided by the efficiency of bution system. In a complex system the local conditions must be

Volts	Type	Miles between substations	
		Single-track road	Double-track road
600	Direct-current, Trolley	10	15
600	Direct-current, 3d Rail	13	19
3,300	Single-phase, Trolley	17	23
1,200	Direct-current, Trolley	19	25
1,200	Direct-current, 3d Rail	38	43
6,600	Single-phase, Trolley	45	50
11,000	Single-phase, Trolley	..	70

studied to determine how many of these cars are liable to be starting at one. In other than city roads a load factor of from 0.3 to 0.5 may be used to determine the maximum load on a substation, and in single-track interurban roads it is customary to assume one car starting and one car running. See article on *Railways, Energy Requirements for*.

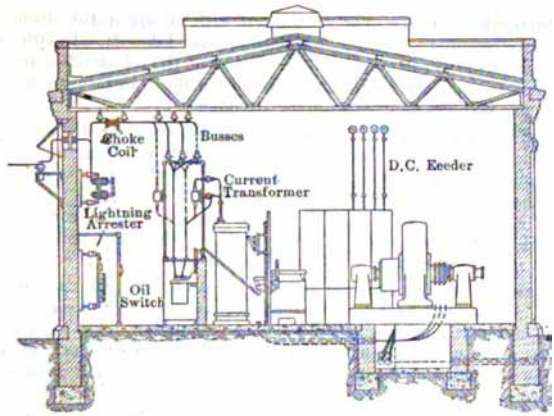
TYPES OF SUBSTATIONS. — In practice there are two types of substations: 1. for transforming from alternating to direct current, and 2. for transforming from high-voltage alternating current to low-voltage alternating current.

In standard direct-current railways it is customary to generate power in the power stations at about 2200-volt three-phase alternating current, step up by means of transformers to 33,000 volts 3-phase, transmit over any distance to the substations at this voltage, transform from 33,000 volts to approximately 400 volts 3 phase and then to convert to direct current at 600 volts in which form the power is used by the motors of the cars. This is the standard a-c.-d-c. substation. In certain single-phase a-c. railways it is found necessary to transmit the power over long distances at a higher voltage than can be collected from the trolley, in which case the a-c.-a-c. transformer substations are installed to convert the alternating current at the high transmission voltage to alternating current at a voltage convenient for the trolley and collector devices.

SUBSTATIONS FOR TRANSFORMING FROM ALTERNATING TO DIRECT CURRENT. — In these stations it is almost universally the custom to employ synchronous converters to convert from a-c. to d-c., rather than motor-generator sets, as the converters have a higher efficiency and may be compounded to give the desired regulation. Thus the converter makes possible a saving in first cost, space and energy as compared to the motor-generator set. A standard a-c.-d-c. railway substation usually contains the following pieces of apparatus: converters, transformers, reactances, blowers, cables, switching apparatus.

Arrangement of Apparatus. — (*See also article on Switchgear Equipment.*) It is customary to arrange the apparatus in a substation so that the current travels in as nearly as possible a straight line across the station. Thus, with the incoming line on one side there are in the order mentioned: the lightning arresters, oil switches, transformers, a-c. switchboard, reactance coils, con-

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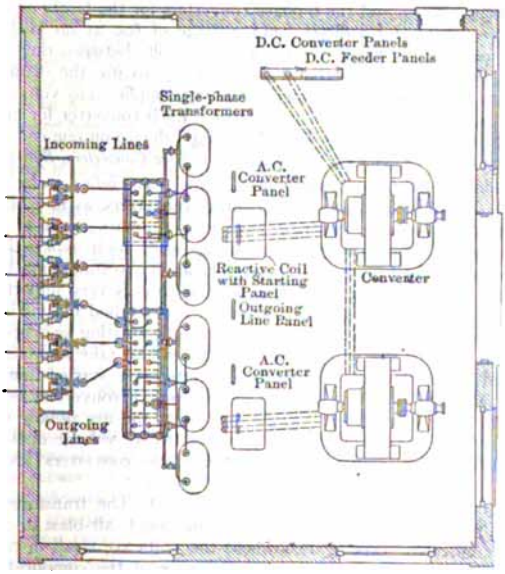


Fig. 1. Plan and Elevation of Typical Railway A-C.-D-C. Substa

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verters, d-c. line panel. A typical arangement for a small station is shown in Fig. 1; see also Fig. 16 in article on *Switchgear Equipment*.

Floor Space Required. — For substations with all apparatus on one level the floor space required is about 0.20 square foot per kilowatt. In cities where real estate is expensive, it may be desirable to put the oil switches and lightning arresters in a gallery on the upper level and the transformers on a floor above, but this involves more expense for attendance.

Standard Voltages and Frequencies. — The following three-phase voltages have been standardized for railway work: 11,000 volts with transformers delta connected on the high-tension side; 33,000 volts with transformers *Y* connected; 66,000 volts with transformers *Y* connected. A frequency of 25 cycles per second is employed in almost all railway installations, as converters are more reliable at this frequency. Certain stations which are obliged to take power from previously existing power stations use a frequency of 60 cycles.

Converters. — (*See article on Converters, Synchronous, for data regarding converters.*) Compound-wound converters are used where the load is variable to provide automatically any desired voltage regulation. The converter by means of its series winding is made to take a leading current which, in passing through the reactance of the line, the transformers or through an additional reactance introduced for the purpose, tends to neutralize the line drop. (*See Transmission Lines.*) In city service where a large number of cars are operating on one section, the load is fairly constant and shunt-wound converters are generally used.

Both 3-phase and 6-phase converters are universally used, the 3-phase for the smaller capacities and the 6-phase converters for the larger capacities. In a 3-phase converter for a direct e.m.f. voltage of 600 at no load, the transformers should supply the converter with 370 volts between rings or between lines. In the 6-phase converter it is customary to use the diametrical connection, in which each transformer secondary supplies 430 volts to the converter, giving 600 volts at the commutator. Each converter for railway work is customarily supplied with a "speed-limiting" device on one end of the shaft and an "end-play" device on the other end. (*See Converters, Synchronous.*)

Methods of Starting Converters. — (*See also below under Operation.*) There are several methods of starting rotary converters, as is explained under *Converters, Synchronous*. Starting from the alternating-current end as an induction motor is most desirable for railway work, as it avoids the necessity of synchronizing and requires less time. The ability to start a machine quickly and get it on the line in the shortest possible time is very important in railway work, and is an advantage inherent in this method of starting. Three-phase converters are started, by means of suitable starting switches, from one-half voltage taps on the transformer secondaries and take approximately full-load current from the line. Six-phase converters are started from ½ voltage taps and take ¾ full-load line current. Since 60-cycle converters usually take a greater starting current than 25-cycle converters and are usually operated on a system supplying power for other purposes, where voltage disturbances are objectionable, special means of starting 60-cycle converters are frequently employed.

Transformers. — (*See article on Transformers.*) The transformers used in railway substations may be either of the oil-cooled, air-blast or water-cooled type. The oil-cooled type is used where the units are small in capacity, i.e., less than 400 kilowatts, and where the expense of the complications for air blast or water cooling are not warranted. Air-blast transformers are used in all except the smallest sizes, and for voltages up to and including 33,000; the objections to their use are the necessity of providing a pit, air ducts and blower

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to supply the ventilation. Water-cooled transformers (which are oil-insulated transformers with water circulating in a special coil submerged in the oil) are built in sizes from 500 kilowatts upwards and for all voltages. Their use depends upon the availability of water for cooling purposes. The usual aggregate capacity of transformers for the various sizes of synchronous converters is about the same as the converter capacity.

Transformer Connections. — The transformers may be either of the single-phase or three-phase type. For small or moderate installations the single-phase type is preferable on account of the economy of maintaining only one single-phase transformer as a spare for a whole station. In railway work it is customary to connect the secondary of the transformers in delta for three-phase, because of the possibility of operating at reduced output on open delta in case of failure of one transformer. The primary windings of the transformer are usually connected *Y* with grounded neutral. It is common practice to provide transformers for railway work with four 2½ per cent taps on the high-potential winding, in order to use similar transformers in all substations and yet make allowances for the difference in the line drop between the power station and the various substations. Either ⅛- or ½-voltage taps are provided on the low-potential side for starting the converters.

Blowers for Air-blast Transformers (*see Blowers and Compressors*) are usually driven by 25-cycle 3-phase induction motors receiving power from the low-tension side of the transformers. The amount of air required per minute per kilowatt rating of each transformer ranges from 3 cubic feet in the large sizes to 5 cubic feet in the small sizes. This air is supplied at a pressure of from ⅜ to 1 ounce per square inch. The blowers must be capable of supplying this amount of air with an allowance of about 10 per cent for leakage in the air-blast chamber. It is customary to provide two blower sets each capable of supplying air for all the transformers in the station and maintaining one as a reserve unit. In a very large station 3 blower sets are sometimes provided, two of which are together capable of supplying the service and the third is a reserve. A rough idea of the size of the motor necessary to drive a blower for a given purpose may be obtained from the following formula:

$$\text{Horse-power} = \frac{(\text{cu. ft. air per minute}) \times (\text{pressure in ounces})}{1200}.$$

Air Duct for Air-blast Transformers. — The pit or trench over which air-blast transformers are placed must be made water-tight and well drained, as any moisture accumulating is liable to be carried into the transformers where it will injure the insulation.

Voltage Regulation. — Use of Reactances. — The voltage at the d-c. bus-bars is regulated automatically by means of line compounding which consists in adjusting the shunt-field excitation of each converter so that the converter takes lagging current at no load, operates at unity power factor at about ¾ load and takes leading current at all loads greater than ¾ load. To accomplish this compounding, it is necessary that there should be a certain amount of reactance between the power-station bus-bars and the converters. (*See Converters, Synchronous.*) There is seldom enough reactance in the transmission line for this purpose, so that additional reactance is inserted either by the use of special transformers having considerable leakage reactance, or by means of reactance coils. The usual reactance coil has a capacity in kv-a. equal to 15 per cent of the kilowatt rating of the converter, i.e. with full-load current passing through the reactance the voltage measured across its terminals would be 15 per cent of the voltage to neutral on the a-c. side of the converter.

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Reactance coils are either oil cooled or air blast depending upon the transformers used and are usually built with the three circuits in one unit, with the starting switches for the converters mounted upon the frame. For 6-phase converters a 3-phase reactance coil is used, but since the current per wire is one-half that of the current of a 3-phase converter of the same rating, the reactance per line must be twice as great for the 6-phase converter.

Switchboards. — (*See also article on Switchboards.*) The following sections of switchboards are standard for converter substations.

1. Incoming a-c. line panel.
2. Outgoing a-c. line panel.
3. High-tension a-c. converter panel.
4. D-c. converter panel.
5. D-c. feeder panel.
6. Equalizer and negative panel (on the converter).

Where a substation is tapped off a transmission line at an intermediate point it is good practice to bring the transmission line into the substation, interpose control switches, and then carry the circuit out of the substation on to the next substation. For this reason, in all but terminal substations, it is customary to provide both an incoming and an outgoing a-c. line panel. In connection with the a-c. panel of the switchboard there are a line switch, lightning arrester, choke coil, current transformers and main oil switch, by means of which potential may be removed from all transformers. Between the transformers and the converter are the starting switches, reactance coil and possibly measuring devices.

Direct-current Panels. — Single-pole switchboard panels are used, the positive main bus-bar being the only one on the board. The negative terminals of the converters are connected with switches to the negative or ground return bus-bar, which is frequently located beneath the converter. The series field is connected on the negative side, and the equalizer, series-field-shunt and field break-up switches are frequently placed on the machine itself. The equipment of a standard d-c. converter panel comprises one of each of the following:

Carbon break circuit breaker with overload and low-voltage release, the latter interconnected to the speed-limit device.
Illuminated dial ammeter with shunt.
Field rheostat.
Two-point receptacle.
Single-pole main switch.
Single-pole double-throw station lighting switch.
Watt-hour meter.

Storage Battery. — In certain installations, where reliability of service is of utmost importance, a storage battery is installed, operating in parallel with the converters, and preferably regulated by a series booster. Such a storage battery will not only take care of the load for a considerable period of time in case either the transmission line or converters are out of action, but it will also improve the load factor of the system and thereby the line regulation. In other cases, where the service does not warrant the outlay for such a storage-battery system, a small storage battery is sometimes installed to take care of the lighting of the substation in case the converters should shut down accidentally. See articles on *Batteries, Storage.*

Ventilation. — As the transformers, reactance coils and converters all dissipate a considerable amount of energy in the form of heat, a substation must be well ventilated in order that the temperature of the air surrounding the apparatus

not so great as to cause an injurious temperature in the apparatus itself. This is particularly important where oil-cooled transformers are used.

Crane. — Where ground space is limited it is good economy to provide a crane in order that the various pieces of apparatus may be lifted over each other when they are taken apart for repairs, as otherwise considerable space must be left to move them about to and from the entrance. See article on *Cranes*.

Operation of Converter Substations. — The only apparatus in a converter substation that requires any great amount of attention are the synchronous converters. As noted above these are usually started from the a-c. supply.

Instructions for Starting a Synchronous Converter from A-C. Supply. —

1. Open all switches except main negative (on machine).
2. Close a-c. line switch feeding busses.
3. Close H.T. transformer switch.
4. Close starting switch on low-voltage taps.
5. When converter reaches synchronism as shown by low frequency of swings of d-c. voltmeter, close equalizer switch.
6. Close switch between series field and the shunt to series field.
7. Correct polarity if necessary by throwing shunt-field break-up switch to reverse position, leaving it closed only momentarily, then throw to running position.
8. Connect a-c. terminals of converter to full voltage of transformers by throwing starting switch to running position.
9. Close d-c. circuit breaker.
10. Adjust field rheostat.
11. Close main d-c. switch.
12. Adjust for correct division of load, power factor and voltage.

Load Factor and Efficiency. — The load factor (q.v.) of a converter substation is usually low, from 30 per cent to 50 per cent, i.e., the load on the station is relatively light except during the morning and afternoon rush-hours, 7 to 9 A.M., and 5 to 7 P.M respectively (*see Train Dynamics*). The all-day efficiency of the station itself, or the ratio of the kilowatt-hours output to the kilowatt-hours input, is less than the efficiency at maximum or rated load; but the over-all efficiency between the a-c. generators in the power house and the cars is about constant throughout the day, since the efficiency of a transmission line increases with decrease of load, thus offsetting the low light-load efficiencies of the transformers and converters. In general practice in inter-urban 600-volt railways the maximum and all-day efficiencies of the various apparatus are approximately as given in the following table:

Apparatus	Full-load eff., per cent	All-day, eff., per cent
Step-up transformers	98	97
High-tension line	95	98
Step-down transformers	97	94
Converters	90	88
Low-tension distribution	85	88
Over-all, a-c. generator to motors	69	69

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Automatic Substations. — To decrease the co
nating the need of attendants, substations are now eq
control and operation are accomplished mechanically a
the voltage on the adjacent section of the trolley fal
(450 volts) a contact-making voltmeter closes a cont
motor-driven controller operating a large gang of
These switches automatically and consecutively acco
tions listed under "Operation." The converters are
so there is no synchronizing, but the polarity of the
field excitation adjusted at the proper time and the sev
in parallel. Protection against overload, low-voltage
vided.

When the load falls below a specified value a contac
a circuit which opens all switches and shuts the co
number of these automatic substations have been i
three converters per station and in sizes up to 2000 kw

First Cost of Converter Substations (1921). —
cost from $10 to $16 per kw. The transformers cost
and the switch-gear from $6 to $20 per kw. rating of s

All the electrical apparatus makes up about 67 per
the station including the building. The floor space re
foot per kw. in large sizes to one square foot per kw. i

In an approximate way the cost of substations inc
and installation, for 33,000-volt transmission, 25-cycle
trolley is as follows:

Station capacity, kw.	No. Converters	Capacity of each converter, kw.	A
300	1	300	
600	2	300	
800	2	400	
1000	2	500	

Cost of Operation of Converter Substations. —
attendants is the principal item in the cost of op
Supplies and maintenance form a very small percentag
only one man per shift is necessary, as the principal
machines in the morning and occasionally during the
step due to a short-circuit. Frequently the duties
combined with that of ticket seller or express agent.
attending to the substation, $2500 to $3000 per year
of operation of a substation, allowing for the two shift

PORTABLE SUBSTATIONS. — Circumstances
which the traffic on a certain branch of a railway is v
weeks in the year, and possibly for only two or three
over traffic may be exceptionally heavy on one bran
and on another branch at another period. In such c
very expensive to provide on each branch substatio
meet the heavy demand. To meet such conditions
are used. These consist of what are practically larg

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nstalled one synchronous converter and the necessary transformers
l devices. Side tracks are provided at points on the branch lines
eeded this portable substation is hauled to the place desired and its
n terminals are connected to the high-tension transmission line, pro-
which must be made in building the line, and its direct-current ter-
connected to the trolley and the rail respectively. Such a substation
great convenience and value for interurban roads where summer
ses and athletic games occasionally render traffic conditions diffi-
car is limited in its size by the standard clearance outlines of the
which it must pass. It usually weighs, with all its equipment,
ons. Apparatus having a capacity of 500 kw. may be installed in
and the primary voltage may be as high as 33,000 volts (*see article*
r Equipment).

OLTAGE DIRECT-CURRENT SUBSTATIONS. — Many
ilways are operated at 1200, 1500, 2400 and 3000 volts d-c. between
ground. For this purpose power is transformed from alternating
means of either motor-generator sets or synchronous converters.
motor-generator set was considered more fitted to the purpose as
of the commutator is not as restricted in a generator as in a con-
he interpole made it possible to operate at a high potential between
ubsequently, synchronous converters with interpoles and operating
were developed, and are now in successful operation. At first two
chines were connected in series to give 1200 volts. Later, machines
oed which would give 1200 volts on each machine and these became
r 2400 volts by connecting two in series. For 3000 volts three-
generator sets are used, one a-c. motor driving two 1500 volt inter-
ors in series.

ATING-CURRENT SINGLE-PHASE SUBSTATIONS. —
-phase railway operating at a high voltage on the trolley (11,000
s not necessary to place substations as near together as in the case
ns. However, even with 11,000 volts on the trolley, there comes a
length of road which may be supplied from one feeding point. In
ecomes necessary to step up the voltage at the power station to
me higher voltage and step down again to the trolley voltage at
tations. A substation for this purpose need contain only trans-
control devices. It is much simpler and less expensive than the
bstation. It has even been a matter of discussion as to whether
ation would require continual attendance to maintain proper oper-
is, however, a matter which must be decided by local conditions.
transformers are used there is no moving apparatus in the station,
need of an attendant is in case of accident or to reset a circuit
se it goes out as a result of an overload.

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SWITCHBOARDS. — (*See also Bus-Bars; C Switches; Switchgear Equipment for Power Stations*
formerly comprised all apparatus in that portion of collecting, measuring and distributing the electric en of the switchgear is mounted on a single structure whic board. In large modern plants the control and mea are frequently mounted on one structure, and the another. In such cases the term switchboard is whether panel, pedestal, or desk type, which suppo handles and similar devices. The following article of apparatus on representative switchboards selecte trend of switchboard design. For a description of arrangements required by direct control and distant *Switchgear Equipment in Power Stations.*

CONSTRUCTION OF PANEL SWITCHBOA
called "panel" boards were made of wooden pane instruments, etc., each on its own base, were attac with the wiring on either the front or the rear. The the elimination of the wooden panel and framework. was mounted on a marble slab, which was arranged f framework, and switchboards were made by combini voltmeter, switch and rheostat slabs to make the pa rators, feeders, etc. This form of construction was en disadvantages ultimately lead to its being supersede panel switchboards with the apparatus grouped on p comparatively large pieces of marble, or slate.

The design of modern panel switchboards has un process that has been applied to all electrical appara requirements the vast majority of plants of moderate control switchboards that are made up by assembling

Framework of Panel Boards. — In general the f switchboard may be divided into two types. The c are mounted on a framework of gas pipe, and usua 4 feet high with a space between them and the flo expensive boards have a total height of about 7 feet the floor, and are provided with an angle iron or pipe

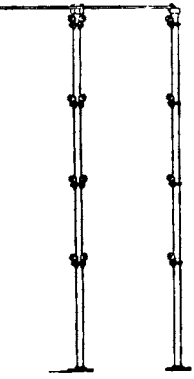
Gas-pipe Frames. — Although the gas-pipe ably lighter than the angle-iron construction it has be these smaller switchboards and in fact some manuf struction for most of their larger switchboard installa of panels does not exceed four or five the complete shipped with the panels attached to the framework an etc., undisturbed, but if the boards are large ones shipped separately.

Fig. 1 shows the pipe framework for switchboard pa is made of 1¼" wrought-iron pipe with one wrough with cast-iron foot nuts and panel supports. The v attached to the vertical pipes by "J" bolts or "U" b fitting is required.

Angle-iron Frames.—Fig. 2 shows a typical switchboard panels 90 inches high. Each panel of a is provided with 2 by 3 by ¼ inch or some similar se narrow web bolted to the panel. These angle irons

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to within ½ inch of the top. The vertical angles on adjacent olted together through the 3-inch web. They are provided with



—Pipe Framework

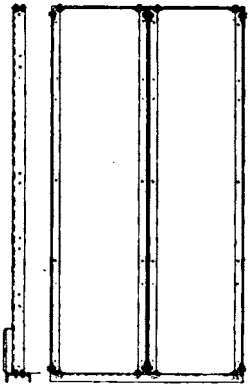


Fig. 2.—Angle Framework

for bolting at the bottom to a 6 by 2-inch channel iron forming he frame and at the top to two ½ by 1⅜-in. iron strips. The and the top irons are made continuous the entire length of the is not over 16 feet. Each panel is shipped bolted to the two angle m its individual frame, which obviates any necessity of disconnect- between the various slabs making up the panel. This practice of framework with the panels reduces to a large extent the breakage handling and facilitates the erection of the board at its destination.

rd Panels. — After trying various materials practically all switch- s have adopted either slate or marble, although in a few instances ick or steel has been used. The marble used in switchboards is grade known as "Blue Vermont," although occasionally "White Pink Tennessee" is used.

arison of Slate and Marble. — Where switchboard panels are black finish the choice of slate or marble is largely a question of ation. Slate is considerably cheaper and somewhat stronger than here the voltage of live metal parts mounted on the panels does not lts it answers just as well.

Used on Panels. — The marble is sometimes polished on the d bevels, and occasionally on the edges and back. The present h for marble is a dull black marine finish applied to honed panels. e, owing to its irregular color and marking, is usually given an rine finish and natural black slate is given an oil finish.

sions of Two-piece Panels. — The total height of standard anels is 90 inches from the channel iron. The division resulting wer slab as furnished by one company is due to the fact that these ensions were best adapted to the line of switches, circuit-breakers which were in use at the time the standard railway switchboard rst brought out. The lower 25-inch slab was used for rheostat face

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plates having the contacts and contact mechanism In order to correspond with the old d-c. panels the a having a lower slab 25 inches high and a main slab 6 design of another company provides panels with sla high which dimensions were suited to their apparat ization.

Dimensions of Three-piece Panels. — W brush-type, carbon-break circuit-breaker was desig to mount this breaker at the top of the panel in ord tendency of an arc to rise. As all these standard b capacity required a vertical space of less than 20 divide the main upper 65-inch panel into two slabs, high to contain the circuit-breaker and the other contain the meters, switches, etc. For this reason of one maker, both for railway and for light and into three slabs, the upper 20 inches high, the middl 25 inches.

As the size of rotary converters has increased to breakers larger than 3000 amperes are often required 25 inches high to accommodate breakers up to 10, middle slabs 45 inches high and lower slabs 20 inches of 90 inches. Another manufacturer uses sections 3 inches having the same total height of 90 inches. slab usually contains the instruments as well as th all switchboard builders have adopted the three-sect heavy capacity carbon circuit-breakers.

TYPICAL DIRECT-CURRENT SWITCHBO equipments described in the subsequent paragraphs lustrate standard practice.

Small Isolated Plant Switchboards. — Whe generator of small capacity with one or two feeders of any additional equipment being needed, a board like Fig. 3 can be used with a main slab 36 inches high, 16 inches wide, provided with a polarized ammeter and voltmeter, single-pole carbon breaker, 2-pole main switch, field rheostat in the generator circuit, and switches with fuses in the feeder circuits. This type of board uses subpanels for the feeder switches and is usually limited to 10 kw. at 125 volts or 20 kw. at 220 volts.

2-Wire Switchboards. — For the control of small capacity, d-c. generators operating in parallel on a 2-wire, d-c. circuit the connections are made as indicated in Fig. 4. Each generator is provided with a 3-pole, single-throw switch, a single-pole circuit-breaker, an ammeter, and rheostat and a 4-point voltmeter receptacle used for connecting the voltmeter to any machine. Each feeder is provided with a 2-pole switch with ground detector is connected across the bus-bars.

3-Wire Switchboards. — Fig. 5 shows the diagra cal d-c., 3-wire installation and indicates the meth

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onnection from the middle point of auto-transformers; the use of series fields the positive and negative circuits; the placing of the ammeter shunts on the

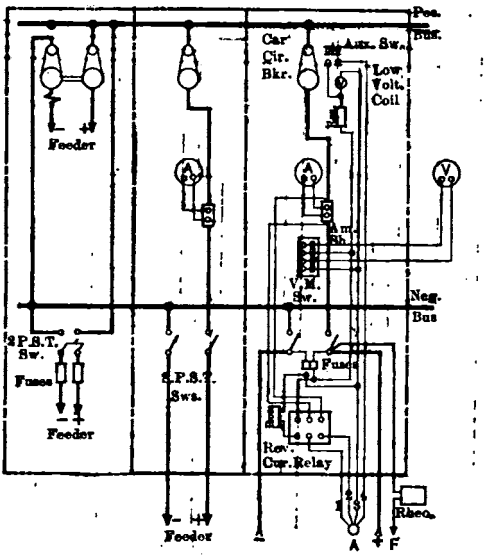


Fig. 4.

terminal boards of the machines so as to be connected inside the series fields; and the 4-pole circuit-breakers or the equivalent two single-pole breakers with equalizer contacts to open the positive, positive equalizer, negative and negative equalizer circuits.

Double-bus Railway Switchboards. — For direct-current railway or tramway work at about 600 volts it was for a long time the standard practice to bring both the positive and the negative leads from the generator to the switchboard and to locate both the positive and negative bus-bars on the switchboards, such boards being called "double-bus" boards. With these boards it was customary to use compound-wound d-c. generators with the series fields in the armature circuit which connected to the overhead trolley. The equalizer connection was usually made through a switch at the machine and the equalizer connection ran from one machine to the other without going to the panel board.

The double-bus scheme is still usually adopted for 250-volt, 2-wire industrial switchboards or any d-c. installation that does not use the ground return.

Single-bus Railway Switchboards. — Modifications in this class of switchboards came from placing the series fields in the grounded circuits instead of in the trolley circuits, and running only one polarity, usually the positive, to the switchboard. The equalizer switch and the negative switch, if the latter is used, are mounted at the machine. Fig. 6 is a typical diagram of a d-c. generator installation arranged for single-bus operation with only one polarity, namely the positive, on the board. The advantages

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of this single-bus d-c. system are greater security against short circ narrowing of the d-c. generator or synchronous converter panel, consequer

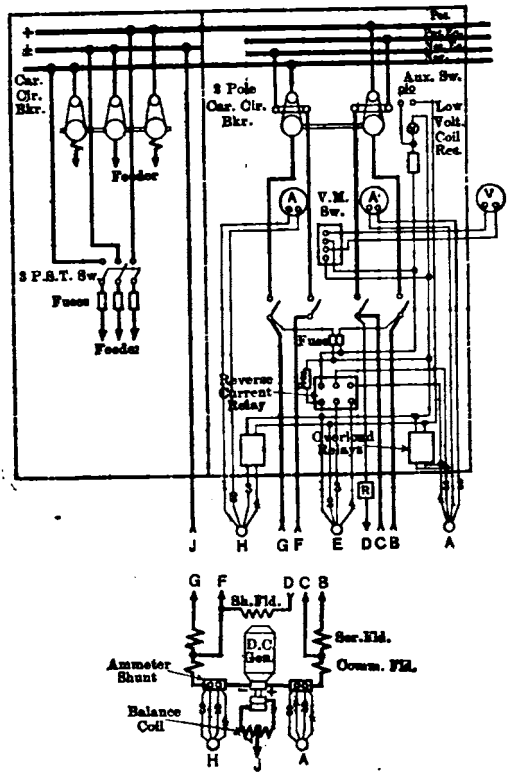


Fig. 5.

reduction in length of switchboard, reduction in amount of cable required and the use of bare copper strap or cables between machines for the negative and equalizer buses.

For converters or motor-generator sets, the panel switchboard if such is used, takes care of both the d-c. and a-c. circuits, which are usually controlled by separate panels. The d-c. panels are practically the same as those used for d-c. generators. The a-c. panels usually correspond with a-c. feeder panels and control the high-tension side of the step-down transformers used with the converter where the latter is made self-starting from the a-c. end. With such machines, in addition to the panels on the high-tension side of the transformers, it is customary to furnish a small slab mounted near the step-down transformers for connecting the converter, first to low-voltage taps for starting, then to full voltage taps for running.

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It is customary to locate the 3-pole, double-throw switch used for starting the synchronous converter, on a panel with the 2-pole double-throw field reversing switch, so that if the converter should build up with its polarity reversed, it is a very simple matter to make the machine slip a pole and build up with the correct polarity. For railway service, the equalizer and negative switches are frequently mounted on the same panel as the starting switch and field-reversing switch.

It is customary practice to provide automatic protection on the alternating-current side of synchronous converters by making the breaker on the high-tension side of the step-down transformer automatic with inverse time element relays, or with inverse time element attachments on the trip coils of the breaker. A low voltage and instantaneous over-load carbon circuit-breaker is provided for the direct-current side. The low-voltage trip of the direct breaker is actuated by a speed-limit switch furnished with and mounted on the converter, the operation of which opens the breaker. It is also actuated by an auxiliary switch that is provided on the oil circuit-breaker so that when this breaker opens the direct-current breaker also opens in this manner providing against the motoring from direct-current and eliminating the liability of reversal in polarity on compound wound machines. For 600-volt railway service where there is an independent source of direct-current power such as an adjacent substation, d-c. reverse current relays are provided, these relays being arranged to trip the alternating-current breaker upon reversal of direct-current power and this in turn opens the direct-current breaker.

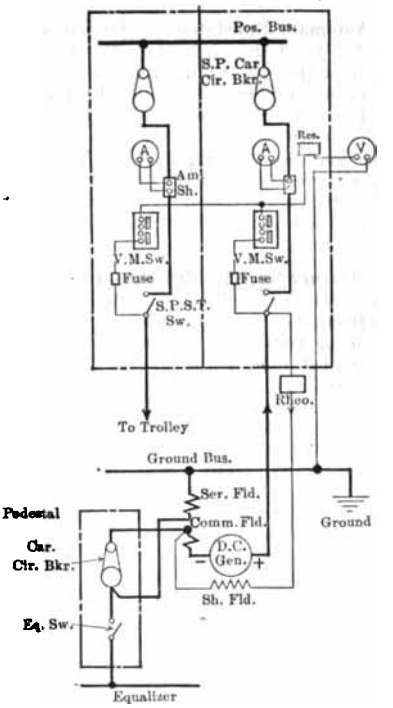


Fig. 6

High Voltage Direct-current Railway Switchboard. — For 1200-volt d-c. railway service the switchboard panels differ from those used for 600 volts, in the increased height of panel and in the fact that the circuit-breaker and knife switch are mounted out of reach and are mechanically operated by an insulated mechanism.

For 2400–3000 volt d-c. service special precautions have to be taken to carefully insulate the circuit-breakers and switches. Owing to the greater likelihood of flash-over occurring on the high-voltage d-c. converters or motor-generators, high-speed circuit breakers have been designed to trip on overload before the current in the machine rises to a dangerous amount. The same

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result is obtained by a high-speed device that places an a-c. short circuit on the converter or generator before the direct-current has an opportunity to rise to a dangerous amount.

Automatic Substations. — On interurban railways operating cars or trains on hourly schedules it has been found advisable in certain cases to install automatic devices for starting a synchronous converter on the approach of a train or car and to shut it down after the train or car has passed.

This is usually accomplished by a series of contactor switches that start the converter and connect it to the lines whenever the voltage on the trolley line drops below a certain percentage of normal, this drop usually being caused by the approach of a car drawing a relatively heavy current from the line. After the car has passed and the current from the substation has dropped to a certain point, the converter will be shut down after the expiration of a definite time interval.

Mercury Rectifier Switchboards. — Another combination of a-c. and d-c. equipment met with in switchboard practice is that furnished for mercury rectifiers used in conjunction with constant-current d-c. arc lights fed from a constant-potential a-c. system. The apparatus supplied usually comprises a two-pole oil switch with fuses for the primary circuit of the regulator, plug switches in the secondary circuit, a mechanism for tilting the bulb of the mercury rectifier, and a high-voltage d-c. ammeter placed under a glass cover. The switchboards furnished with low-tension rectifiers are of similar arrangement, except that they are fitted with low-tension meters and switches, and have a single-pole starting switch which automatically applies a rheostat load for starting.

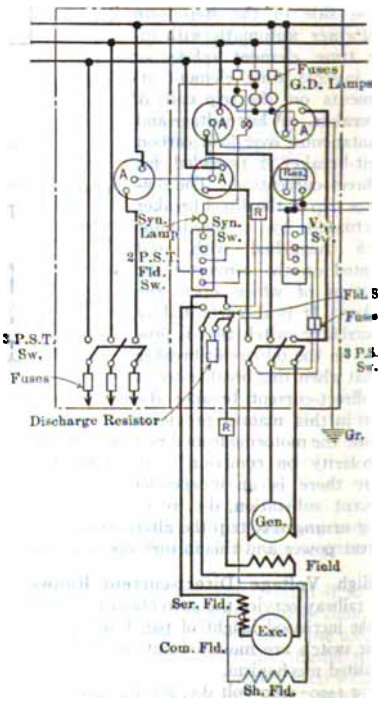


Fig. 7.

Other Arc-light Switchboards. — For use with d-c. series arc generators, switchboards are frequently supplied with a multiplicity of plug switches to permit any generator or feeder circuit to be connected in series with any other circuit to circuits. (*See Switches.*)

Exciter Panels, although d-c., are almost invariably combined with and form part of a-c. switchboards. The d-c. sections of the board are naturally considered with the a-c. sections and made to correspond with them in general design

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els are either single or double, depending on whether they control machines. Usually no fuse equipment or other automatic provided with exciter panels, as the sudden opening of the field to the blowing of an exciter fuse or the tripping of an exciter pt to injure the insulation of the generator and cause far greater the plant than the overloading or short circuiting of an exciter. e are several large exciters operating in parallel with each other or age battery, it is occasionally considered good practice to furnish ent circuit-breakers in the exciter circuits.

L ALTERNATING-CURRENT SWITCHBOARDS. — Some uipments are described and illustrated in the following paragraphs.

ow-voltage A-C. Boards (Fig. 7), made for circuits of not over s capacity at 500-volts, are usually built of panels 48 inches high on . Each a-c. generator may have its own exciter as shown in Fig. 7, ers may be operated in parallel and controlled from exciter panels. n this diagram the d-c. circuits are taken care of by an exciter rheostat, rheostat and a 2-pole field switch with discharge resistance. Each or is provided with a 3-pole single-throw knife switch, three ammeters, ltmeter switch, and a synchrononizing switch. Each feeder has a ch and an ammeter. A lamp ground detector and a voltmeter are n such a manner that the voltage can be read across any phase of e. In this diagram lamps are used for synchronizing.

igh-voltage A-C. Boards. — A similar arrangement of panels may small-capacity high-voltage switchboards, using oil switches in place itches in the generator and feeder circuits, and operating the volt- amp ground detector from potential transformers.

ow-voltage A-C. Boards. — For low-voltage a-c. circuits of greater an can be readily handled by the 48-inch panels, larger panels made hree sections with a total height of 90 inches are usually employed. vice where the voltage does not exceed 550 volts, knife switches are used but the practice is rapidly growing, of utilizing oil circuit-break- moderate voltages, owing to the greater safety, greater convenience, dvantages. Where the voltage does not exceed 2400, or the amount es not exceed 3000 kv-a., it is customary to use oil circuit-breakers rectly on the switchboard panels. Fig. 8 shows a typical switch- panel-mounted oil breakers arranged for the control of two exciters, ators, and two feeders.

ket devices comprise two voltmeters, one connected through trans- the bus, and the other arranged to plug on any phase of any of the ators through suitable transformers, one synchronoscope with two ng lamps, and one voltage regulator. The first panel on the left o exciters and is provided with two d-c. ammeters, one d-c. volt- rheostats, two 2-pole switches, and one equalizing switch. three panels are generator panels, each being provided with an a-c. . polyphase indicating wattmeter, field ammeter, field rheostat, , voltmeter and synchronizing receptacle, ammeter switch and a tic breaker.

wo panels on the right are feeder panels and are each provided with eters, a watthour meter, two overload relays, and an automatic

e disconnecting switches are furnished for disconnecting the oil kers from the busses, to facilitate the inspection of the breakers.

e voltage exceeds 2400. or the amount of power to be controlled is

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in excess of about 3000 kv-a., it is preferable to locate the oil breakers apart from the board and to control them either electrically or mechanically from the panel.

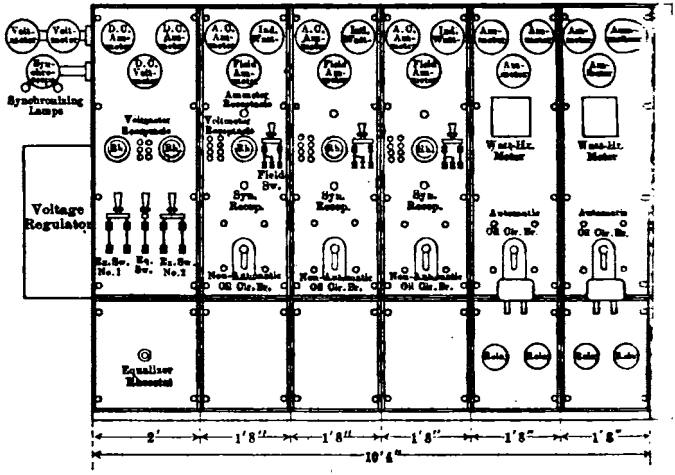


Fig. 8.

Large Distant-control A-C. Switchboards. — Where the amount of power to be controlled is large or the voltage is above 3300 it is customary to mount the oil circuit-breakers apart from the board and to operate them either mechanically or electrically. On these boards the usual equipment of instruments is mounted at the top of the panel, the switch-control handles are in the middle and the time-limit relays at the bottom. Targets and signal lamps to indicate the condition of the feeder are furnished with electrically operated boards.

Fig. 9 shows diagrammatically the various standard arrangements for electrically controlled equipment. *a* illustrates a typical vertical panel board with the instruments, control switches, relays, and similar devices mounted on the face of the panel.

b shows an arrangement of a control desk with the control switches placed on the desk and the instruments mounted on a wall in front of the operator. *c* shows an arrangement of control desk where there are comparatively few meters, these being set flush in the face of the desk. *d* shows a modification of the desk arrangement with the meters on a small slab or bracket extending up from the horizontal slab of the desk. *e* shows the control desk arrangement with vertical panels forming the back of the desk, the vertical panels containing the indicating meters. *f* is a further modification of the control desk arrangement with vertical panels containing the indicating meters and a complete switchboard at the rear to contain the recording meters, relays, and similar devices. With this arrangement a self-supporting control desk is provided. *g* shows the so-called gallery type of desk with the meters located on a framework supported above the horizontal slab of the desk at such a height that the operators standing at the control desk can look above the edge of the desk and

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e meter panels to observe from the switchboard gallery the machine is controlling. *h* is a modification of the gallery type of control is a modified arrangement of control desk using a separate instrument

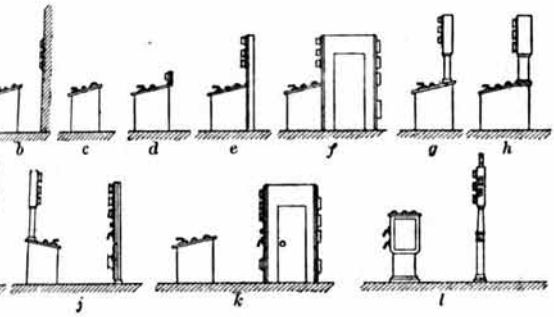


Fig. 9.

rted on ornamental pillars, these pillars as a rule, being arranged upports of a gallery railing.

e combination of a gallery type control desk for the generators panels switchboard for the feeder.

combination control desk and panel board, the generator breakers ed from the desk, the generator instruments being on the vertical l of the feeders being controlled from the vertical panels. The ers, graphic meters, and relays are placed on an auxiliary board vith the feeder board.

arrangement of control pedestals and instrument posts correspond- rrangement adopted by the Ontario Power Company at Niagara n this control room pedestals and posts are provided for a total eel generators, 12,000 volts, the units averaging about 8770 kv a ach generator being provided with its own control pedestal and t.

DESKS (Figs. 10 and 11). — Where it is desired to have a very gement and to control the generators and feeders from the same e control desk has many advantages; particularly where a group ts is used and it is desirable to have a miniature bus-bar to show me of connections and the arrangement of circuits in use. The ted on it the field switches, field-rheostat handles and small erating electrically the various controllers, circuit-breakers etc. es and rheostats may also be operated electrically.

rrangement of the control devices and the meters is indicated as may be noted, various combinations can be readily secured. vhere a control desk is placed in a gallery, a so-called gallery oves to be the most advantageous. With this type of desk hes and indicating lamps for the electrically operated breakers uits are placed on the nearly horizontal portion of the desk. g control switches for the field and excited circuits are on the he desk. The indicating instruments are placed on vertical wn to the horizontal part of the desk and graphic meters, relays, and calibrating jacks are placed on separate panel ck with the main desk.

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On the horizontal section of the desk a miniature bus is often placed show the connections made by the main breakers.

Each generator is provided with three ammeters, one per phase, a polyp indicating wattmeter to show the amount of power delivered to the main bus

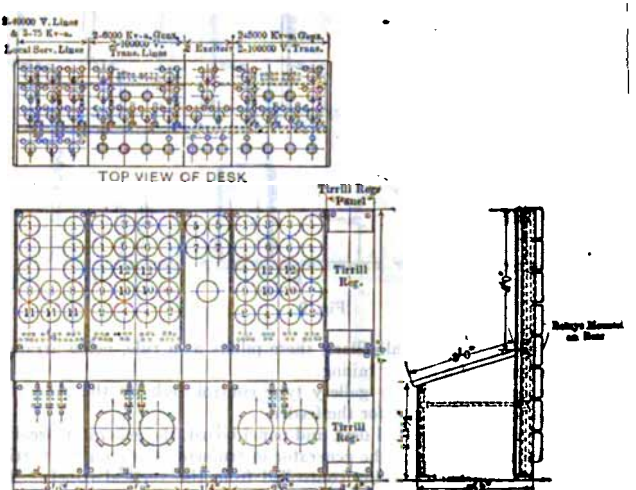


Fig. 10. Contral Desk with Instrument Panels.

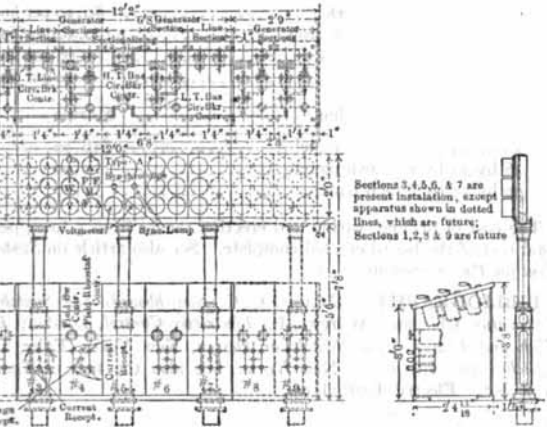
polyphase indicating wattmeter to show the amount of power going over the transfer bus, a synchronoscope, power factor indicator, field ammeter, ammete in the circuit of the synchronizing bus, a frequency meter, and an indicati temperature meter. In addition to the indicating temperature meter a pote tiometer is sometimes provided with a dial switch for other temperat readings.

Control Desk with Separate Instrument Frame. — Fig. 11 shows the plan view, elevation and side view of a control desk provided with 7-inch diameter round pattern meters located on an instrument frame back of and above the desk. The height of the instrument frame is 7 feet 8 inches, which corresponds to the height of standard 90-inch switchboard panels mounted on the usual 2-inch channel iron base. This control desk with a total length of 11 feet, when fully equipped, is to take care of six 10,000-kv-a., 3-phase, 6600-volt generators, six banks each of three 3333 kv-a. step-up transformers, and four 110,000-volt transmission lines.

As shown by the miniature bus system placed on the top of the contro desk, each of the six sections intended for a generator and its bank of transformers is provided with a generator ammeter, transformer ammeter, generator indicating wattmeter, power-factor meter, voltmeter, and field ammeter, as well as four circuit-breaker controllers. Each generator, with the low tension side of its bank of step-up transformers, is provided with three breakers, one in the main generator circuit connecting the generator to generator bus, one for connecting this generator bus to a main bus, and th

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necting the generator bus to the low-tension side of the step-up . With this arrangement under normal conditions each generator current to its own bank of step-up transformers, but in emergency or or any transformer can be connected to the low-tension bus,



ig. 11. Control Desk with Separate Frame for Instruments.

tionalized in the middle by means of an electrically operated the high-tension side each bank of transformers connects ngle breaker to a high-tension bus that is sectionalized in the eans of an electrically operated breaker. Two high-tension lines ach half of this sectioned bar.

nsions of Panels. — The smaller panels intended for use with ework are made either in single slabs and as a rule have a height of a width of either 22 inches or 32 inches, although some of the aller. As few of the smaller d-c. panels have to be made wider s or 24 inches and as 1¼ inches is ample thickness for a 24 by he thickness of 1¼ inches has been adopted as a standard for most -c. panels. In order to secure sufficient mechanical strength the s are made 1½ inches thick. As these wide panels are usually lternating-current generator panels this thickness of 1½ inches ly adopted as standard for a-c. panels. For heavier panels 2-inch ate have been adopted as standards for mechanical reasons. This quired for the heavy switches, circuit-breakers, etc., often furnished hboards. When a board has both a-c. and d-c. panels the thick- els is made the same.

d Edges. — The edges of all panels are usually beveled to appearance and to insure against chipping, as it is almost handle square-edged marble or slate slabs without injury. The re ordinarily beveled with a 45-degree bevel of either ⅜ inch or

ATIONS AND TESTS. — See article on *Switchgear Equipment ions* and *Standards of the A. I. E. E.*

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COSTS. — The cost of any particular type of s
summing up the costs of the various instruments,
this the cost of the framework, slabs and wiring.
are approximate only:

Gas pipe for framework	
2 by 3 by ¼-inch angle iron	
6 by 2-inch channel iron	
½ by 1⅜-inch strips	

Slabs only, without drilling

48 by 24 by 1¼-inch panel	
48 by 32 by 1½-inch panel	
90 by 24 by 2-inch panel	

The cost of drilling, wiring and erection ranges
total cost of the board erected complete. See also
ment for Power Stations.

BIBLIOGRAPHY. — Adams, C. C., *Switchbo*
Apparatus, Chicago; Andrews, L., *Electricity Co*
High and Low Tension Switchgear Design, New
Switches and Switchgear, New York; See also t
G. E. Rev., Electric Journal, etc.

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(*See also Circuit Breakers; Switchboards; Switchgear Equipions; Wiring of Buildings.*) A switch is a device for making ng connections in an electric circuit. Various types of knife, switches are used; some representative types are described

lequirements are (1) a switch must, when closed, carry the ut excessive drop, usually from 5 to 25 millivolts, or excessive ° C. temperature rise; (2) it must take care of overloads met nust be designed to prevent or render harmless any arcs that eing opened; (4) it must, when open, insulate all live parts otential of the circuit.

CHES.— The rules of the National Board of Fire Underknife switches advise for pure copper blades a current density of not over 75 amperes per square inch. The recommended between points of opposite polarity for various currents and n the accompanying table.

Inches between points of opposite polarity		
125 v. d-c.	250 v. d-c. 500 v. a-c.	600 v. d-c.
1¼	2¼	4½
2¼	2½	4½
2¾	2¾	4½
3	3	4½

es of Switches. — A switch closing a circuit only when on is called a single-throw switch; a switch closing a circuit her of two positions (e.g., up or down) is called a doublevitch closing only one side of a circuit (one blade) is called a one closing both sides (two blades) is called a double-pole bbreviations are used, such as S.P.S.T. for single-pole single- or double-pole double-throw.

ti-blade Knife Switches.— Up to 1000 amperes in capacity sually made with single blades. For larger capacity two or le are supplied in order to secure sufficient contact surface blades and jaws of abnormal width.

The smaller capacity switches are made both rear connected , while the larger switches are almost invariably made for p to approximately 1000 amperes the standard studs for hes are circular and the switch studs are attached to their ed on these circular studs. Additional nuts are provided onnections or terminals.

pacity switches employed on low-voltage boards, strap con- invariably used and to facilitate the employment of the he switch studs are frequently made laminated. A modiated studs employs copper studs cast under high pressure by conductivity of the cast studs is approximately 90 per cent r. With the laminated stud switches the laminations can be

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Knife Switches for A-C. Service. — Up to 800 able difference in the heating of knife switches on di For larger capacities it is found that for the same sary to rate lower for alternating-current. The co designs and different capacities, a typical case being of 3000 amperes (d-c.), 30 degrees; 2500 amperes, amperes, 60 cycles, 30 degrees; 2400 amperes (d-c.) 25 cycles, 20 degrees; 1800 amperes, 60 cycles, 20 The 30-degree rise is that covered both by the N and A.I.E.E. Rules.

Field Switches (Fig. 1). — A modification of the knife switch (q. v.) as shown in Fig. 2 is furnished connection with field circuits. These field switches single-pole or double-pole, single-throw or double-t provided with an auxiliary contact and extra jaw used for connecting a resistor across the field termin the field is disconnected from the source of supp field discharges through this resistor without any kick such as will occur on the sudden opening of a ductive circuit without such a device.

Auxiliary Breaks and Quick-break Attachm furnished with knife switches in many cases so as t impossible to draw a dangerous arc by opening t slowly. Fig. 2 shows a typical quick-break knife blade here carries auxiliary blades, which are atta a hinge and spring. When the switch is opened, the auxiliary blades are held in the jaws by friction until they are suddenly jerked out by the spring tension. A similar attachment is used on the field switch shown in Fig. 1.

Starting Switches. — A modification of the standard knife switch is the multi-point starting switch used occasionally for starting d-c. motors, or synchronous converters or motor-generator sets from the d-c. end. These multi-point starting switches consist usually of single-pole, single-throw switches with several break jaws connected to various steps of the starting resistor.

Disconnecting Switches. — In all high-tension circuits it is customary to install knife-type disconnecting switches for isolating feeders, oil circuit-breakers, etc., or for making various connections that do not have to be opened under the knife switches for 2500 volts or less are usually of soapstone, marble or similar material; for higher vo kinds are used to support the switch jaws. Up to necting switches are made for either front connectio but for higher voltages they are almost invariably only.

Fig. 3 shows a disconnecting switch built in ca amperes at 7500 and 15,000 volts, and up to 600 a up to and including 66,000. In this switch a corr insulator is used with the switch part attached to t the bottom of the insulator attached to a metal bas

or proves defective, it can readily be replaced without the necessity g the balance of the switch. Owing to the severe mechanical stresses the instant of short circuit on f large capacity, latches are on these disconnecting switches them being blown open.

ecting Switches on Post sulators. — For voltages of d above, it is customary to sconnecting switches mounted in posts of the built-up type a sufficient number of sections secure the voltage test desired, indoor or for outdoor service. ype of switch if an insulator amaged or defective, the units dily unbolted from the built- nd replaced by a new section.

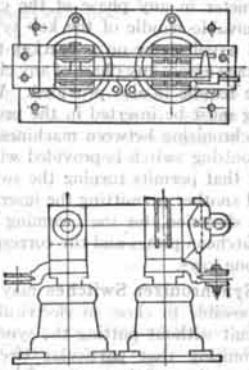


Fig. 3

SWITCHES are often used fically-operated devices such as field switches and circuit- In the type shown in Fig. 4 ing handle and direction dial ed on the front of the switchboard, while the contacts are back of and are made part of a drum-type controller. This construction en the d-c. operating voltage from the front of the board and readily

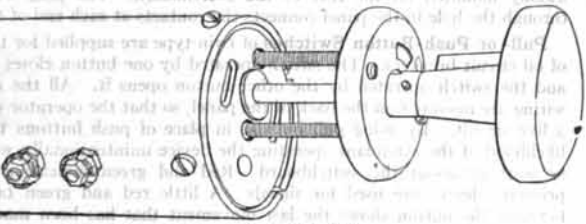


Fig. 4. Drum Control Switch

f for use on 550-volt control circuits. The handle is so designed urning to the trip position it can be pulled out in such a manner as t the control switch and extinguish the indicator lamps. For use ntrol switch lamp indicators with colored prisms are furnished.

WITCHES are commonly used for interrupting small currents at . They are particularly applicable for such uses as reading the oss various phases or circuits. By placing suitable receptacles on d feeder panels and using only one voltmeter plug switch, one n a suitable location can be used for reading the voltage across any circuit without the possibility of trouble from an attempt to con- more circuits to the voltmeter at the same time. Other types of nd plugs are used in connection with current transformers for con- uments into any phase of any circuit. By using suitable current l receptacles it is feasible to connect in testing meters for calibrat- hboard instruments without removing them from the board.

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The latest designs of instrument switches are bui attached or removable handles, depending on thei switch usually has an attached handle and the swit ammeter in any phase of the circuit. The voltme removable handle of the key type so that by havi and a voltmeter on a bracket the instrument can voltage across any phase of any circuit With the sy able handle is also provided. When synchronizing plug must be inserted in the proper receptacle and synchronizing between machines the escutcheon pla chronizing switch is provided with two slots, one pe key that permits turning the switch in one directio and another permitting the insertion of a key for tur site direction, for the incoming machine. Proper escutcheon plates and the corresponding pins on the wrong keys.

Synchronizer Switches may be fitted with auxi impossible to close an electrically-operated breaker circuit without putting the synchronizing plug in t chronizing that particular circuit. The tripping independent of the synchronizing receptacle so that out independently of the position of the plug.

Plug Switches for Arc Service are built in capac suitable for use on circuits up to 10,000 volts. Eac of fiber or similar material, with socket contacts at sisting of a metallic rod or tube with an insulating h usually mounted on the rear of the switchboard. through the hole in the panel connects the contacts

Pull- or Push-Button Switches of twin type are of oil circuit-breakers. The switch operated by one and the switch operated by the other button opens wiring are mounted on the back of the panel, so that a live circuit. By using pull buttons in place of p likelihood of the attendant operating the device uni or working about the switchboard. Red and gre prismatic lenses are used for signals. A little red between the button shows the last movement that the target shows one color and the indicating lamp the breaker has been tripped automatically.

Push-Button Switches with Signal Devices a former-type ground detectors, engine-room signal These are frequently arranged as the equivalent of mally maintained in one position by a spring to m and making other connections when pushed in by ha

Button and Snap Switches of various designs circuit (*see Wiring of Buildings*).

OIL SWITCH. — (*See Circuit Breakers.*) The drawn between the terms "oil switch" and "oil ci some cases the term "oil switch" is applied to a contacts that tend to remain closed, and the term "oi to a device with butt, brush, cone wedge or similar open and must be held closed by a toggle, latch c circuit-breaker" is the term usually employed.

END-CELL SWITCHES. — (*See Batteries, Storage.*)

COSTS. — Switches vary so much in design that it is impossible to give a comprehensive table of costs in a limited space. The following table gives the approximate range of (1922) prices of a few typical switches:

S. P. S. T.,	100–3000 amps., 600 volts.....	$3.50 to $130.00
S. P. D. T.,	100–3000 amps., 600 volts.....	5.00 to 200.00
D. P. S. T.,	100–3000 amps., 600 volts.....	6.50 to 235.00
D. P. D. T.,	100–3000 amps., 600 volts.....	9.00 to 360.00
S. P. D. T. Q. B.,	100–3000 amps., 600 volts.....	9.50 to 375.00
Disconnecting Switch,	15,000 V., 400 A.....	30.00
Disconnecting Switch,	37,500 V., 400 A.....	40.00
Disconnecting Switch,	73,000 V., 600 A.....	75.00
Disconnecting Switch,	115,000 V., 400 A.....	150.00
Simple Plug Switch.....		3.00
Simple Snap Switch.....		.50

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SWITCHGEAR EQUIPMENT FOR POWE

also Bus-bars; Circuit Breakers; Fuses; Lightning P Substations; Switches; Switchboards.) This article i practice in regard to the arrangement of the control in generating stations, transforming stations and c special building arrangements to suit the switching cussed.

In the earliest plants the switchgear, which then com plugs, fuses and lamps, was scattered around the stat hazard way, or possibly assembled on one of the wa space was allotted to it that could possibly be used for next step with increasing amount of auxiliary appar of the switchgear on a panel switchboard near the w was taken up by it. As stations grew still larger, pr had to be allotted to the switchgear, until in the m capacity plant, one portion of the building, or in som is assigned to the switchgear and designed especially f

As regards switchgear equipment power statio follows:

Generating stations distributing at generator v
With direct-control panel switchboard.....
With distant-control switchgear.....
Generating stations distributing through step-u
Step-down transformer stations:
Indoors.....
Outdoors.....
Converting stations:
In buildings.....
In movable cars.....

The switching requirements of the several classes following.

DIRECT-CONTROL SWITCHGEAR IN GEN

— Direct-control panel switchboards are usually inst ing, power and railway service of low voltage and m boards for such plants are of the panel type and may floor, on a platform or in a gallery. All the switchin directly on the panels of the switchboard. With s simple to locate the switchboard in such a manner a the amounts of connecting cables and similar materia tive position of the switchboards and generators.

The amount of space required and the amount of c needed in a direct-current railway generating station imum by arranging to have only one polarity, usually board, and to place the negative and equalizer busse conduit near the machine, locating equalizer and machine.

DISTANT-CONTROL SWITCHGEAR IN A-C TIONS DISTRIBUTING AT GENERATOR V

that distribute current at the generator voltage there for the bus-bars, oil circuit breakers and control app pally on the amount of space needed for this portion locations are: 1. at the end of the building; 2. at th 3. in a separate switch-house.

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of Switchgear. — The end of the building is a favorite location for ear when the number of feeders is such that this location provides ace for the breakers and the bus-bars, making due allowance for ture additions. With this arrangement it is customary in large ovide a number of galleries for the switching equipment. The is usually placed on one of the upper galleries so that the station an readily watch the operation of the machines which he is con-

e end of the building does not provide sufficient space the switch- ent is frequently located along one of the side walls, usually the from the boiler room in a steam station, or from the incoming pen- ydraulic station. The switching equipment when arranged in one eries along the side of the building can easily be extended, as the of the building provides for the switchgear proportionately with ailable for the generating equipment. With this arrangement it is mary to locate the generator breakers directly opposite the individ- s and to run the bus-bars the length of the station; the length of r leads will then be reduced to a minimum and it is sometimes possible conductors for these leads. The switchboard itself, if electrical provided, may be located either on one of the side galleries or at he building in such a position that the switchboard attendant can h the operation of the machines which he is controlling.

on of this scheme of utilizing the side walls is to provide a separate and to control all of the apparatus electrically from a switchboard building or from a switchboard in the switch-house as preferred.

s for Bus-bars and Circuit Breakers. — The arrangement of ng structures for bus-bars and circuit breakers is influenced chiefly ge and capacity of the circuits. For circuits of moderate capacity ts or less, mechanical control is usually employed, though electrical metimes used; for circuits of large capacity or of higher voltage ctrical control is practically universal.

tures for Mechanical Control. — Fig. 1 shows a typical arrange- nt mechanical control applied to circuit-breakers mounted on the metal framework. The view shows a section through a 2300-volt, rator circuit. Each circuit is provided with a 3-pole oil circuit- h can be connected to the three-phase bus-bars supported on the . Sprocket-operated face plates with suitable resistors are located ent to allow for the regulation of the voltage on the generators. and voltage transformers for the instruments are located back of a suitable framework or on the wall.

tures for Electrical Control of Moderate Capacity. — Fig. 2 on and the front and rear elevations of a part of the structure for breakers and bus-bars for the control of four 500-kw., 2300-volt, rators, nine 3-phase feeders and six single-phase feeders. Though and voltage of these machines would have permitted the use of l oil circuit-breakers, other considerations caused the adoption of ration for the breakers and of inclosed bus-bars. The relative be circuit-breakers, disconnecting switches, series transformers, rmers, bus-bars, etc., are indicated in the cut. The bus-bars of pper strap are supported on petticoat insulators, and porcelain e used for insulating the leads where they pass through the back ructure. The breakers here used are self-contained and all three he same compartment. The disconnecting switches are mounted apstone bases.

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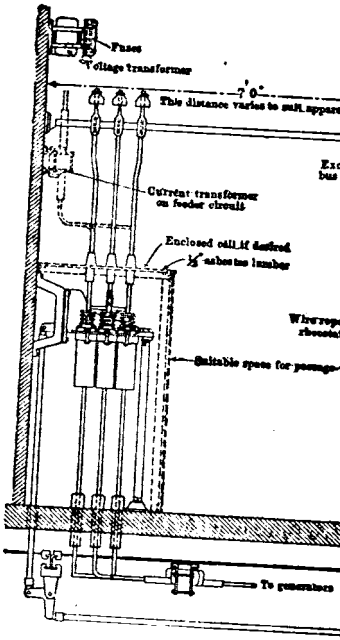


Fig. 1. Structure for Distant Control of 2300-vol

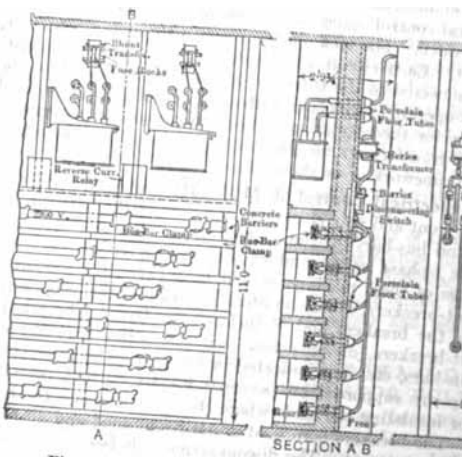


Fig. 2. Structure for Electrical Control of 2300-volt,

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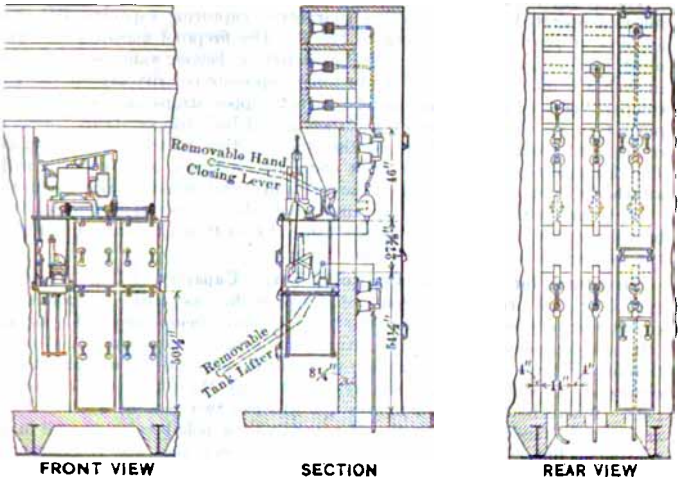
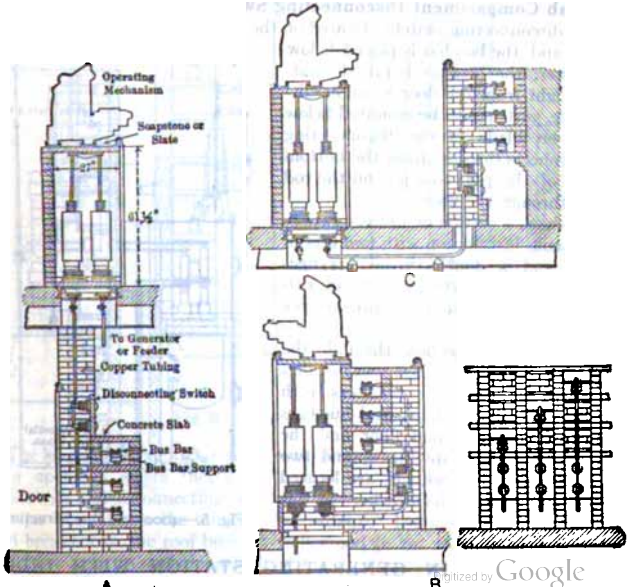


Fig. 3.—Structure for Top-connected 6600-volt Breakers



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Fig. 4.—Structure for Bottom-connected 11,200-volt Circuit Breakers

The front, rear, and side views of a structure solenoid operated breakers with a guaranteed ru amperes at 7500 volts are shown in Fig. 3. The ment, bus-bars, connections, etc., are separated by in such a manner that no two conductors of oppos compartment. The bus-bars and laminated copp pillar type insulators resting on the shelves and l connections from the bus-bars to the disconnect The disconnecting switches are front connected, m attached to a steel base located on the rear wall of t

With the type of breaker shown, employing solen brought out at the top of the breaker tanks, taken the connections can then be run either up or down.

Structures for Electrical Control of Large C typical way of arranging bottom connected, mote circuit-breakers for connecting to the bus-bars plac (*B*), or independent of (*C*), the structure containing tion of this breaker used particularly when the lead connection brought through the rear wall from pots. Where both leads are to run upwards the arranged in tandem so that the six pots of a thre continuous line. The breaker illustrated has 8-i rupturing capacity of 23,000 amperes at 7500 vo same type with 10-inch pots and a guaranteed ru amperes, and a still larger breaker with 12-inch pot capacity of 52,900 amperes at 7500 volts.

Sub Compartment Disconnecting Switch have the disconnecting switches located on the same breaker, and the bus-bar is placed below the breaker, the breaker is raised a sufficient height from the floor to allow disconnecting switches to be mounted below them. The blade of the disconnecting switch connects directly from the bottom terminal of the pots to a jaw on the rod running through the floor.

Fig. 5 shows a section of a heavy capacity 4000-volt installation with two sets of bus-bars and a double-throw arrangement carried out with two sets of disconnecting switches and one breaker per circuit.

Fig. 6 shows a section through the switching galleries of a 22,000-volt installation where the generator breakers with their disconnecting switches and bus-bars are located on the second floor and the feeder circuits, duplicate buses, and two sets of disconnecting switches are located on the first floor. The breakers in this installation are guaranteed capable of rupturing 5350 amperes at 25,000 volts.



Fig. 5

SWITCHGEAR IN GENERATING STA TRANSFORMERS. — Fig. 7 shows a sectional

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ntains four 16,000 h.p. vertical shaft water wheels driving 12,000 kv-a. 6600 lt generators, and four three-phase transformers. The leads from the gen-ators are taken through the breakers to the 6600-volt main bus, back from at bus through similar breakers to the low-tension side of the transformers. cross connection allows the generators to feed directly to the transformers.

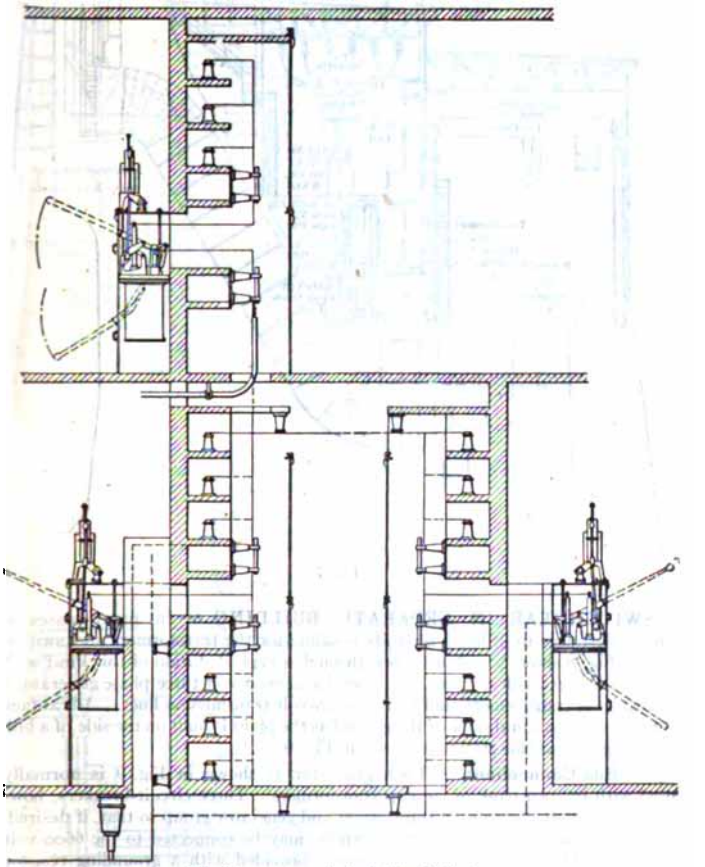


Fig. 6.—22,000-volt Switching Galleries

The leads from the high-tension side of the transformers are taken up through loor openings where they are attached between insulators, thence through choke coils and disconnecting switches to the high-tension breakers and to the high-ension bus. From the bus the current passes through disconnecting switches nd breakers to the roof bushings and so out to the lines. A grounding switch s located near these roof outlet bushings for grounding the high-tension circuit. The electrolytic arresters are located on the roof.

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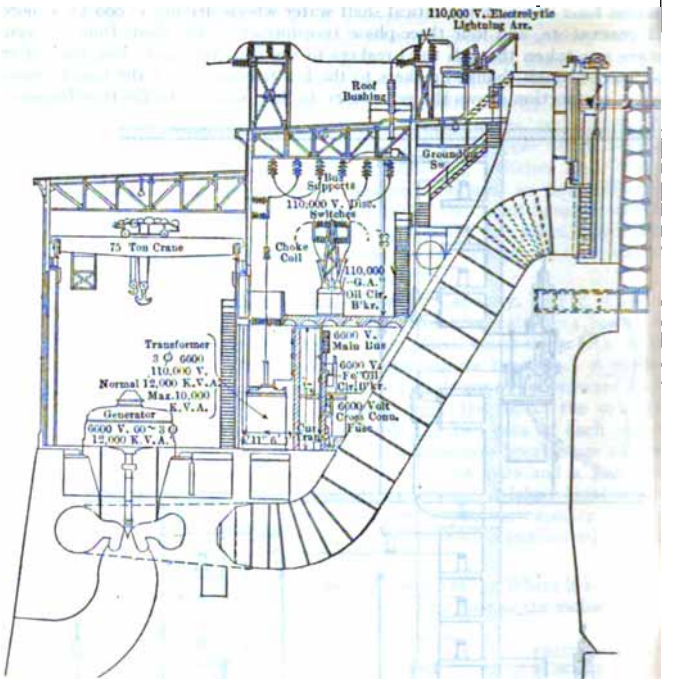


Fig. 7

SWITCHGEAR IN SEPARATE BUILDING. — In many cases it proves desirable to utilize a separate building for the transformers and switchgear. Fig. 8 shows a sectional view through a typical station of this kind with two 500-kw. 250-volt exciters, six 12,000-kv-a. 6600-volt three phase generators, six banks of transformers, and four 110,000-volt transmission lines. Advantage is taken of the natural slope of the ground as the plant is built on the side of a hill. The diagram for this station is shown in Fig. 9.

Bus Connections. — Each generator as shown in Fig. 9 is normally used with its own bank of step-up transformers. Three circuit-breakers, however, are provided with each transformer and generator group so that, if desired, any generator or any bank of transformers may be connected to the 6600-volt bus-bars. The low-tension neutral bus is provided with a grounding resistor and each generator is furnished with a single-pole, single-throw knife switch for connecting it to this grounding bus. In a similar manner the high-tension neutral bus is provided with a grounding resistor, and each bank of transformers is furnished with a single-pole, single-throw knife switch for connecting its neutral point to this ground bus.

Ventilation of Generators and Field Rheostats. — It should be noted that it is intended to locate directly opposite each machine a field-regulating panel containing electrically operated field rheostats and field switches, the

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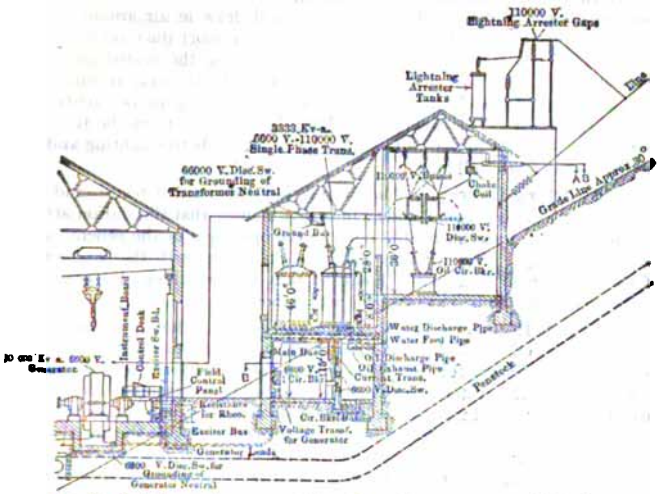


Fig. 8. Switchgear Arrangement for a 60,000-kv-a., 110,000-volt Hydro-electric Station

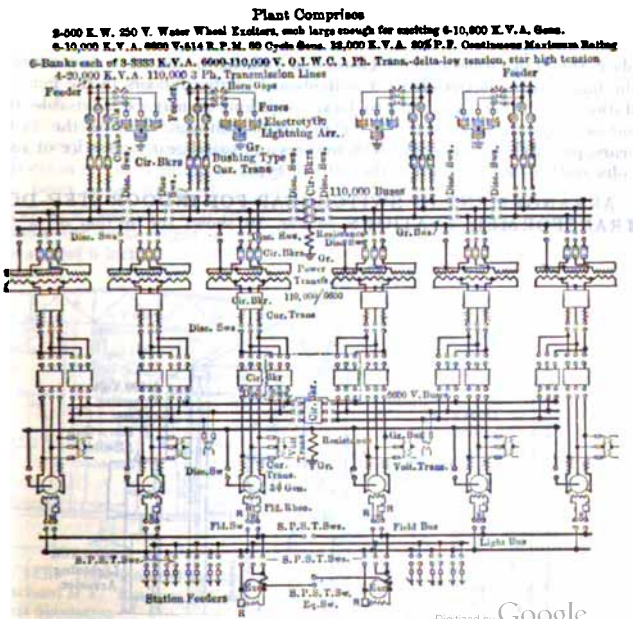


Fig. 9. Diagram of Connections for Plants

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grid resistors used with these electrically operated f
just outside the building. Each generator will dra
and discharge it at the bottom of the stator to a
the tail race. With this arrangement of dischargi
generators into the tail race and locating the fiel
generators outside the building, the question of se
greatly simplified. The generator building is separ
and switch house by about 20 feet in order to secur
ventilation for both buildings.

Switching Gallery. — The control desk, ins
switchboard are placed on a gallery in such a manne
standing at the desk can readily observe the opera
he is controlling. The switching gallery is on a le
of the transformer and switch house so that the
readily pass into the basement of the switch house.

Switch House. — The basement of the swi
cally operated oil circuit-breakers, bus-bars, discon
potential transformers for the 6600-volt generator a
well as the oil and water piping for the various tr
circuit breakers and bus-bars are inclosed in maso
110,000-volt circuit-breakers and bus-bars are open,
and expense of installing masonry compartments f
doubtful benefit to be obtained by such a course.
formers are arranged in one row and are mounted
with wheels in such a manner that any transform
low truck and then pulled outside the building, aft
oil pipes, low-tension and high-tension connections h

In many cases, even for generating stations, it h
place the transformers and high-tension switchgea
the high-tension devices from a switchboard locate
station. In other cases due to local conditions it
indoor apparatus, particularly for moderate volta
years, probably 80 per cent of transformers and swit
volts and above have been of the outdoor type.

ARRANGEMENT OF SWITCHGEAR FOR TRANSFORMER STATIONS. — Fig. 10 sho

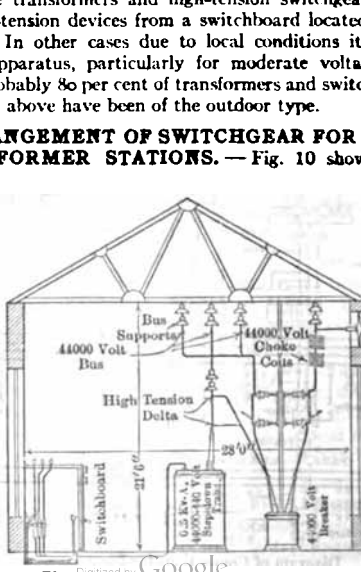


Fig. 10. 44,000-volt Step-down Transfor

n for the control of two 44,000-volt, 3-phase incoming lines, four of three 625-kv-a. single-phase step-down transformers, and a 00-volt feeder circuits. The 44,000-volt lightning arresters with o disconnecting switches are placed out of doors, and the circuit nsformers, disconnecting switches, and busses are located indoors he incoming leads pass through porcelain bushings in the walls to s and through disconnecting switches to the 44,000-volt breakers. reakers the current passes through other disconnecting switches volt bus-bar that is hung from the ceiling by means of suspension rom this bus the current passes through other disconnecting he circuit-breakers, and thence to the high-tension side of the nsformers.

arison of Top- and Bottom-connected Breakers and Closed iring (Fig. 11). — (*See also Bus-bars; Circuit Breakers.*) In order he difference in the design of the station made necessary by the -connected breakers and inclosed bus-bars for the high-tension 11A, 11B, and 11C show designs of switching equip- control of 66,000-volt, down transformers (each supplying current to the ,200-volt bus-bars.

hows the general arrange- circuit breakers, bus-bars, etc., using bottom-con- rs of standard design and ocate the 66,000-volt bus- ir disconnecting switches loor. In order to provide room for lifting the coils of a transformer case, it slide the transformer into y and run it along to the of the building where the raised under the control a manner as to provide the necessary headroom. With this he total height of the building from the floor line to the roof t 6 inches.

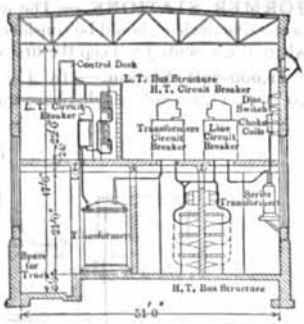


Fig. 11A. Bottom-connected Breakers, Inclosed H.T. Bus-bars, 66,000-volt Substation



Top-connected Breakers, H.T. Bus-bars, 66,000- tation

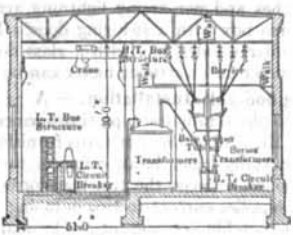


Fig. 11C. Top-connected Breakers, Open H.T. Bus-bars, 66,000-volt Substation

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Fig. 11B shows the arrangement necessary if it i
breakers and still inclose the 66,000-volt bus-b
the 66,000-volt bus-bars, as well as the 13,200-vo
bus-bars, and the control desk, are placed on the
volt breakers themselves with their disconnecting
main floor near the transformers. With this a
can have its coils or iron removed as soon as it is s
building arranged in this manner requires a heig
floor line to the roof girders and requires a secon
Fig. 11A.

Fig. 11C shows the arrangement of this sam
breakers and open bus-bars and wiring for the 66
arrangement there is no necessity of a second floo
is greatly reduced as the distance from the floor
girders is only 30 feet.

**ARRANGEMENT OF SWITCHGEAR F
FORMER STATIONS.** — The use of outdoor
protective devices should be considered when desig
where it is essential to keep the first cost of the ins

11,000-volt Station. — In Fig. 12 is show
50-kv-a., 11,000-volt, single-phase transformers wit

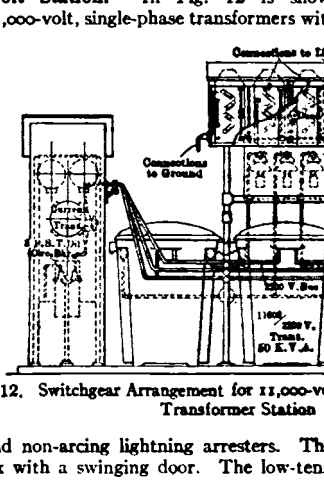


Fig. 12. Switchgear Arrangement for 11,000-v
Transformer Station

switches and non-arcing lightning arresters. Th
wooden box with a swinging door. The low-ten
a similar wooden box with a glass door so that
voltmeter and watthour meter can be taken with

33,000-volt Installation. — A 33,000-volt in
single-phase radiator type transformers and one
Fig. 13. All of the apparatus furnished is suitabl
Each transformer bank connects through its br
sectioned between the two transformers, and eac
bus supplies current to two outgoing feeder circu
their switching equipment are located immediatel
ing station and the low-tension breakers and co
station.

When installing outdoor equipment of this char

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nd it is advisable to obtain samples of the oil from the bottom circuit-breaker tanks at regular intervals, and if any evidence

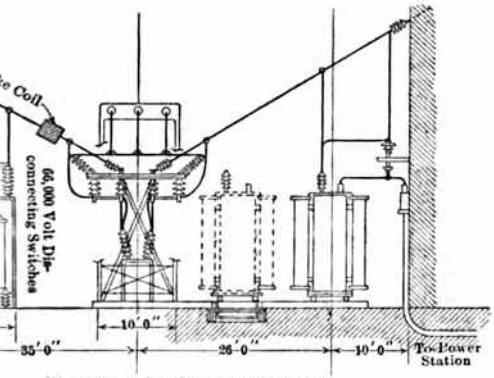


Fig. 13.—33-kv. Outdoor Switchyard

ount of carbon appears in the oil, the oil should be immediately d.

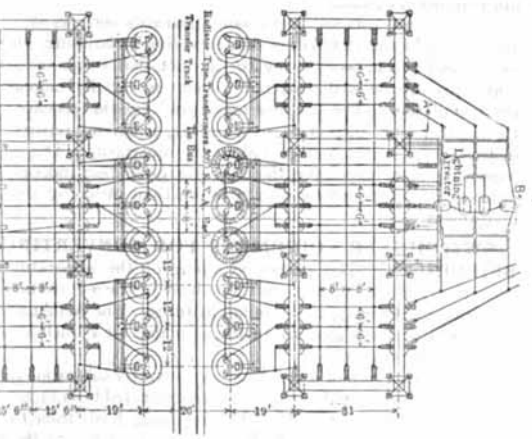


Fig. 14.—110-kv. Outdoor Switchyard

Installation. — Fig. 14 shows in plan view a typical 110-kv., mer and switching station with four 110-kv. lines, six banks of ch of three 5,000 kv-a. capacity of the radiator type. At this ension switchgear is located in a switch-house but all of the high- us is outdoor. The high tension leads from the transformers pass nects and breakers to either of two sets of bus-bars.

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154,000-volt Installation. — Fig. 15 shows yard for an installation of six banks of step-up t three 7500 kv-a. units with four 154 kv. outgoi yard is close to a large hydro-electric generating stat switchgear is located in that station. In the high former bank, and each line circuit is provided w sets of disconnecting switches so that it may be co two sets of busses that are sectioned in the middle with its steel work and special weatherproof equip

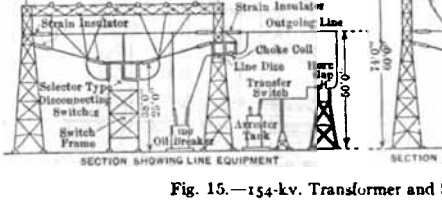


Fig. 15.—154-kv. Transformer and

about 13 per cent less than the corresponding building to house it.

Advantages and Disadvantages of Outdoor illustrations of outdoor stations indicate the tendenc tions. The advantages of outdoor apparatus suc cheapening of the installation due to saving in bui in life and fire hazard, owing to the fact that in apparatus can be well scattered without material the installation. The disadvantages are: (1) the the weather when inspecting, overhauling, or makin of trespassers to themselves and to the apparatus somewhat more expensive than the corresponding difference in cost will be usually more than offse investment.

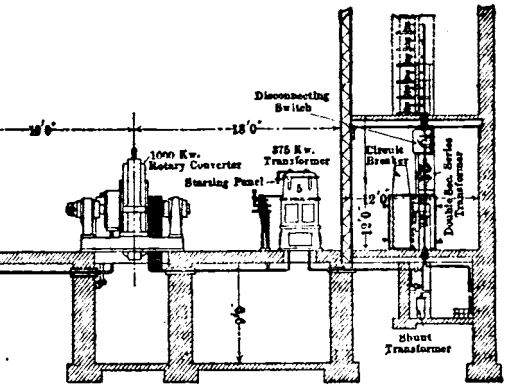
SWITCHGEAR EQUIPMENT FOR CONV BUILDINGS. — The proper grouping of the a converter station depends on the voltage of the a- type of transformers, and similar features. The provided the shape and size of the available lot is design of the station.

The sectional view of a synchronous-converter sub 6-phase converters with air-blast transformers fed fr circuits is shown in Fig. 16. The incoming leads through an oil breaker and disconnecting switche located on a gallery. Provision is made for an addi additional set of disconnecting switches to be inst any breaker may be connected to either of the two

The circuits from these bus-bars pass back t switches and breakers to the high-tension termina the air-blast transformers. The low-tension lead to a starting panel provided with double-throw sw ages to be impressed on the converter for the purpo

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The converters are provided with series fields on the negative



rangement of Switchgear Equipment in Rotary Converter Station

nd equalizer switches are placed on a pedestal at the machine, e and equalizer busses run on a bracket in the basement. The nn to the panel board near the left-hand wall and the positive the back of this board. The railway feeders are run out through ıcts. All of the high-tension a-c. circuits are provided with ated breakers controlled from the main switchboards. It will e entire design of this station hinges on the proper arrangement equipment.

AR EQUIPMENT FOR PORTABLE CONVERTING Many interurban electric railways have portable substations t cars and arranged for ready transportation to whatever point mporary service. A typical installation of this kind consists of converter; oil-insulated, self-cooling transformers; and the switchboard, high-tension oil circuit breaker, and lightning-es. The apparatus may be so arranged in the car that the enient to the handle of the high-tension oil breaker, the panel the commutator end of the synchronous converter.

TIONS FOR SWITCHGEAR EQUIPMENT. — The great ions to be met and the numerous ways of meeting each con-board work make it impossible to write specifications in the uitable for general use. This specification is therefore in the f memoranda to assist in writing a more specific one. (*See also Specifications.*) The items are ararnged in alphabetical order.

urpose. Material. Method of support. Dimensions.

ontrol. — Number of cells. Discharge rate. Style of rack. osed copper from acid fumes. Condition of cells when handed r (whether charged or not).

ee Switchboard).

Material. Conductivity. Style of joints. Minimum length ion to be supported in. Protection, if required, in case of d H. T. bus.

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Bus-bar Insulators, H. T. — Type. **Material.**

Bus-bars, Insulators and Supports, L. T. —

Bus-bar Compartment, H. T. — Material. lithic or in blocks as described. State quality quality and color. Style of windows, if any. Styl

Circuit Breakers, D-C. — Style. **Voltage.** R Description of current-break features. Overload r features. Device to sound gong when circuit bre may be ruptured without injury to the contacts.

Conduits in Floors and Walls. — Size. Finis tractor is notified that floor is ready. Junction boxe of stated finish and shall be provided with a neat floor. Style of pipe joint to be such that any sin without disturbing others.

Crane Service Connection. — Apparatus requ

False Floors. — Material of slabs. Descriptio piers for supporting slabs. Style of fastening betw

Gongs. — Type and location. To what apparat

Ground Connections. — General description.

High-potential Tests. — After installation, the be subjected to the potential tests specified in th being performed in accordance with the Standardiz Institute of Electrical Engineers. (Give table o classes of apparatus and wiring, preferably from S *Rules*, q.v.)

Instruments. — Type. Finish. **Rating and** racy at various parts of the scale to be within sta cation and style of terminals. Style, rating and Magnetic shielding.

Insulation (*see Insulating Materials*).

Lightning Arrester Equipment. — **Type and** parts. Removability of all parts which may be inj Switches for disconnecting arresters from line. D and ground connections. Choke coils. **Barriers.**

Name Plates. — Description. Dimensions.

Relays. — Style. Location. Function.

Rotary-converter Starting Accessories. Met tus pertaining thereto.

Station Shunt. — Style. Location. Whether Rating and temperature rise.

Switchboards. — Purpose. Material and color. or upright. Number of sections per panel. Style and finish (should not be painted if they are to b bevel. Barriers: material, size and finish. Illumi

Switches, H. T., Electrically Operated. — S Voltage. Rating and temperature rise. Accessib tion of concrete or brick compartment. Descriptio Style of doors. Structure in base or elsewhere Voltage limits between which control apparatus Device to indicate positively at the controlling boa open or closed. Device to sound gong when oil sw to be supplied.

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Oil, Hand-operated. — Style. Number of phases. Voltage. mperature rise. Location.

Knife or Toggle, Hand-operated. — Style and material. les and throws. Voltage. Rating and temperature rise. Quick , if required. Current density in metal and at contacts shall not l value. With or without base, and style of base, if any. Front nals. Style of terminals. Long-handled hooks for h.t. knife

nd Circuit Breakers, L.T., Electrically Operated. — Circuit *lso Circuit Breakers, D.C.*). Switches (*see also Switches, H.T.*). cate positively at control board whether switch is open or closed. between which control apparatus will operate sucessfully.

rs for Instruments. — Style. Ratio. Rating and temperature um permissible percentage error in ratio.

wer Circuits. — Use. Location. Shall be clamped so that e dislodged should any joint or terminal become loose. Descrip- ion where cables pass through floors or walls. Tagging with uit. Conductivity. Size or carrying capacity. Conductivity rminals. Style of insulation.

Control and Instruments. — Use. Location. Accordance nances and rules of "National Board of Fire Underwriters." onductor shall be tagged with numbered tags of stated material tened with brass wire. Wires which it is inadvisable to keep e in different pipes as directed by the Engineer. Size. Style

t is impossible to give reasonably accurate figures upon the cost tch-gear equipment because of the large number of independent each case, such as type of station, voltage, number of generators, rmers and lines, single-throw or double-throw switching arrange-

APHY. — See bibliography under *Switches*.

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SYNCHRONIZERS AND SYNCHROS

nating Currents; Converters, Synchronous; Generato
Stations; Substations; Switchgear Equipment for

principal functions of any synchronizing device are
circuits to which it is connected are operating at
when the voltages of the two circuits are in phase
ages of the two circuits must also be equal in effec
termined by means of voltmeters connected to th
of synchronizing is simplified if the synchronizer is
to be synchronized is operating at a frequency low
system to which it is to be connected.

The name "synchroscope" is usually applied to
to indicating synchronism, shows whether the mach
or slow (*see Standardization Rules of the A.I.E.E.*)
is used in a broader sense for any kind of synchro

Synchronizing Lamps. — The simplest form
two incandescent lamps shunted around the mai
machine to the bus-bars; see Fig. 12A, p. 669. E
and phase between the bus-bars and the machin
indicated by continued darkness of the lamps. Fo
arrangement may be used, if the lamps are conn
phases of the two machines which are to be brough
other. If the machines are not in synchronism t
brightness of the lamps will be proportional to the
of the two machines. The lamps do not show wh
too fast or too slow, nor is the point of exact sync
cated, as it requires an appreciable voltage to ca
latter difficulty may be avoided in the case of single
the connections shown in Fig. 12B, p. 669; when
they indicate synchronism when at maximum brig

It has been shown by Robbins (Elec. World, V
chronizing "dark" is to be preferred to synchroniz
that incandescent lamps require an appreciable fra
to glow perceptibly. Tungsten lamps respond to
of rated voltage than carbon lamps, and are ther
chronizing dark, while carbon lamps are preferable

Use of Transformers with Synchronizing
frequently used in connection with the lamp.
transformers is to have the primary of one connect
machine, and the primary of the other connected a
windings are connected in series with the lamp.
may be arranged so as to have either darkness o
instant of zero phase displacement between the
age of the machine. Instead of using two separat
former with two primary windings and one seconda
a transformer is called a "synchronizing transfor
are usually connected to give full voltage across

Siemens and Halske Three-phase Synchron
lamps L_1, L_2 and L_3 are connected between the
of the machine and the bus-bars B_1, B_2 and B_3.
corresponding phases, that is, between A_1 and
between A_2 and B_3 and lamp L_3 is connected betw
will be reached when L_1 remains dark; L_2 and L

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e falls out of step, the lamps will successively grow bright and
on, no two lamps being in darkness or at maximum brightness at
, i.e., the light will appear to travel from one lamp to another at
d and in a definite direction. The speed of rotation of the light is
o the difference of frequency between the voltage of the bus-bars
e machine. The direction in which the light appears to travel
her the frequency of the machine is greater or less than that of
For high-tension circuits, potential transformers are required.
tatic synchronism indicator differs from the preceding arrange-
electrostatic "glowers" instead of lamps. These glowers are
he lines to be synchronized through the electrostatic capacity of
tors. This arrangement dispenses with the use of potential

ng with a Voltmeter. — Instead of lamps, a dead-beat volt-
imes used for synchronizing. When connections are made for
such as would be made for synchronizing "dark" with lamps,
iculty that a-c. voltmeters are very insensitive at the lower part
To overcome this, it has been suggested by Keinath (E. T. Z.,
455), to replace the wire resistor of an a.c. voltmeter by a metal-
Such a lamp when cold has only about one-tenth of the resist-
and thus the sensitivity of the voltmeter for small voltages is
d. When the machines are in opposition, so that the voltmeter
he sum of their voltages, the greatly increased resistance of the
voltmeter current to a safe value.

oscopes. — Dial synchroscopes are similar in construction to
icators (q.v.), but are connected between the two circuits which
t into synchronism. They are designed to indicate by a movable
the machine to be synchronized is running too fast or too slow,
n synchronism with the circuit to which it is to be connected.

Type. — A fixed coil is connected through a resistor across the
se circuits across one phase. The movable coil is connected
nser to the terminals of the machine to be synchronized, and
in a position at right angles to the fixed coil by means of a
ill be no torque acting on the movable coil when the machine
are either exactly in phase or 180° out of phase with respect
cause in either case the currents in the fixed and movable coils
e. When the two circuits are not in synchronism, the pointer
novable element will swing back and forth over the scale. In
ish the point of synchronism from that of 180° phase dis-
nslucent glass scale is placed in front of the pointer, the scale
by a lamp connected to the low-tension side of a "synchroniz-
which causes the lamp to be lighted when coincidence of phase
and bus occurs. Hence the pointer is visible only during
g, i.e., it will appear to rotate in one direction; the direction
tes whether the machine is fast or slow.
t is applicable to single-phase as well as polyphase circuits,
nnecessary to indicate synchronism of more than one phase
The moving-coil synchroscope is ordinarily used with trans-
the line voltage down to 110 volts.

vane Type. — This instrument is similar to the moving-vane
tor meter (q.v.). The movable iron vane is magnetized by
connected across the machine to be synchronized. A rotat-
ced by passing current from the bus-bars through a split-
two fixed coils placed nearly 90° apart. The pointer indicates

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at any instant the phase displacement between the voltages of bus-bars and machine. The speed and direction of its rotation depends on the difference in frequency of the two circuits. When exact synchronism is reached the pointer will remain at rest in a vertical position. The instrument is usually connected through potential transformers; on polyphase circuits only one phase is used.

Lincoln Synchroscope. — This instrument has a rotating iron core carrying two coils placed nearly 90° apart; one coil is connected through a resistance across the other through an inductance, both being supplied from the machine to be synchronized. A bipolar, laminated iron field is magnetized by means of a coil connected to the bus-bars. The operation of this instrument is similar to that of the moving-coil type of single-phase power-factor meter. A pointer attached to the moving system indicates at every instant the difference of phase angle, as well as the approximate difference of frequency, between the voltages of the bus-bars and that of the machine to be synchronized. The current is led into the armature coils through slip rings as the armature is free to revolve. These instruments are furnished for direct connection to circuits of 110 or 220 volts; other circuits require transformers.

Weston Synchroscope. — This consists of an electrodynamometer instrument having the fixed coils connected to the buses through a non-inductive resistance and the moving coil to the incoming machine through a condenser. When the voltage of the machine is either in phase with or in opposition with the bus voltage no torque is exerted on the moving coil, and the pointer is vertical. For any other phase relation the pointer will be deflected to right or to left when the incoming machine is ahead or behind. The pointer is back of a translucent screen, and only its shadow, cast by a synchronizing lamp, can be seen. Thus when the shadow is seen to be vertical, the incoming machine is in step and when the machine is too fast or too slow the shadow appears to rotate in the clockwise or counter-clockwise direction respectively.

Use of Reactance in Synchronizing. — Synchronous machines may be connected to the bus through suitable current-limiting reactors, and brought up to speed by an auxiliary motor. They will synchronize after a few oscillations. With large machines, considerable current rushes will occur when the reactors are short-circuited. Osnos has described (Elektrotechnik und Maschinenbau, Vol. 19, p. 29, 1917), the use of reactors having an auxiliary d-c. winding which may be connected in the field circuit. The field current is very small at starting, and as it increases the d-c. flux in the reactors reduces their reactance gradually to a value permitting the machine to synchronize as it approaches normal voltage. The reactors may then cut out of circuit without disturbance.

COSTS. — A moving-coil synchroscope costs approximately $80, a polyphase moving-vane synchroscope costs approximately $70; a Lincoln synchroscope for voltages of from 110 to 220 costs from $55 to $65; transformers and accessories are extra in all cases. Only one synchroscope or synchronizer is required in a station, although a spare instrument is usually installed. (1922 prices.)

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PH INSTRUMENTS AND APPARATUS. — (*See also nication; Telegraph Lines; Telegraph Systems.*) The more impor- nts and apparatus used in the various systems of telegraphy are *n.*

A telegraph key is essentially a switch for opening and closing a us types of keys are in use.

Morse Key (Fig. 1). — The knob end of the lever is normally s to open the key by an adjustable coiled spring. The auxiliary nstitutes the "circuit closer" by it of the line is kept closed, through the key is not in use.



Fig. 1. Standard Morse Key

ng Key. — While the key of the ustrated in Fig. 1 is still standard, ms, having a sidewise rather than n motion of the lever, have come e. One type of these, known as the double-acting key, has its arranged to swing in a horizontal arc between two stationary The key lever normally stands clear of both points, leaving the movement either to the right or left will close the circuit.

Another type of key is represented by such instruments as which are more properly semi-automatic transmitters. The ey lever in this is similar to that of the double-acting key just ver normally standing in the middle or open position. When d to the left, it closes the circuit in the ordinary way to make ushed to the right, a vibratory reed is set in motion, which opens ircuit rapidly to form a succession of dots, the number of dots by the length of time the key is held in this position. By this tor is relieved of the muscular effort of rapidly vibrating the .

Paralysis. — The objects of the double-acting key and of the ther similar transmitters are, in the main, twofold: To relieve malady known as "operator's paralysis" or "loss of grip," s follows long continued use of the ordinary key; and to d of transmission.

C TRANSMITTERS. — (*See also Telegraph Systems.*) The utomatic systems usually employ a paper tape, perforated in the code to be sent. This tape, so prepared, is caused, by ng rollers, to pass rapidly through the transmitter, the perfo- s they pass to permit electrical contacts to be made which mpulses to the line.

(Fig. 2). — A standard form of in Fig. 2. The winding of the connected directly between the own on the base of the instru- nature is attached to a lever nions in a fixed support. The provided for the lever permit a n movement of its free end, the ent being caused by the pull of , and the upward one by the force of an adjustable retractile ged construction of the armature lever and its co-operating to produce the necessary loudness and quality of sound.

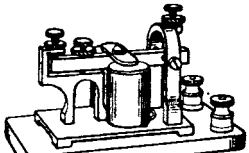


Fig. 2. Morse Sounder

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This, with the heavy retractile spring necessary for the prompt return m ment of the lever, makes the instrument require more energy for its oper than can usually be delivered to it directly over the line wire. On this acc the sounder magnet is usually placed in a local circuit, which is in turn contr by the more sensitive relay, the magnet of which is placed directly in the lin

When used in local circuits sounders usually have a magnet resistanc about 4 ohms, and require about ¼ ampere for their proper operation. Wh the sounder magnet is placed directly in the line, it is termed a main line sou and differs in no respect from the local sounder except that its magnet is wo to about 20 ohms.

RELAYS. — Two kinds of telegraph relays are employed; the ordinar Morse relay, and the polarized relay. The armature of a Morse relay al moves in the same direction irrespective of the direction of the current impu while the armature of a polarized relay moves in one direction for a posi impulse, and in the opposite direction for a negative impulse.

Morse Relay (Fig. 3). — The Morse relay has the same essential p as the sounder, with the addition of a pair of contacts closed by the arma lever when in its attracted position. The armature lever is usually mounted vertically, and is made light in construction so as to be capable of the necessary rapid to and fro movements with a minimum expenditure of energy. The retractile spring is light and delicately adjustable. An extra pair of binding posts is added to form the terminals of the local circuit, these binding posts being wired to the armature and the magnet frame, respectively, so that the circuit between them will be closed upon attraction of the armature. The back contact of the relay is non-conduct so as to avoid closing the circuit when the armature is released. A typ form of relay, known as the "pony relay," is shown in Fig. 3.

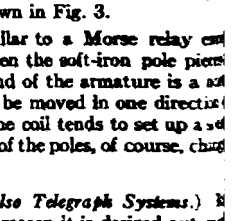


Fig. 3. Morse Relay

Polarized Relay. — A polarized relay is similar to a Morse relay ex that the end of the armature which plays between the soft-iron pole piece permanently magnetized. For example, if this end of the armature is a n magnetic pole, then, obviously, the armature will be moved in one direction the other, according as the magnetizing force of the coil tends to set up a n pole in one or the other of the poles. The polarity of the poles, of course, chan with the direction of the current in the coil.

RECORDERS OR REGISTERS. — (*See also Telegraph Systems.*) R corders or registers are used only where for some reason it is desired autom cally to record a message. Simple forms of comparatively slow speed regis are used in connection with district telegraph messenger and fire alarm telegr service. More elaborate high speed recorders are used in connection with au matic and printing systems. A special form of recorder, known as a si recorder, is used on submarine lines.

Slow Speed Registers. — The paper upon which the message is to recorded is a narrow strip of tape, carried on a reel. A clock-work mo is provided for moving the tape at uniform rate under the recording pe stylus. The receiving magnet of the register is placed in a local circuit co trolled by a relay in the line, and this magnet, when attracted, serves eit to move the pen or stylus against the tape or the tape against the pe stylus, in either case resulting in a mark upon the tape. Some registers re by merely embossing the tape; others by marking thereon with a pen or pe and still others by actually punching holes in the tape.

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peed Recorders. — In very high speed automatic and printing eiving devices have been developed giving a record in ink on ordi-, or a record on a sensitized paper, or in ordinary print. For a of the more important printing recorders see below under *Telegraph*

nical Recorders. — For very high speed work with non-printing he chemical recorder has been generally found the most satisfactory. ape is impregnated with a solution of some unstable chemical com- will easily be decomposed upon the passage through it of an electric which, either by changes within itself or by combination with the he pen through which the current passes, will cause a definite dis- the tape upon the passage of the current.

n sensitizing solution is formed of 5 parts of prussiate of potash, ammonic nitrate, and 100 parts of water. Under electric decom- solution sets free an acid which attacks the iron of the pen, leaving on the paper.

Recorder. — The high electrostatic capacity of long submarine necessary some modification of the methods ordinarily employed work. This high capacity results in the variations in the signaling less sharply defined than on land lines. The receiving apparatus es must, therefore, be responsive to minute variations in current xtent as to preclude the use of the responsive devices employed

recorder is merely a special form of recording galvanometer. The proper is of the D'Arsonval or swinging coil type. The motion imparted to a very light glass tube bent to form a siphon and sus- its long end opposite the receiving tape and its short end dipping ank of ink. The siphon moves across the width of the tape, the the tape being agitated so as to be nearly frictionless. Displace- record line to the left of an imaginary zero line represent dots, ight, dasbes. The Continental code is universally employed when rder is used.

APH REPEATERS. — When, for any reason, it is desired to ages from one line to another line without manual retransmission, repeater is used. By its use lines of excessive length may be a consequent increase of speed may be attained. Also, the en useful in automatically transmitting messages from a through le circuit.

natic or "Button" Repeater (Figs. 4 and 5). — A fundamen- of the repeater may be gained from Fig. 4, where a relay magnet

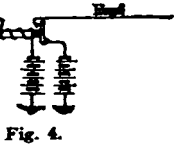


Fig. 4.

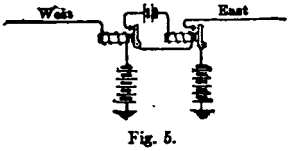


Fig. 5.

line causes an armature to act as a key to make and break the his conception may be carried a step farther by considering Fig. 5, magnet in the West line receives impulses from the distant West ontrols a local circuit containing a battery and a second relay latter causes its armature to act as a key in transmitting signals

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to the East line. From these two figures it is obvious that such a repeating scheme would transmit in one direction only, providing no facilities for transmitting from East to West.

The "button repeater" of early telegraph history consisted practically of two such sets of relays as are shown in Fig. 5, these sets being arranged for transmission in opposite directions. Only one set of relays could be kept connected to the line, for when both are connected in, the impulses sent out from the repeating station on, say, the West line react on the line relay of that line at the repeating station in such way as to act through its local circuit to send impulses back on the East line. This difficulty was overcome in the button repeater by providing a button switch, operated by an attendant at the repeater station, this switch being thrown manually in one direction or the other, according to the direction of transmission desired.

Automatic Repeaters. — The necessity of an attendant for the purpose of working the switch of a repeater has long since been overcome by the production of the so-called automatic repeaters, of which there are many forms. In these the arrangement is such as to automatically prevent the transmitter of the line that is being repeated into from reacting to make and break the line over which the signals are initially sent.

The Milliken Repeater (Fig. 6). — This is one of the most common of the automatic repeaters for the simple Morse system. Its action may be

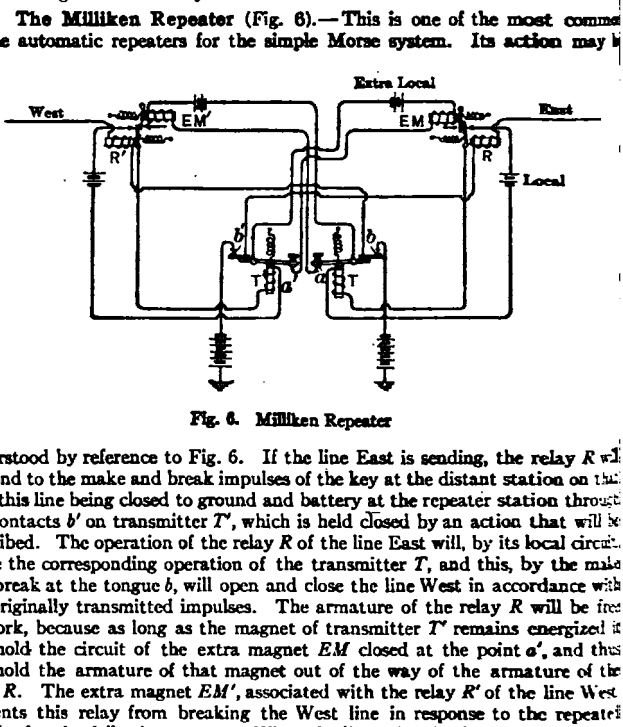


Fig. 6. Milliken Repeater

understood by reference to Fig. 6. If the line East is sending, the relay R will respond to the make and break impulses of the key at the distant station on this line, this line being closed to ground and battery at the repeater station through the contacts b' on transmitter T', which is held closed by an action that will be described. The operation of the relay R of the line East will, by its local circuit, cause the corresponding operation of the transmitter T, and this, by the make and break at the tongue b, will open and close the line West in accordance with the originally transmitted impulses. The armature of the relay R will be free to work, because as long as the magnet of transmitter T' remains energized it will hold the circuit of the extra magnet EM closed at the point a', and thus will hold the armature of that magnet out of the way of the armature of the relay R. The extra magnet EM', associated with the relay R' of the line West, prevents this relay from breaking the West line in response to the repeated signals, for the following reason. When the line West is closed by the transmitter T, the current through the relay R' holds its armature attracted. When

st is opened, however, by the transmitter T, the circuit of the extra
' is also opened by this transmitter, and the retractile spring of the
et prevents the armature of the relay R' from falling back. In this
relay of the West line cannot react on its own transmitter to cause
breaks in the transmitting line. When the operator at the distant
he West line breaks, the relay R' is then permitted to open and thus
ansmitter T' to open the line East.

lex and Quadruplex Repeaters. — Automatic repeaters are
for duplex and quadruplex systems than those already described
wire working. The reason for this is that in the duplex or quadru-
smission from a given sending operator is always to a corresponding
rator, and — as between these operators — it is never in the reverse
Hence, a one-way repeater only is required for any one of the several
transmissions. It therefore suffices to place the transmitter at
station under the control of the neutral or polar relays of the duplex
x, the repeating operation for each set being in one direction

T SUPPLY. — Either a battery or a dynamo may be used to
rrent required for telegraph transmission.

attery. — The gravity battery was once almost universally used
current in telegraph systems. It is still largely used on unim-
and in small offices where it is not economical to employ machine
secondary batteries.

attery. — The storage battery, on account of its extremely low
ance, is capable of handling any desired number of lines in parallel,
the use of the so-called "universal battery system," in which a
, with one pole
ves the line wires
pped off from the
uitable resistances
in the lines of
ce, if desired, to
r the variation in
ng the lines. One
used, would not
office, however,
various systems
quadruplex work-
sary to send cur-

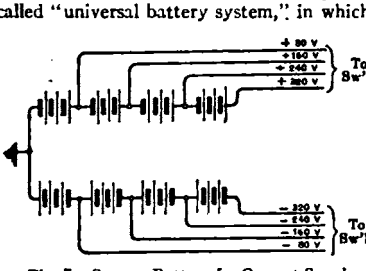


Fig. 7. Storage Battery for Current Supply

ite polarity to line, thus making necessary the use of another
s opposite pole grounded. Usually also a reserve is provided
ese batteries, so that one can be used while another is being

shown an arrangement of storage battery supply that provides
f voltage of either polarity in an obvious manner. By using
his arrangement, one set may be used while the other is being

o. — The dynamo has generally supplanted both the primary
batteries in all offices large enough to warrant its use. In Fig. 8
gement employed by the Western Union Telegraph Company
this five machines constitute a set, their armatures being
ries, taps being made as indicated to give the required volt-
ese machines are separately excited except the fifth, which

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latter is a shunt machine and furnishes current not only for line supply b also for exciting the fields of all the other machines. Each field circuit provided with a separate rheostat *R* for varying the field strength. Anoth set like this is employed to furnish currents of the opposite polarity, and a another set of five machines is employed as a reserve, this being so arranged th

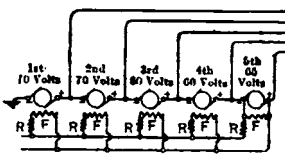


Fig. 8. Western Union Dynamo Arrangement

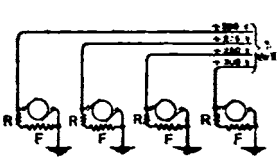


Fig. 9. Postal Dynamo Arrangem

it may be made to generate either positive or negative according to which of t regular sets it is to replace. The dynamo arrangement employed by the Pos Telegraph-Cable Company is shown in Fig. 9.

TELEGRAPH SWITCHBOARDS (Fig. 10). — Telegraph switchboa were the precursors of the vastly more complicated telephone switchboar The telegraph switchboards which have been most commonly used in America are of two types — the "strap and disc" and the "cross-bar."

A simple "strap and disc switchboard" with its connections is shown in Fig. 10. The lines terminate in the vertical straps and the instrument circuits, each including key and relay, terminate in the horizontal rows of discs, the discs in each row being connected together, as indicated by the dotted line. This figure also shows a typical method of line and instrument protection.

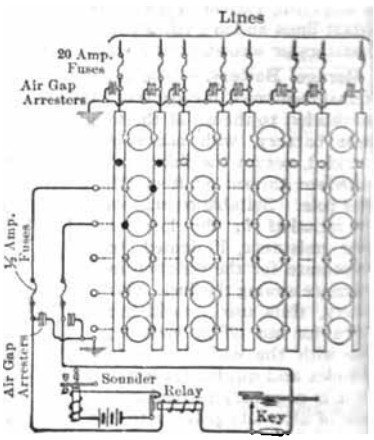


Fig. 10. Strap and Disc Switchboard

COSTS (Pre-war figures). — The following prices were current prior to the World War, standard Morse key, $2.20; double-acting key, $10.00; Vibroplex, $12.00; standard Morse sounder, $3.00; standard Morse relay, $7.0 polarized relay, $20.00; ink recorder, $35.00; punching recorder, $75.00. S also *Batteries*, *Generators*, etc.

BIBLIOGRAPHY. — See Bibliography in article on *Telegraph Systems*.

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APH LINES. — (*See also Poles and Cross-Arms; Telephone nsmission Lines; Wires and Cables.*) The conductor over which n is effected is commonly referred to as the line. These conductors s open wires, or they may be disposed in aerial, underground and cables.

WIRE LINES. — Most of the open-wire telegraph lines are of hard- per or of galvanized iron. Recently a wire known as copper-clad sting of a core of steel wire with an outer shell of copper welded appeared as a competitor. For the properties of these wires *nd Cables, Bare.*

wn copper wire is vastly superior to iron in point of conductivity ability to withstand the action of the elements. Galvanized-iron ntageous in point of first cost, it has a somewhat greater strength, fe ranging from 4 to 20 years, according to atmospheric conditions. steel has a conductivity superior to that of iron, but inferior to that It is stronger and somewhat cheaper than hard-drawn copper, and ss the same ability as copper to indefinitely withstand the action of .

ohm values (i.e., the weight in pounds of a wire one mile long sistance of one ohm) of the various grades of wire used for tele- poses are as follows: E.B.B. iron, 4700 pounds; B.B. iron, 5500 l, 6500 pounds; hard-drawn copper, 895 pounds; copper-clad steel uctivity 40 per cent of solid copper), 2010 pounds.

k S. gauge hard-drawn copper wire, weighing 209 pounds per mile, than any other size of hard-drawn copper wire for telegraphic pur- o. 8 B. W. G. galvanized-iron wire, B.B. grade, weighing 378 pounds he principal standard in iron wire.

CABLES. — The paper-insulated, lead-covered cable of the type telephony (*see Telephone Lines*) but with single wires instead of , is rapidly supplanting the old form of rubber-insulated cable l in telegraphy. Sometimes the cores are saturated with insu- und, and sometimes they are left "dry," according to whether the for greater safety outweighs the desirability for lower capacity. rk such cables are supported from messenger wires, either by means a wrapping of marline around both the cable and the messenger, n of support being applied by means of the well-known "Spinning

ROUND CABLES. — (*See also Wires and Cables, Insulated.*) telegraph cables are of the same type as those used for aerial. f placing them in ducts extending from manhole to manhole, so e their withdrawal, has largely replaced the older practice of ble in such manner as to necessitate its being dug up for replace- s.

NE CABLES. — For comparatively short lengths, in crossing where the current is not swift and the bottom is of such a nature o embed the cable, ordinary multiple-conductor, lead-covered ther paper or rubber insulation, provided with a heavy braiding , are often employed. Where paper insulation is used, it is cus- raphic work to thoroughly impregnate the core so as to minimize of moisture; but this increases the electrostatic capacity of the

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Where great tensile stresses or abrasion are likely to oc
provided with its lead sheath, is served with a thick cu
jute, and then with an armor of closely wrapped galv
which an additional protecting layer of tarred jute is s

Long Submarine Cables. — For long submarine
across the Atlantic Ocean, a single conductor is empl
form of stranded copper, weighing from 70 to 650 p
This conductor is then encased in several layers of gutta
core, so formed, is protected with a thick layer of jut
armoring of galvanized-steel wires is placed. After bo
cable is sometimes covered with a thick layer of tarre
of cables, where there is greater liability to mechanical
a layer of very heavy galvanized-steel wires.

LIMITING TRANSMISSION DISTANCE. —
over which a signal can be transmitted depends upon th
impulses sent out, the sensitiveness of the receiving ins
and capacity of the line and upon the number of statio

Open Wire Lines. — The following table, compile
shows the result of his calculations as to the limit
working (no intermediate stations) of simplex, duplex
transmission with standard apparatus over open wire
having different resistances per mile, and also the ma
way circuits equipped with 35-ohm line relays.

Resistance per mile in ohms	Limiting length of line for Through Working, miles			Li
	Duplex	Simplex	Quadruplex	A*
2	783	597	531	597
3	658	510	442	510
4	580	459	386	459
6	485	376	313	376
8	425	331	268	331
10	384	299	236	299
15	318	248	186	248
20	278	217	156	217
25	250	195	135	195
30	229	179	120	179
40	200	156	98.7	156
50	180	140	84.3	140

* *A*, stations at ends of line only, *B*, stations every 10 mile

CONSTRUCTION OF LINES. — (*See Telepho*

BIBLIOGRAPHY. — See Bibliography in article

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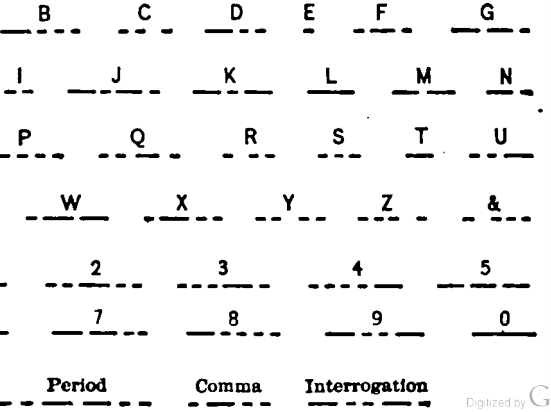
APH SYSTEMS. — (*See also Telegraph Instruments and Ap-legraph Lines.*) The following is a brief table of contents of this

h codes ..... p. 1611
system 1612
systems 1614
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tic systems 1620
telegraphs 1622
telegraphs 1624

ht modification the original system of electric telegraphy devised still largely used, the great bulk of telegraph work still being done its simplest form it consists of a circuit, connecting the points ich intelligence is to be transmitted, a battery or other generator it for supplying the current, a key at each station for facilitating and closing of the circuit by hand, and a sounder for giving response ng and closing of the circuit by audible clicking.

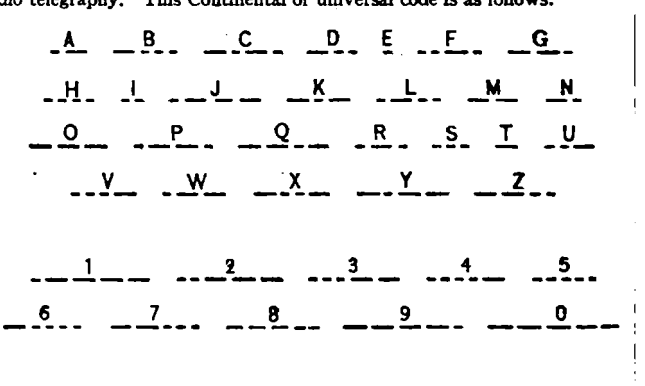
APH CODES. — Two different codes are used in telegraphy, ode and the Continental code.

ode. — The Morse code is an arbitrary system of interpreting the rs, numeral digits and punctuation marks employed in writing, this n being intelligible either audibly or visually. This code is formed es and spaces. The dot is made by a quick depression of the key its immediate release; the dash by a depression of the key with a se; and the space by permitting a short interval to elapse between on of two dots. Thus, the letter *a* is represented by a dot and a is formed by depressing the key, immediately releasing it, depress- again and holding it a slight interval before release. Similarly, is represented by two dots, and it is formed by depressing and key twice in rapid succession. The letter *o* is an example of a so- letter, and is represented by dot-space-dot. It differs from the in that an interval of time is allowed to elapse between the two Morse code, as it has been employed practically without modifi- the time of Morse, is as follows:



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Continental Code. — The so-called Continental Code differs from the Morse code in that it is composed entirely of dots and dashes, employing no spaces. It is almost universally used for submarine lines, for land lines in nearly all countries except the United States, and is the world's standard for radio telegraphy. This Continental or universal code is as follows:



SIMPLEX OR MORSE SYSTEM. — There are two types of circuit used, the so-called "open-circuit" system and the "closed-circuit" system. In both cases but one line wire is employed, the earth forming the return circuit.

Closed-circuit System (Fig. 1 and 2). — This system is mainly used in the United States. In its simplest form the keys and the sounder magnets are placed in series in the line with a source of current, as shown in Fig. 1.

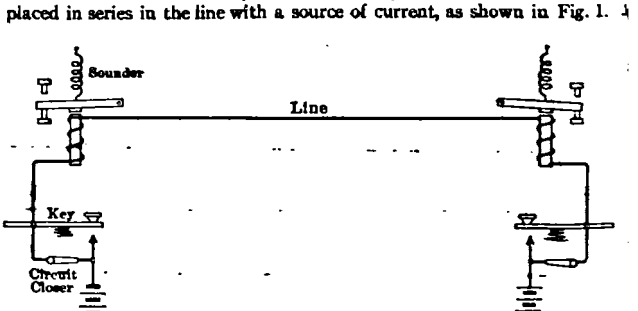


Fig. 1. Simple Telegraph Circuit

switch or "circuit closer" is provided with each key, the function of which is to keep the line circuit closed around the key contacts when the key is not in use. When an operator begins to send he opens this circuit-closer, thus making his key effective in controlling the line circuit. When the line is idle, the circuit is closed at all stations, and all sounder levers are held down by the magnetizing effects of the current flowing in the line.

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but two stations are shown, one at each end of the line. Obviously
e or way stations could be added by merely placing the necessary
unders in the line circuit at the desired points.
ommon practice is to employ a line relay at each station as the device
ponsive to the line currents, using this line relay to control a local
aining a local battery and a sounder. The reason for the choice of
more complicated system for commercial practice is that the sounder,
make the necessary amount of noise, is required to be of a rather
re and is not as readily responsive to the comparatively small line
s the relay, which, having no other function than to be responsive,

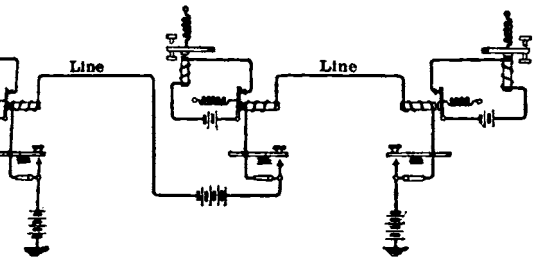


Fig. 2. Closed Circuit System with Way Stations

le of the required sensitiveness. A line equipped for three such
own in Fig. 2. While the constant flow of current in the closed-
results in the use of a greater amount of current than would
ecessary, it has the advantage of keeping the line under test at all
ot requiring a line battery at each of the stations, as is the case
circuit system.

it System (Fig. 3). — This is largely used abroad. A battery
each station. Each key has a front and back contact so arranged

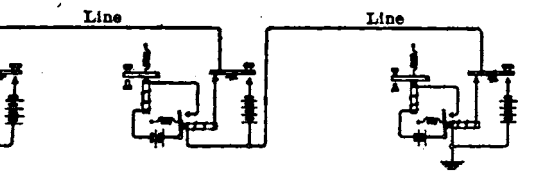


Fig. 3. Open Circuit System with Way Stations

relay in the line circuit when the key is raised, and to cut the
line circuit and substitute the battery for it when the key is de-
e, therefore, the line circuit is normally closed from one end to
elays are not energized, since there is no current in the line. As
he line and the local batteries stand in normally open circuits,
waste of current. Besides requiring a line battery, sufficient
n of the entire line, at each station, this system does not hold
instruments under automatic test conditions, which is auto-
by the constant flow of current in the closed-circuit system. A
en-circuit system is shown in Fig. 3.

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Sound Reading. — In the first use of Morse t
acters were recorded on a moving tape and subs
found in practice, however, that the operators so
coming over the wire by the clicking of the inst
method of sound reading was condemned at first
survived to such an extent that the major port
the world is to-day received in this way.

Speed of Handling Messages by Morse Sys
ling messages by Morse was limited by the speed
writing down the message, as long as this was d
The use of the typewriter for transcribing has, ho
the possible speed, and the limitation where the ty
sending operator to "write" the Morse code. T
where the line conditions permit. A poorly work
the possible speed far below the limitations pres
operators. While speeds of over fifty words a mi
experts during short periods of time, and while ope
ceive thirty-five and forty words a minute in a
average under working conditions is far below t
twenty words a minute.

DUPLEX SYSTEMS. — Duplex telegraph
ous sending of two messages in opposite directio
different methods are employed for making the re
sive to the home key. These two methods are te
"bridge" methods, respectively. There are also
sending impulses over the line, one of which depe
strength and the other on changes in current direct

Differential Method (Fig. 4). — The differen
stood from a consideration of Fig. 4, which sho
windings in opposite directions. Current
from the battery is supplied through one
of these windings to the line, and through
the other of these windings to the artificial
line represented by a resistance at the left.
The resistance and other characteristics of
the artificial line are made approximately
equal to those of the real line, so that im-
pulses of current sent by means of the key
from the battery to the line will produce
no effect on the relay, because an equal
current passes also through the artificial
line. Obviously, however, there is no such diffe
currents, and, therefore, the relay is re-
sponsive to currents from the distant
station.


Fig.

The differential method is ordinarily
employed in land telegraphy.

Bridge Method (Fig. 5). — The
bridge method of rendering the home
relay unresponsive to the home key and
responsive to the distant key is illus-
trated in principle in Fig. 5. In this
the resistances shown are so proportioned with res
line that the line relay will receive no current upo



Fig. 5.

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reason that the galvanometer in a Wheatstone bridge does not respond he bridge is balanced.

bridge method finds its chief use in overland and in submarine telegraphy.

rns Duplex for Land Lines (Fig. 6). — The Stearns duplex for land perates on the increase and decrease in current strength, without chang- direction of current flow; and for the reason that it employs the differ- method of making the home relay unresponsive to the home key, it is nly referred to as the Stearns differential duplex system.

mplified diagram of the Stearns differential duplex is shown in Fig. 6. be noted that the batteries at opposite ends of the line have their opposite rounded, so that whether one or the other, or both, of the batteries are

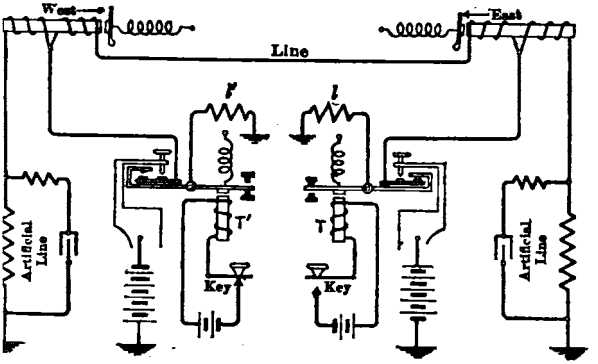


Fig. 6. Stearns Differential Duplex

circuit the current flows in the same direction. The key controls a local of an electromagnetic transmitter T or T'. The tongue of each trans- normally engages the contact on the under side of the bend in the lever; the latter is attracted by its magnet upon the closure of the key, the makes contact with the adjustable screw on the standard, and this pre- the tongue from moving farther upward, so that the making of this con- immediately followed by the breaking of the normally closed contact of ngue. Because these transmitters make one contact before breaking the they are called "continuity-preserving transmitters." When the key is the corresponding transmitter keeps its end of the line connected to d through the resistance l, but upon the closure of the key the trans- causes the substitution of the battery at that end of the line for this re- ce. This resistance l sometimes is called the "spark coil," since its use to prevent sparking at the transmitter contacts, and its function is to nsate for the internal resistance of the line battery.

artificial line shown at each station is composed of resistances and con- rs arranged for ready adjustment, so as to balance not only for the re- ce of the line, but for its capacity also.

earns Duplex for Submarine Cables. — Fig. 7 shows the Stearns x arrangement of terminal apparatus for cable working. This is a bridge od. The normal position of the keys grounds the cable conductor, thus arging it. Alternately depressing the two keys gives the cable alternate itive and positive charges, thus sending dots and dashes. By moving the

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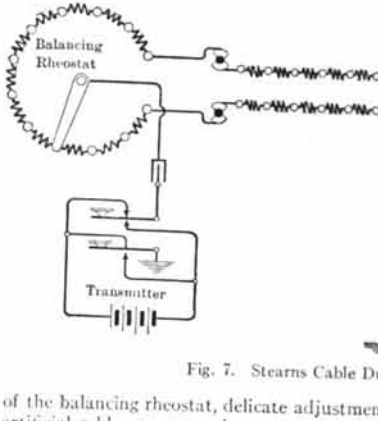


Fig. 7. Stearns Cable D

arm of the balancing rheostat, delicate adjustmen
and artificial cables are secured.

Jacobs' Duplex for Submarine Cables — Submarine cables frequently have two conductors, making

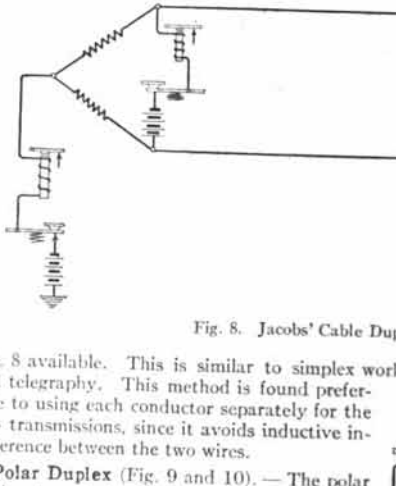


Fig. 8. Jacobs' Cable Du

Fig. 8 available. This is similar to simplex worl
and telegraphy. This method is found prefer-
able to using each conductor separately for the
two transmissions, since it avoids inductive in-
terference between the two wires.

Polar Duplex (Fig. 9 and 10). — The polar duplex depends for the principal feature of its operation on the fact that a polarized relay will move its armature oppositely for opposite directions of current. The key used in sending operates to close and open a local circuit which controls a pole-changing transmitter. The action of this is made clear in Fig. 9. With the key closed, as shown in that figure, the negative side of battery will be connected to line and

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th the key open, the reverse will be true. The circuit of the polar duplex hown in Fig. 10.

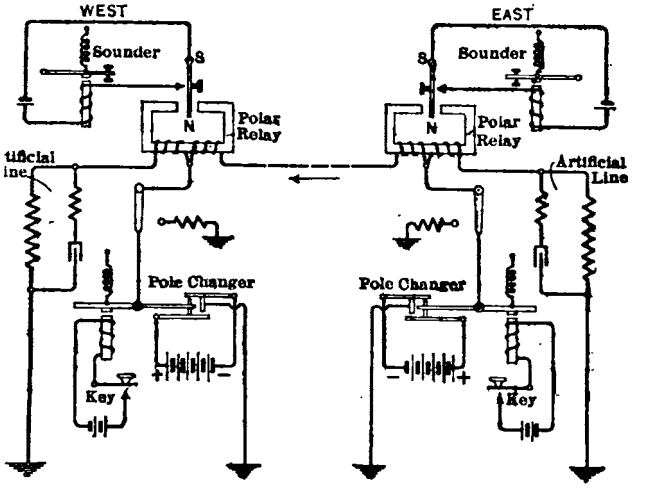


Fig. 10. Polar Duplex

QUADRUPLEX SYSTEMS. — In quadruplex systems four messages, in each direction, may be transmitted simultaneously over a single line

Edison Quadruplex (Fig. 11 and 12). — The Edison quadruplex depends its principle of operation on a combination of the two duplex systems, Stearns and the polar just described. At each station two relays are pro-d, one, the neutral relay, responsive to currents in either direction, and other, the polar relay, responsive only to currents in one direction. At each

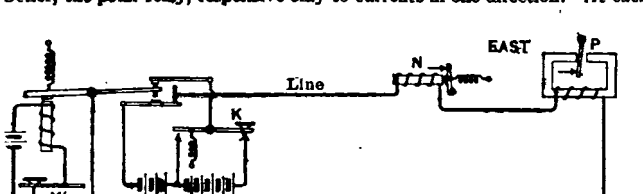


Fig. 11. Principle of Edison Quadruplex

on also two key-controlled transmitters are provided, one of which operates, the polar duplex, to change the direction of current in the line and the r, as in the Stearns duplex, to increase and diminish the strength of cur-flow.

ie principle of transmitting in one direction by means of the Edison quad-x is indicated in Fig. 11, where *N* is the neutral relay and *P* the polar relay e East station. *K* and *K'* are transmitting keys at the West station, key

K operating to alternately weaken and strengthen the line current, and [illegible] operating as a pole changer to reverse the line current. As shown, the line wi[illegible] always have some current flow, the amount being determined by key K and th[illegible] direction by key K'. As the neutral relay will operate on currents of eith[illegible] direction, if strong enough, it will be responsive only to key K; and as the po[illegible] relay will operate on either current strength, if in the right direction, it will b[illegible] responsive only to key K'.

The circuits of the Edison quadruplex are shown in Fig. 12. The windings [illegible] the neutral relays N and of the polar relays P are in each case made different [illegible] for the same reasons as pointed out in connection with the Stearns and pol[illegible]

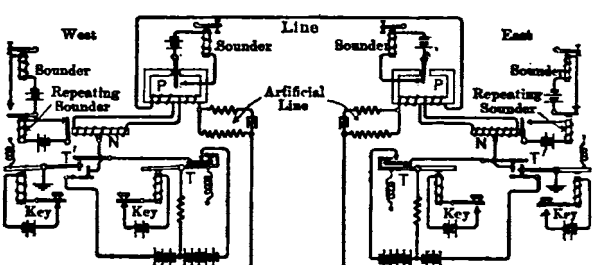


Fig. 12. Edison Quadruplex

duplex systems. At each station of the "quad" system one winding of ea[illegible] relay is in the line, and the other in the artificial line. As will be seen from Fi[illegible] 12, the two transmitters at each station modify the main battery current, [illegible] pointed out in connection with Fig. 11, the continuity-preserving transmitter [illegible] controlling the current strength and the pole-changing transmitter T' contro[illegible] ling its direction.

Key Systems for Quadruplex Working.— In the quadruplex so far de[illegible] scribed, the current was supplied by batteries, and the strength-varying tran[illegible] mitter operated to accomplish its purpose by alternately cutting a portion [illegible] the line battery out of and into the circuit. Where dynamos furnish the cu[illegible] rent, a different scheme is employed. One system, known as the Field key sy[illegible]

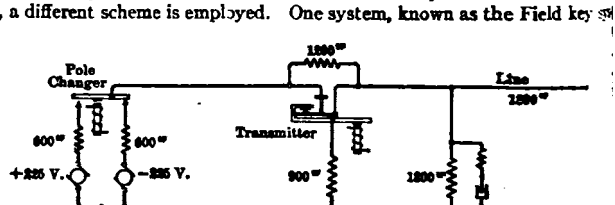


Fig. 13. Field Key System

tem, is illustrated in principle in Fig. 13. Two dynamos are employed, havin[illegible] opposite poles grounded. The pole changer merely chooses between the tw[illegible] live poles for securing its reversals in polarity. The continuity-preservin[illegible] transmitter varies the current strength in the line by changing the resistanc[illegible] relations as shown. Thus, when the key is closed, the 1200-ohm resistance i[illegible] short-circuited and the 900-ohm "leak" resistance to ground is cut off. Th[illegible]

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these circumstances flows to line at full strength. When the key 1200-ohm resistance is introduced in the line and the 900-ohm ffective. The resistances shown are those for an 1800-ohm line.

EX SYSTEMS. — The term "multiplex" should include duplex ex systems, but practice has been otherwise, and has resulted he term "multiplex" principally to a system wherein two moving switches, one at each end of the line, serve to connect ing sets of telegraph instruments momentarily and successively lation with the line. While each set of instruments, therefore, is the line for only a small fraction of the total time, the successive cur so rapidly as to afford, to all intents and purposes, a practi- s use of the line.

nchronous Multiplex System (Fig. 14). — The principle of the onous multiplex system is shown in diagram in Fig. 14. Six sets , each consisting of a pole-changing key and a polar relay, are end of the line. The two switch arms of the synchronous rotary

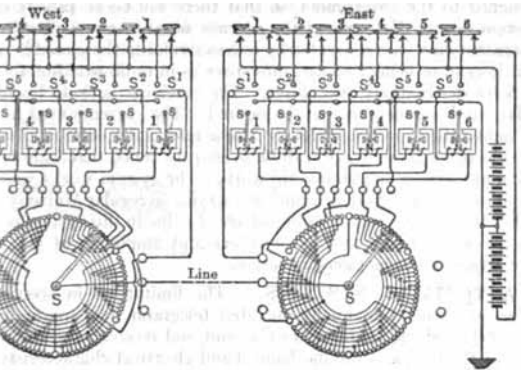


Fig. 14. Delany Synchronous Multiplex

nade to revolve in unison, so that the correspondingly numbered nts at each end will be simultaneously connected with the line. rms make about 180 revolutions per minute, and as each set of onnected with the line twelve times at each revolution, it follows f instruments is connected with the line thirty-six times per a much shorter interval than that required to make the short- erefore, any closure of a key which an operator may make will a time during which at least one connection will be made with particular embodiment of the Delany system shown polarized changing keys are used, the advantage of this being that the will remain in the position to which it was last brought by a in spite of the rapid interruptions caused by the synchronous l switch lever, S^1, S^2, etc., is associated with each key and ed by the operator to one or the other of its positions, accord- e is sending or receiving.

zing mechanism for the switch movements is ingenious and two arms are each driven by step-by-step motors, the driving egulated by means of tuning forks, as accurately tuned to each

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other as possible. Obviously, complete synchronism this means alone, and, therefore, the two driving de association with the line by the rotary switch arms s tion, the arrangement being such that if one switch dead or synchronizing contacts slightly in advance corrective measure to its motor device, which will t corrective measure is in the form of an electromagn tuning fork vibrates, and the energization of this m fluence on the rate of vibration, and, therefore, on synchronous switch.

This system has been used to some extent comm simultaneous transmissions on comparatively short long lines. Obviously, the time constant of the lin to a greater extent than in the ordinary systems of

Squier or " Wired Wireless " System. — Gen developed a system of multiplex telegraphy in which by electromagnetic waves directed by wires. Paten assigned to the government, so that there will be system during the terms of the patents nor of cou magnetic waves are generated by means similar to th but instead of being radiated into space as in radio definite destinations over wires. The receiving is relays and sounders as may be desired. The curre so unlike those used in ordinary Morse telegraphy o the electromagnetic waves can be so sharply tuned t for multiplexing and composite work. The system ments of line circuits that would stop service on regula tubes (thermionic valves, audions) are of value in thi of the wave-energy and as detectors and amplifie See article on *Radio Communication.*

AUTOMATIC SYSTEMS. — The limitations over an ordinary manually operated telegraph lin the ability of the operators to transmit and receive tics of the line, and the mechanical and electrical c ments which it has been possible to devise, permitti On this account, the so-called "automatic systems, and the receiving of the message are automatically into being.

Wheatstone Automatic System. — This is o veloped and widely used of the ink recording autom is shown a piece of the tape and a plan of the die for perforating it. The perforator has three levers usually adapted to be struck by mallets in the hands of the operator, these levers punching the necessary holes to form dots, spaces and dashes, respectively. Striking the left-hand le 2, 3, directly across the paper, this being the combi Striking the center lever punches a single small ho tape, thus making a space, while the third or right-ha arranged as 5, 6, 7 and 8, thus setting up a combina tion of the small holes along the center line of the driving of the tape, these being engaged by the poi

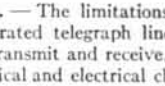


Fig. 15

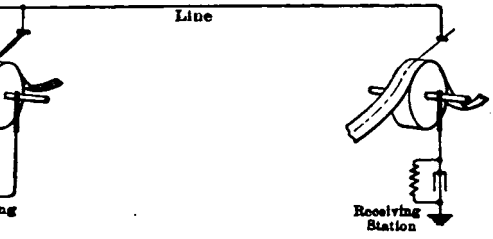
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he feeding mechanism. As this tape is driven through the trans-
w of larger holes determines the intervals at which the positive
tery shall be put to line, and the other row of large holes the inter-
ich the negative pole is connected. As the two members which
oles are arranged so that one is slightly in advance of the other.
the holes 1 and 3 will cause first a negative impulse, immediately
ositive impulse, this being the combination for a dot. The two
will likewise cause a negative, followed by a positive, impulse,
l be separated by an interval of time, this being the combination
he Wheatstone is thus a so-called "double-current" system,
s operation on the actual reversal of the line current.

one Receiver. — The receiver of the Wheatstone system is
polarized relay, the armature of which will stay in either of its
s even though the current which moved it there ceases. The
y a very small ink wheel which is constantly rotated in close
moving paper tape. The shaft on which this ink wheel revolves
to be deflected by the movements of the relay armature. The
s its ink on the back stroke from another wheel which revolves
On the forward stroke the ink wheel is brought close enough
per tape to make a mark, although there is no actual contact
el and the tape.

tems. — These systems, once employed in commercial work
extent, have been in large measure superseded either by the
stems or by ordinary Morse. They present possibilities for
nt, however, which give them more than an historic interest.

Chemical Automatic System (Fig. 16). — The salient
erson chemical automatic system are shown in Fig. 16. The



ig. 16. Principle of Chemical Automatic System

the transmitting tape under the contact pen serves to short-
ting battery and thus cause a cessation of current in the line.
he receiving end, previously charged by the flow of current
hen discharges into the line, this being intended to cause an
current flow. This is an interesting example of so-called
orking with a single battery. At the receiver the chemically
ses under a contact pen, so that the current is compelled to
per. Its flow decomposes the solution and marks the paper,
l. The reverse flow of current from the condenser tends to
nce of "tailings."

Anderson System. — This system, like the Wheatstone,
dashes, and, according to Maver, it has been found capable
words per minute over a 1000-mile line having a resistance

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of 2500 ohms, under all sorts of weather condition
in length, having a resistance of about 700 ohm
words per minute has been accomplished.

WRITING TELEGRAPHS OR AUTOGR
ing or autographic telegraphs are to be dist
graphs in that they write the received message
systems actually print them as from type.

In these systems the message to be transmitted
as with a pen or stylus, while at the receiving end
executes the same movements and thus writes th
similar handwriting. Nearly all autographic sy
movements of the transmitting pen or stylus int
movements at right angles to each other, electro
component rectilinear motions at the receiving s
there into the resultant movement, which, therefo
imating that originally made by the sending styl

Robertson System. — Fig. 17 is a schem
and clearly illustrates the principle of autograp
are employed, each including a battery and

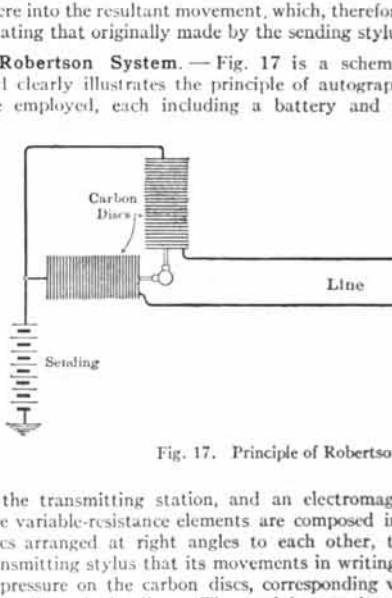


Fig. 17. Principle of Robertso

at the transmitting station, and an electromag
The variable-resistance elements are composed i
discs arranged at right angles to each other, t
transmitting stylus that its movements in writing
in pressure on the carbon discs, corresponding v
paths through the discs. The receiving pen is ac
mon to the two magnets at the receiving end. A
two magnets are at right angles and vary as the
ing, the two components of the transmitting sty
are recombined to produce the corresponding mo

Telautograph. — This is another autograp
Elisha Gray. It employs two wires, and like
solves the complex motion of the transmitting pe
ponents at right angles, reproduces these at the
them to obtain the facsimile writing. The tra
bell-crank arms carrying rollers which operate ov
the variations in resistance and current strength.
is attached to the arms of two bell cranks which

iform magnetic fields and which, under the influence of the vary-
assing through them, cause the required movements of the bell

g System. — In this the message is prepared by perforating
assage of which through the transmitter results in currents
the two line wires in proper sequence, direction and strength
eiving instrument to record the message in a style very similar
riting. Two circuits are obtained from the two wires; one
cuit and the other the two wires in parallel with earth return.
end two instruments closely resembling telephone receivers are
currents received over the two circuits. The diaphragms of
control the movements, on horizontal and vertical axes, respect-
mirror. A ray of light reflected from this mirror is caused to
idly moving strip of light-sensitized paper, and the co-ordinated
he two axes of the mirror under the influence of the currents
in writing. The photographic paper is automatically passed
essary developing and fixing baths, the time required in this
ly about twelve seconds.

TELEGRAPHS. — These are systems in which the received
omatically recorded in print. Most printing telegraph systems
nchronism being maintained between the two wheels at the
l receiving stations; although in some systems, such as the
ance, no such requirement exists.

ns. — In the ticker systems, which are widely employed for
k-market quotations, the type wheels are moved synchronously
either by causing the same set of line impulses to affect each,
e wheel at the sending station, in its revolution, to transmit
urn the distant wheel. The wheels must not only revolve at
t a given letter on each must come opposite a given fixed point
By stopping the wheels when the desired letter is brought
r, an impulse of different character is sent which causes the im-
. Some ticker systems operate over one line wire, and the
ause the rotation of the type wheel occur so rapidly as not
nting magnet, but upon their cessation the printing magnet
me circuit is brought into play. Many of the ticker systems
line wires and employ two type wheels, one carrying letters
ures. Means are provided for shifting either the wheels or the
t from either as desired.

System. — This is largely employed in Europe, and is a
-wheel system in which the type wheels revolve contin-
n by step-by-step movements. Electric motors furnish the
The wheels are adjusted to revolve at as nearly the same rates
uitable corrective means are brought into play over the line
omplete synchronism. The transmitting apparatus resembles
piano, a key being assigned to each character. In connection
d there is a rotating contact device revolving in synchronism
els, and the arrangement is such that the depression of any key
t to be made at the exact instant when the letter correspond-
in printing position at both instruments.

Hughes System. — The Hughes system is capable of oper-
accuracy at a speed in the neighborhood of from thirty to
inute.

. — The Phelps system is a modification of the Hughes and

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operates on the same general principles. It has
tem in the United States.

The Buckingham System. — One difficulty wi
system is that the great number of impulses require
down the speed. The Buckingham printing systen
a maximum of six current impulses per letter, the
ters being effected by various combinations of sho
in either direction, with short and long intervenin
system resembles the Wheatstone, in that the spac
rents and the dots and dashes by positive. As
also, the message is prepared by perforating the t
matically to send the required combinations of d
a different code is used, in which each letter and
of three positive impulses, dashes or dots, or both,
or short negative impulses, corresponding to spa
mechanism at the receiving end these positive an
of being received in dots and dashes on a movi
proper selection of the various printed characters,
order in page form. The type wheels are four in
side on the same shaft and rotating together. E
letters or characters, making thirty-two in all. B
by electromagnets, the type wheels are, under the
given any desired lateral or rotary motion to bring
printing position. The space between the letters is
impulse.

Tape-punching Machine for Buckingh
punching machine of the Buckingham system em
keyboard, one depression of the key effecting the t
character. The maximum speed possible is abo
against 20 to 40 words per minute in the mallet met
tape.

Speed of Buckingham System. — This s
speed of transmission of about 100 words per min
worked on a duplex circuit between New York a
speed of 80 words per minute in each direction.

The Barclay System. — This has been em
Western Union Telegraph Company, and resembles
ingham system. It uses the same code alphabet a
of transmitting, but the impulses received result in
magnets which in turn affect the operating levers o
which does the actual printing. The printing is
blanks.

Speed of Barclay System. — The rate
approximately 100 words per minute in each di
duplex.

The Rowland System. — This is one of the
printing systems, and was for a time used to consi
Telegraph Cable Company between New York an
cuits. Essentially the system is a one-way quadr
being worked duplex it becomes in effect an "
simultaneous messages in each direction over one

The line current employed is alternating, generat
which runs a synchronous motor at the other, thu
chronism. The necessary current combinations

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ven letter are brought about by reversing certain of the half waves of line current waves. The simultaneous transmission of four ne direction is provided for by an adaptation of the multiplex ibuting switch giving each set of four transmitting and receiving ccessive and simultaneous control of the line. Since each letter by a specific combination of positive and negative currents, it is ans of these combinations to effect the closing of the proper local receiving end to cause the paper to be pressed against the type ne when the letter required is opposite it.

f Rowland System. — Each transmitter and receiver has a 30 words per minute, making a total transmission of 240 words n the octoplex method of working is employed.

Automatic System. — This is a non-synchronous printing ges are first prepared by perforating a paper tape. This tape the transmitting device and permits currents to flow over the anner as to cause the receiving device, which in itself is a tape-hine, to perforate another tape there. This receiving tape is transmitting tape, and when passed through an automatic erforations are translated into Roman type letters, the message m.

Murray System. — This system is capable of transmission f 200 words per minute, but speeds of from 100 to 125 words been found to be the best for practical working.

n System and Modifications. — This system is in wide use tes. The Western Union Telegraph Company uses it in a form nt from the original. It is capable of being quadruplexed the method described under *Delany Synchronous Multiplex* ne use of the line among the four sets in regular succession. receives tape perforated manually before transmitting begins; one on electrically operated typewriting machines which write page form. The paper is fed to the machines from a roll. (capital) letters are used, and these are of the simplest and , known to printers as Gothic. The use of the system has unt of manual key-sending and ear-receiving between the ry greatly.

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TELEPHONE INSTRUMENTS AND

Radio Communication; Standardization Rules of I
Telephone Traffic.)

The chief subjects treated in this article are:

Receivers
Transmitters
Ringers or Bells
Batteries and Pole Changers
Impedance, Induction and Repeating Coils
Telephone Repeaters
Protective Devices
Telephone Sets
Party Line Circuits
Central Office Equipment
Private Exchanges
Phantom Circuits
Joint Telephone and Telegraph Circuits
Costs
Bibliography

The telephone transmits speech and other so
sound waves in air vibrate a diaphragm; this
current in a line joining the transmitter to a di
current produces vibration in the diaphragm of
produce sound waves in air.

Bell's original telephone utilized one device as
It survives in its original form as a receiver, but s
more powerful devices having supplanted it.

RECEIVERS. — The original telephone consi
wire and a diaphragm, arranged as in Fig. 1. *d* i

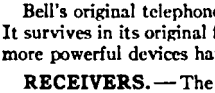


Fig. 1. Principle of Permanent Magnet Receiver



Fig. 2. Principle of Bipolar Receiver

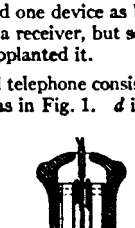


Fig. 3. Section of B
Receiver

and *a* is a coil. The magnet was first made of s
from direct currents in the line; a permanently
with soft iron poles (Figs. 2 and 3) soon was sub

Bipolar Receiver. — The bipolar receiver is
in Fig. 2, in which *d*, *m* and *c* represent, as b
and coil. Both poles of the permanent magnet a
being extended by soft iron pole pieces, each carry
silk-covered or enameled wire. The wires of the
series. When used to transmit speech, such an
neto transmitter.

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winding and diaphragm of a receiver are assembled in a case of an imitation thereof, adapted at one end to fit the ear and at the on a hook switch. Fig. 3 is a section of a typical assembled re- re permanent magnets, arranged to produce opposite poles at soft iron cores carrying the windings *w*, *w*; *d* is the diaphragm. receivers the entire mechanical arrangement of parts is supported d of the shell and not from the other end. This precaution is r to prevent the adjustment of the pole pieces to the diaphragm he difference in expansion of the shell and magnet.

t Receiver (Fig. 4). — For use in lines carrying direct cur- versation, as in common-battery systems, the iron-core type ly has been revived. They are extremely simple and cost little not yet established that they are as efficient as permanent-, hut the difference seems to be slight. They have the virtue n of flow of direct current through them is not important.

Telephone Manufacturing Company uses a receiver which has ndings, as in Fig. 5. One pair is of serving to magnetize the cores, while ller impedance, serves to actuate the ect currents pass through both pairs r magnetizing effects being additive, urrent through the coils farther from is the larger. Voice currents pass irs of windings and their effects are voice currents through the windings phragm are the larger.

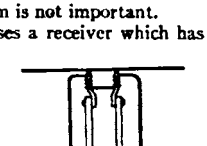


Fig. 5. Monarch Receiver

er. — A head receiver is a compact one carried by a band r's head, leaving her hands free. The compactness is gained agnets small and placing them parallel with the diaphragm.

ERS (Figs. 6 and 7). — Present standard carbon transmit- es more powerful than the best magneto transmitters. Carbon their circuits take many forms, but in all o produce current fluctuation as a conse- gm vibration caused by sound. of a transmitter are a diaphragm, two bon electrodes, and a charge of polished Vibration of the diaphragm moves one ress and release the granules between the 6 illustrates the elements; *d* is the dia- ovable and *f* the fixed electrode. Fig. 7 is cal granular carbon transmitter. smitters operate by varying the resistance proportionally to movement of the diaphragm. Receivers, on re caused to operate by a varying magnetic flux. The reason ction of carbon in varying its contact resistance under pres-

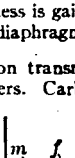


Fig. 6. Principle of Transmitter

BELLS (Fig. 8). — The present standard telephone signal , actuated by alternating current. Its principle is that of raph relay. Its construction, as in Fig. 8, is of two coils, et *N*, two gongs and an armature *S*.

erator (Fig. 9). — The bells of telephones in all exchanges ating current sent out from the central office power plant. ns the subscriber calls the central office by operating a which is a part of his telephone, and with this generator

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magneto generator, which is a part of his telep
the subscriber also rings other bells on the same
is a standard part of subscribers' equipment for
being the best way for a subscriber to do signalin
on one line. The armature has many turns of fi

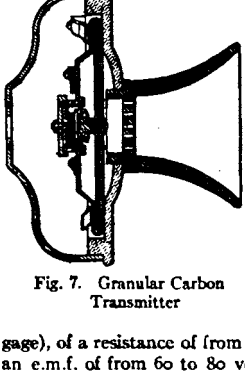


Fig. 7. Granular Carbon Transmitter

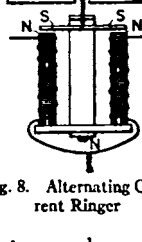


Fig. 8. Alternating C
rent Ringer

gage), of a resistance of from 300 to 1000 ohms.
an e.m.f. of from 60 to 80 volts can be produce
by hand.

BATTERIES. — (*See articles on Batteries.*) T
set requires direct current and produces from it
fluctuating) voice currents, which pass over the li
central storage battery furnishes the direct curre
battery systems," or "central energy systems."
the direct current in systems not having a central s

Dry Cells. — The primary battery usually i
associated directly with the telephone set. Such
local battery set. Two or three cells are used in s
of about 1.5 volts, and can give a current on short
Dry cells, designed particularly for local battery
internal resistance than those intended for gas en
current intermittent work. Longer life, with c
obtained by increasing the internal resistance. I
few minutes at a time.

Gravity Cells. — Other types of primary cel
mitters. Gravity cells are suitable for operators'
and can furnish current steadily with no period
not stand long on open circuit. They give about
in series are suitable for a transmitter.

Fuller Cells are suitable for heavy service
day), and also can stand on open circuit without
the storage battery in e.m.f. (about 2 volts) a
and costly to maintain and are used less widely n

Storage Batteries give good results in loc
charging by direct current from outside themsel
the lack of frequent charges. They are suitable
battery use for those reasons. The most wid

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orage batteries is by motor-generator sets, the motor being adapted to the source energy and the generator being shunt wound. Shunt-wound generators driven internal-combustion engines are used as emergency charging equipments.

POLE CHANGERS. — Ringing current in central offices is usually produced by alternating current generators or by pole changers. The latter are vibrating contact-makers having natural frequency corresponding to the frequency of the current desired. They are operated by direct current from a storage battery or other source. The Warner pole changer, Fig. 10, is widely used for ringing ordinary telephone bells at a frequency of from 16 to 20 cycles per second. Pole changers for multiple frequency are also used to ring harmonic bells on party lines.

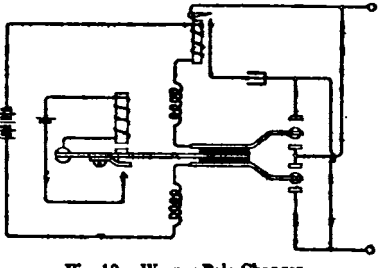


Fig. 10. Warner Pole Changer

IMPEDANCE COIL. — An impedance coil is a single coil of wire wound on an iron core. In telephony the iron core usually is of wires, or occasionally sheets.

INDUCTION COIL. — A step-up transformer used in a telephone circuit called an induction coil in telephone parlance. Fig. 11 shows the use of such transformer in a local battery set. The battery and the carbon button are connected in series with its primary winding; the line and the receiver are connected in series with its secondary winding. The function of the induction coil is to convert the feeble variations of direct current of low e.m.f. into alternating currents of higher e.m.f. in order that it may pass over the line with less loss.



Fig. 11. Induction Coil in Local Battery Set

Local battery induction coils have a large ratio between the two windings. The primary winding is of low resistance and of fewer turns than the secondary winding. Single silk insulated wire is used for both windings; practice varies as to wire sizes and turns; a representative example has 350 turns of No. 20 B. & S. gage wire in the primary and 2400 turns of No. 30 B. & S. gage wire in the secondary. Other examples use from 200 to 700 turns in the primary, 700 to 3000 turns in the secondary, No. 20 to No. 28 B. & S. gage wire in the primary and No. 26 to No. 36 B. & S. gage wire in the secondary.

The induction coils in common battery sets have different functions from those in local battery sets. Figs. 12 and 13 show two forms of common battery telephones using them. In most cases one function of the induction coil is to in-

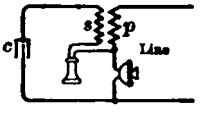


Fig. 12.

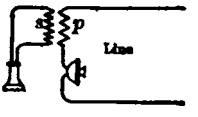


Fig. 13.

sulate the receiver from the direct current of the line, so that its permanent magnetism never shall be opposed by direct current flowing in its coil. In Fig.

12 the induction coil has the further function tha
denser c it assists the transmitter to convert the
an alternating voice current. The condenser alte
charges, responsive to the state of the varying
This particular transforming function is lacking in
type of Fig. 13.

REPEATING COIL. — A repeating coil is a
phone circuit. A one-to-one ratio repeating co
such a manner that when equal currents flow thro
(or opposite, depending upon the point of refer
fields of the two currents neutralize each other,
impedance is offered to the flow of such current
has a high impedance. As the result of such an a
offers a high impedance to any current tending
which is not accompanied by an equal current i
other winding. The use of a repeating coil in a
shown in Fig. 29, and in phantom circuit practice

HOOK-SWITCH. — The time during whic
idle much exceeds the time in which it is in use.
to receive or to make a call. When in use, its trans
direct currents and its receiver to receive voice
makes these changes automatically.

PROTECTIVE DEVICES. — Telephone app
from damage due to abnormal currents by means
important co-operating elements. The latter are
arresters"), and air-gap arresters. Heat coils ope
of contacts when small currents flow for long time
for short times. Air-gap arresters operate when p
exist at their terminals. The operation of eith
arrester short circuits the line, grounds the wires i
On account of the high resistance of the telepho
current in the line may not be large enough to blo
short circuit. The heat coil insures such a short
or duration of the current exceeds a safe value.

The relation of the three elements to each other
shown in Fig. 14. The fuses should be located at
wires which are "exposed" and wires which are "
tact with a source of dangerous current. All aer

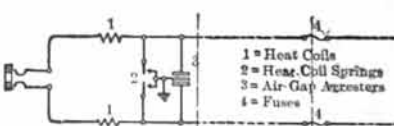


Fig. 14. Arrangement of Protecti

exposed. Underground and indoor wires are to be
indoor wires are run in accordance with good rules,
Electrical Code.

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ONE SETS. — The several elements necessary at a subscriber's ssociated to form series magneto sets, bridging magneto sets and ery sets.

agneto Sets (Fig. 15) are suitable for use on single party lines, ly so used in exchange practice, and, unfortunately, to some s having more than one telephone (party 15 is the circuit of a series set. When s on the hook, the bell is connected be- minals of the set, the battery and receiv- oth are open, and if the generator is not nature winding is shunted. When the urned in calling, the shunt is broken

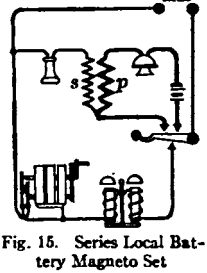


Fig. 15. Series Local Battery Magneto Set

s the voice currents must pass in series one of the ringers of a line. The im- e ringers, therefore, must be as *low* as igh enough to respond to ringing cur- able e.m.f. 80 to 100 ohms is the usual oth coils of a series ringer. The cores rter than in bridging ringers.

agneto Sets (Fig. 16) are better than series magneto sets for he ringer is bridged across the line permanently. The generator s the line when the crank is turned. The ransmitter circuits are closed when the hree of the four circuits of the set are not in use, as in Fig. 16.

sets the voice currents must pass *by* all of a line. The impedance of the re, must be as *high* as possible, yet low ond to ringing current of reasonable 1800 ohms is a usual resistance for the ridging ringer. The cores are usually eries ringers.

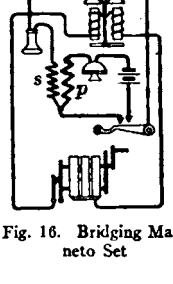


Fig. 16. Bridging Magneto Set

attery Sets (Figs. 17–19) have no al battery and can, therefore, be used eading to a central office. A storage central office, common to all the lines, of the instrument. Common battery not send out current to ring bells, as lephones; when used on a party line fore, call each other only indirectly, entral office operator to send the nec- urrent over the line. Common bat- rly always bridging sets.

and 19 are typical circuits of com- ephones. Fig. 17 is that used in the the Associated Bell Telephone Com- estern Electric Company's apparatus orld. As the condenser is "opaque" , but "translucent" to alternating current in a degree dependent ncy, no direct current from the central office normally will flow

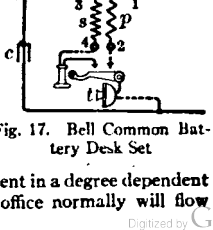


Fig. 17. Bell Common Battery Desk Set

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through the set when the hook switch is down, b
the central office can actuate the ringer. When
current from the central office flows through the tra
of the induction coil.

In the circuit of Fig. 18, used by the Kellogg Swit
the ringer, in series with a condenser c_2, normally
When the switch-hook is up, the transmitter is in
vary its current. The receiver is in a path "opa
"translucent" to voice current, because of the
path, including the condenser c_1 is shunted by a c
high inductance, which is opaque to voice curren
currents. No direct currents can pass through the

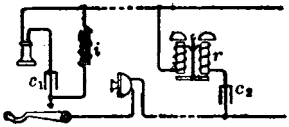


Fig. 18. Kellogg Common Battery Set



Fig. 19.

The circuit of Fig. 19 is one in which all of the d
allowed to pass through the receiver. The latter
(i.e., is of the "direct current" type, Fig. 4 or 5), ar
current from the central office to magnetize its core

Wall and Desk Sets. — Telephone instrument
two forms, wall sets and desk sets. The latter a
having the receiver, transmitter and hook switch c
can be carried about. Wall sets are self-contained
if needed. In local battery and common battery d
arately mounted, usually upon a wall. Local batt
quire housing for batteries, and magneto desk sets
hand generators.

A desk set is connected to line and ringer, and
used, by a flexible cord. The number of strands
type of circuit used, and on whether the induction
mounted in the portable set itself or on the wall w
18 and 19 the parts of the circuit carried by cords be
portions of the set are shown by dotted lines.

Desk sets are more convenient for use but are mor
wall sets. They fail frequently, breaking transm
shells, and other parts. Supporting arms for desk

Extension Set. — An extension set is a set used
set; the extension set usually has no bell; signals a
terminal set, and if the user of the extension set
a separate signal, such as a buzzer, operated by t
terminal set. Any number of extension sets may
one of them may make a call. None can receive a
office nor from another station on the line unless
not then from other stations on the line unless the

PARTY LINE CIRCUITS. — Party line sets d
only in methods of signaling. The apparatus used
ing up depends upon whether the party lines are to b

Non-Selective Party Lines. — On such lines a

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e line operates the ringers at all stations. Each station has a particular group periods of bell ringing, which group only it is meant to answer. Up to five ations from one to five short rings per station serve well. Beyond five, long d short rings are combined. Magneto sets, both series and bridging, are used non-selective party lines. The generator of the magneto set at any station n ring all the bells of the line at once, and operate the central office signal also, the line leads to a central office. The bridging system is so used on many ivate lines, farmers' co-operative lines, rural toll lines, and, to a degree, on change party lines in towns.

Non-selective stations should not answer other calls than their own; this tra listening on lines is an extra drain on local batteries in sets having them; also destroys privacy. A receiver off the hook impairs signals unless circuits e specialized; for example, as follows:

If a condenser of low capacity, say one-half microfarad, be placed in series th the receiver, it will obstruct ringing current (frequency 20 per second) nsiderably, but voice currents (mean frequency 800 per second) very little.

Selective Party Lines are equipped with ringers arranged to respond each its own call, the others remaining silent. There are three such methods in e in the United States, and still a fourth method, which has certain very de- led advantages, is coming into use.

Metallic Circuit Two Party Lines (Fig. 20.) — On metallic circuits ective two party working is simple. Fig. 20 is the standard system of the

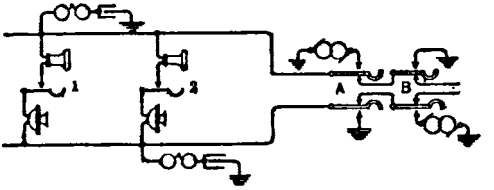


Fig. 20. Two Party System

sociated Bell Telephone Companies in the United States. Each wire of the etallic circuit is used as a private grounded ringing circuit to one station, and e pair of wires is used as a talking circuit by each station. Key *A* connects e ringing generator to the upper wire, ringing station No. 1; key *B* rings ation No. 2. If a station answers while being rung, the other station is not ng falsely, the ground on the non-ringing side of the used key preventing that.

Harmonic Selective Systems (Fig. 21) operate on the principle that ringer having a spring-supported armature will ring for one frequency of cur- nt but not for any other frequency. Frequencies of 16, 33, 50 and 66 per

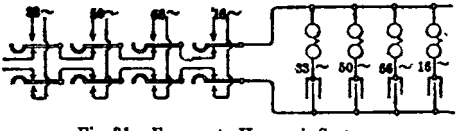


Fig. 21. Four-party Harmonic System

cond are used in the Dean four-party harmonic system. Each calling cord the central office switchboard can be rung upon by one of four keys, as in

Fig. 21. The ringers are alike except as to the cylinders of metal, heaviest for the lowest frequenc for the highest frequency.

The number of selective stations may be made twi by connecting harmonic ringers from each wire to g of across the line as in Fig. 21. This enables eigh line leading to a four-frequency central office.

Biased Ringer Systems (Fig. 22). — The uses unidirectional pulsating current for the selecti party lines. An improvement on that system (Fig

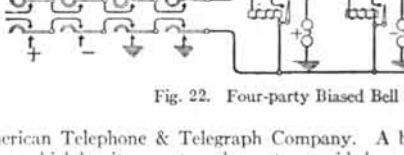


Fig. 22. Four-party Biased Bell

American Telephone & Telegraph Company. A b ringer which has its armature drawn to one side by a in one direction only will operate the ringer. Cond with such ringers would interfere with the selective necessary to prevent ringer connections from inte of common battery lines. In common battery sy each station, as in Fig. 22, connects the ringer to the ringing. The same current that operates the ringe

Step-by-Step Party Line Systems selec the operation one after another of a set of switches controlled from the central office. Step-by-step p come into wide use, but the development of auto central office use is increasing knowledge, faith a step mechanism. *(See article on Dispatching of Tra*

Semi-Selective Party Lines. — Semi-selective than two stations on a line, as in Fig. 20, by conn to each wire, ringing code signals on key *A* for the ri ringing code signals on key *B* for ringers on the low

CENTRAL OFFICE EQUIPMENT. — Te general ways: (1) On a line permanently connecti this line not being connectible to another, and, (2 more telephones, this line being connectible at will lines. In the second case a switchboard and the ducing the various kinds of current required must any line to any other. Such a switchboard and its tral office." A "telephone exchange" is an organiz offices and the connecting lines and apparatus empl service to a community. A central office is, therefo

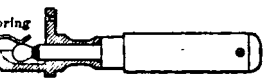
A "manual switchboard" is one in which a huma connects the lines by hand, as instructed by the sub speech. An "automatic switchboard" is one in w disconnect the lines in response to electrical chang functions of manual and automatic switchboards s named "semi-automatic systems" or "automanual

A switchboard designed to interconnect telepho

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magnetos is called a "magneto switchboard," while a board de-
connect telephone sets supplied with current from a single battery
office is called a "common battery switchboard." When each of
ng a central office is permanently connected to a single "jack" or
oard is called a "simple switchboard." When each line is per-
ected to a plurality of jacks, located at different parts of the board,
led a "multiple switchboard." A multiple switchboard is divided
ch section accommodating three operators, and containing a jack
ntering the central office. The group of jacks in each section is
he "multiple." "Simple switchboards" can be used only in case
ines connected to the central office is small (less than about 300),
nking in the central office is resorted to. It should be noted that
oscriber of central office switchboard equipment increases as the
cribers increases when the total number of subscribers is sufficient
se of multiple switchboards.

gs, Jacks and Drops. — As principally used, manual
onnect lines by means of flexible conducting "cords" tipped
ch fit line-terminal-sockets called jacks. The plug contains
parts, electrically insulated from each other but connected to
ads of the cord terminating in the plug. There are two strands
simple magneto switchboards, and therefore two parts in the
to two conductors of the jack. Fig. 23 shows a jack and



g. 23. Jack and Plug



Fig. 24. Diagram of Plug and Jack

rand cord. Few switchboards require circuits calling for more
uctors in regular switching cords. Plugs and jacks for that
can be made in compact and serviceable forms. Fig. 24
tically a three-conductor jack and plug, in which it is intended
e plug shall engage the short spring, the ring of the plug the
he sleeve of the plug the tubular sleeve or thimble of the jack.
plugs are associated with keys, signals, wiring and current
nks which the operator uses to do her work upon the lines made
jacks. At *D* in Fig. 25 is shown diagrammatically the type
d on magneto manual switchboards. This signal, called a
bridged across the switchboard end
same manner as the ringer at the
n. When the core is energized by
nagneto, at the subscriber's station,
tracted, lifting the catch and releas-
llowing it to fall forward by gravity.
alled gravity drops for this reason.



Fig. 25. Magneto Drop and Jack

— The power plant is an organiza-
a central office to furnish to the
that office the several kinds of currents required. The
of power plants are storage batteries, charging generators
rnating current for ringing.

battery system one storage battery usually supplies current
whether of subscribers or operators, and actuates all principal
ignals. In magneto offices storage batteries need only be

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large enough to supply operators' transmitters an magneto equipments usually have primary batteri

Magneto Manual Switchboards (Figs. 25 a diagrammatically the central office end of a subs cludes the essential elements of a magneto cord one plug is connected through the cord to the tip true of the plug sleeves. When a subscriber rings The central operator then inserts the plug P_1 (Fig. 26) of an idle cord circuit in the jack of this subscriber's line; this disconnects the line drop, the shutter of which is returned to its normal position either by hand or automatically. She then connects her telephone set to this cord by closing the switch A and gets the number of the subscriber wanted, and inserts the plug P'_2 in the corresponding jack. By closing the switch B she connects to the central office source of ringing current, wh tinuously. The called subscriber's bell rings as lon ringing key. When she releases it, direct connec results. When the called subscriber answers, con the close of it the subscribers are expected to signal The gravity drop D (Fig. 25), in this case called a across the cord circuit, and in response to this signa plugs. The line signals of both lines thus are recon calling signals.

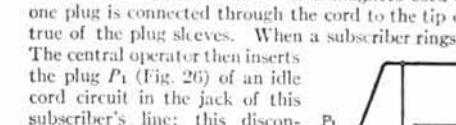


Fig. 26.

The operator's set is connectible to the cord circu cord circuit, enabling her to answer the calling subs to the conversation, and, by releasing one listenin to shift her telephone set from cord circuit to cord variety of conditions, an operator can utilize from transferring her telephone set from one to another

In Fig. 26, ringing current can be sent out only Calls, therefore, are answered by using the left-ha lines being taken up by the right-hand plug. Some be equipped with calling keys, in which case the le an arrangement symmetrical with that of the right-

The shutters of gravity drops used as line or clea to their upright position by hand in most simple m merly the drops were placed in one group and the jack restored directly by the operator's fingers. Latterly are associated together, so that the plug as inserte shutter by some thrusting movement on the part of to form a tongue upon the jack spring, this tongue t into its latch.

Large magneto switchboards have been equippe distance from the jacks and out of reach of the ope stored after operation by electro-mechanical means, in the jack of a line closing circuits to restore the sh

Jacks are adapted to be mounted in insulating stri

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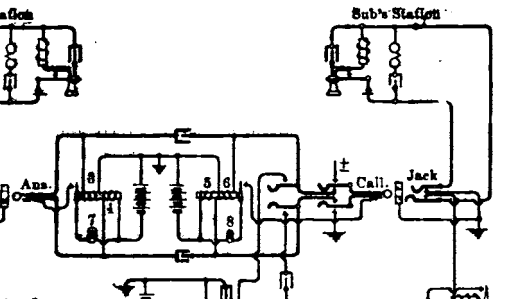
any jack of a group may be dismounted. When more compact desired, jacks are made up in strips of ten or twenty, an entire ust be removed from the framework of the switchboard to enable nspected or worked upon.

of light telephone traffic, as at night, it is desirable to use as few handle the traffic satisfactorily, and, in small exchanges, even rator to sleep between calls. On a long switchboard a drop may way from the night operator and its falling be unheard. A night provided by equipping each drop with a contact closed by the utter. These contacts of all the drops of a group are wired in ttery, bell and switch which is closed at night. When any drop lls, the bell will ring if the switch is closed.

lugs, when not in use, stand vertically in a plug shelf, the cords thin the switchboard framework and kept reasonably taut by ed pulleys. Weights should be heavy enough to enable cords o position after disconnection, and not so heavy as to shorten of the flexible conductors within the cords.

ed circuits are connected to metallic circuit switchboards and ection with metallic circuits, a ground connection must be pro- the second limb of the line, as switchboards now are built llic circuits. Such grounds must be connected to jacks in one r two grounded circuits may be connected so as not to be able her. The usual practice is to connect the line wire to the spring he ground to the sleeve.

mon Battery Switchboard (Fig. 27). — The circuits of a mple common battery switchboard are shown in Fig. 27 and



7. Circuits of Simple Common Battery Switchboard

ellogg Switchboard & Supply Company. They are a type of . The subscribers' lines terminate in cut-off jacks. There er line. The calling plugs only are equipped with ringing

rations of such a system is as follows: The subscriber removes he hook and as there is no plug in the jack of his line at the ine relay is actuated, lighting the line lamp and operating the pilot relay, in turn, lights a pilot lamp, of which there is one

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for a considerable number of line lamps, and with alarm signal can be associated. Responsive to which in practice is mounted close to the line jack, ing plug in the jack, breaking the line relay circui guishing the line lamp. Operating her listening k talking set with the cord circuit, asks for the sub by inserting the calling plug in the jack of the lir already is occupied by a plug. If it is occupied, that the called line is busy. If it is not occupied, sl rings. At this stage, the supervisory lamp 7, adja dark and the supervisory lamp 8, adjacent to the cating that the calling subscriber's receiver is off scriber's receiver is on the hook. When the called s to the ring, lamp 8 is extinguished. At the close of will re-light as the respective receivers are hung u can tell at all times the state of the connection and to the final lighting of both supervisory lamps, she positive knowledge that the conversation has been

The heavy lines in Fig. 27 are those over which takes place. In the cord circuit the two conducto are continuous from tip to tip and from sleeve to sl a condenser is interposed in each of the two co actuate subscribers' transmitters is furnished to t

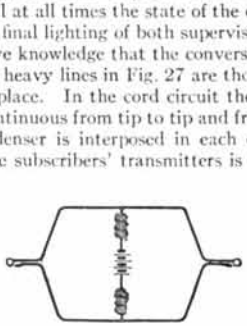


Fig. 28. Impedance Coil Cord Circuit

Fig. 29.

the windings 3–4 of the answering supervisory relay through the windings 5–6 of the other. Each supe purposes, one being to supply the subscriber's t other being to co-operate with the ground at the line visory lamp if no direct current flows through th supervisory lamp while the direct current does so f

There are three general ways in which direct curre circuits to subscribers' lines. In Fig. 28 current is coils without condensers. Such a plan is suitable where all the lines of a switchboard are of about equal resistance, as in a private exchange. If the lines are of varying resistance, a high resistance line will be denied proper current when connected through such a cord circuit to a low resistance line (low compared to the resistance of the impedance coil). The circuit of Fig. 29, using a repeating coil, is free from this objection and is standard & Telegraph Company. The circuit of Fig. 30, us densers, is as efficient as that of Fig. 28, though e It is widely used in manual and automatic switchbo American Telephone & Telegraph Company.

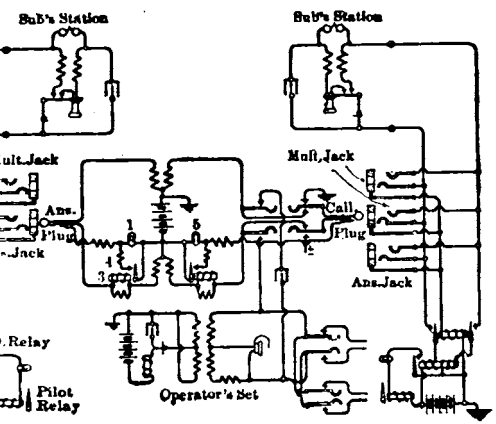
Fig

Comparison of Magneto and Common Bat

best in small towns and country exchanges. Magneto systems hanges under 500 lines and common battery systems best above No positive rule can be laid down. For example, the magneto arranged in exchanges which start with little equipment and do d 500 lines while the equipment still is in good condition. Con- n battery systems may be warranted in exchanges as small as 200 he conditions are favorable and the need of the highest grade of

stems or Local Trunking. — When it is desired to use a or common battery system in an office requiring more than so that there will be lines beyond the reach of each operator, provide local trunks or transfer circuits to interconnect lines e reached directly. These are called transfer systems or local s. If an operator has a call for a line which she cannot reach rts the calling plug in a jack of a trunk which leads to the sec- e jack of the called line. At that section an operator connects with the called line and assists in disconnecting it at the end These systems have service disadvantages which in most cases veigh the savings, and the best practice is to use multiple ere simple switchboards are outgrown. An important excep- f large cities where the majority of calls would have to be com- second central office in any event. Under such circumstances or the trunks only are provided, the subscriber's line being t a single jack and practically all calls are trunked irrespective on.

itchboards (Fig. 31). — A multiple switchboard is one in es of the office are brought within reach of each operator by



ig. 31. Circuits of Multiple Battery Switchboard

e with a number of jacks, distributed over the board in such h operator can reach at least one of these jacks. The usual p each line with one answering jack, at which all its calls will

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be answered, and in addition with a plurality of li
a plug may be inserted when that line is called. A
where the called line may be taken some guard is
tor t king the line when it is in use at another pa
guard is called the "busy test" and is provided b
of a metal thimble of each jack of a line whenever
all the thimbles of all the jacks of a line are at the
of all idle plugs. Touching the tip of a plug to t
line produces no electrical result. But when an
plug to the sleeve of a line which is busy, differe
and sleeve causes current to flow and a click to be
then tells the calling subscriber the called line is b

Fig. 31 shows the complete circuits of a calling l
necting cords of the Western Electric Company
which is the standard of the American Telephone
cycle of operations is exactly as described with ref
battery switchboard with the addition of testing
Current supply to the cord circuit is of the form s
have fewer parts than in the simple switchboard
relay is disconnected from the line by a cut-off
jack. The cut-off relay is operated by current f
plug is placed in any jack of the line. This curre
potential to all jacks of a line so long as a plug is
which actuates the subscriber's transmitter also ene
shunt 4 around the supervisory lamp 1. It results
lighted or dark, depending upon whether the swi
or up.

All principal common battery multiple switchb
use have the common features of an audible busy
supervisory signals per cord circuit — one for each
answering jacks supplementing the multiple (or ca
requires more than two wires in the subscriber's lin
but the system of Fig. 31 requires three wires in th
board. Other systems require only two wires thro
in these systems the busy test and cut-off relay fun
other functions of one of the wires of the line. Th
over the three-wire system lie principally in the gr
and the fewer wires necessary in the switchboard c

Common battery multiple switchboards for use
lines sometimes are provided with cut-off jacks, av
cut-off relays. Some such switchboards use magn
substitute for lamp signals. This is not the b
have decided advantages. They are compact, can
to jacks, show great contrast between actuated
and are not easily obscured by cords.

A and B Operators. — Manual multiple
bring all the lines of the office within reach of eac
boards cannot concentrate more than 10,000 lines
jacks are made smaller than is considered the best
contains more than 10,000 lines, it is customary to
This makes possible a saving in lines and things r
calls to be trunked from one office to another. In
for example, there would be ten switchboards of 1
board serving a district of the exchange.

Calls *originating* in one district will be *for* lines

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in the originating district can be completed in the switchboard . Calls for subscribers in all the nine other districts must be accomplish this, the operators in a multi-office exchange have bling them not only to complete calls directly in the multiple it to connect subscribers with trunk lines leading to the other ch office furthermore there are operators and equipments adapted complete calls trunked to them from the offices where they

o answer subscribers are called *A* operators; operators who s incoming from other offices are called *B* operators. The cycle a call for a line not in the office first called is as follows: sub- receiver and his line lamp lights; operator answers and asks g by prefix that call is for a subscriber in a distant office, opera- marked with that prefix, so connecting her telephone set with irectly to a receiver of a *B* operator in the distant office; *A* the number desired, following with the *prefix of her own office;* stant office names back a trunk number; *A* operator inserts multiple jack of that trunk and simultaneously distant *B* the plug of that trunk in the called line; method of ringing e of apparatus; at close of conversation *A* operator discon- lights disconnect lamp before *B* operator, who disconnects in ishing signal.

stributing Frame. — The main distributing frame is a device terminated, usually upon opposite sides, the lines from sub- switchboard apparatus. Between these terminals connect- , called "jumpers," are soldered. The purpose of the main e is to enable a subscriber's line to be connected semiper- given switchboard line. A subscriber may move anywhere of his central office and may utilize any pair of wires entering t relinquishing his particular telephone number, as his switch- be connected by jumper to whatever entering cable wires Protective apparatus, consisting of sneak current arresters and resters, is associated with all lines entering a central office. devices customarily are mounted on the switchboard side of ing frame.

ate Distributing Frame. — The intermediate distributing on which lines to multiple jacks and lines to answering jacks cessible for inter-connection. Its object is to enable a given n an answering jack at any part of the switchboard and this semi-permanent. By this is meant that when a subscriber's ected by jumper to an answering jack on a certain operating lls of that line will be answered at that position until the rmediate distributing frame has been changed. The purpose affic originated by the subscribers of an office to be divided operators. This equalization is not automatically done by stributing frame, as is the intent in the automanual system.

OR MACHINE-SWITCHING SYSTEMS. — There f switching lines in a central office by means of machines. lly known as the automatic system, connects and disconnects ed lines by the agency of central office machines under the g subscriber. The other utilizes machines similar in function he automatic system, but these are controlled by skilled ntral office, and the subscriber gives his call orally to these common battery relay manual system.

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The fundamental merit of machine systems
machines over human beings in doing certain thin
line switching has become so fully standardized th
tage to machine methods, with diminution of err
same order as resulted from the adoption of typ
as substitute for script and mental addition.

Such systems are in successful use in many ex
and to a growing degree abroad. Their use lat
rising labor costs and by the difficulty of secu
skilled women operators for the manual system
system managers throughout the world recently
machine switching, principally for economic rea
fuller but perhaps belated recognition of what m
do.

Machine switching systems so far most widely
principle. In the system of the Automatic Elect
wide use, selector and connector switches take as
there are units in the digit called.

In manual multiple switchboards, all the lines of
operator. At the time of making a connection th
of a cord circuit may be considered as a terminal
line and seeking the called line in the multiple o
transfer switchboard or in the trunking of a call fr
exchange having several offices with multiple swit
operator must co-operate to complete certain con

A machine system represents a third case in wh
co-operate to complete a connection. In a word
are engaged in making a connection as there are
less one.

Success in machine telephony came with the a
multiple principle and the adoption of the comp
had been abandoned in manual telephony some ti

Selector and Connector Switches. — T
type of machine trunking system is that the calli
"selector switch" to seek an idle trunk from a
which lead in a direction determined by the first
This first switch makes as many vertical steps a
digit called, and immediately thereafter seeks out
of that group. On the calling of the next digit
selected trunk takes as many vertical steps as
digit, and immediately seeks out and appropriate
This process is repeated until all but two digits h
the connection to the last switch which will be
"connector" and has vertical and rotary motion
but, unlike them, both vertical and rotary moti
control. As he calls the next to the last (tens) d
vertical steps as there are units in that digit but
matic rotation. It rotates in response to the call
many steps as there are units in that digit and st
tact with terminals of the called line. Ringing o
caused by automatic means or by relays responsiv
ing subscriber's telephone. Disconnection ensue
hangs up his receiver.

Automanual System. — What has just been s
under subscriber control, in which all the digit-m

hes are dictated by the subscriber's turning of a disk attached e. In the second type of machine-switching apparatus, of later t formerly called automatic, there are in the central office opera- e by telephone the orders of subscribers as in the manual system, e those orders wholly by machines. The latter are controlled ike those of an adding machine. Disconnection is instantaneous up of subscribers' receivers. Very high efficiencies are attained s, and operators' labor costs are low, as few operators are required is done under most favorable conditions.

ems share the advantages of the use of machines; one requires o operate a dial, the other requires him to state his wants orally; ermined which shall be properly called the "natural" method n both systems, however, a higher quality of service is attain- manual system, and operating costs are somewhat reduced.

matic System. — The subscriber-controlled system first operates on the step-by-step method within the central office. natic system contains no such devices, but consists almost relays, much like those used for telegraphy or for relay manual urrent impulses resulting from the operation of the sub- uate these relays in the central office, connecting the lines. llows hanging up the receiver of the calling station. Further- ms of this type may be used in connection with dial-less tele- lition of trunk lines leading to operators in automanual central the requirements of many small rural exchanges adjacent to Calls from the rural subscribers are answered by city operators, relay equipment in the rural exchange over signal trunks. onnections are made the trunks are released for other use. the subscribers' lines follows hanging up the receiver of the ny rural exchanges thus can be operated from one city office, th its other work, the rural offices requiring no operators or ace.

CHANGES. — A private exchange is a group of telephone g apparatus subordinate to a central office, and usually on the the uses of a single business. Private exchanges are widely rtment houses, factories and suites of offices.

es are of three types: those using simple switchboards which erators through whom all local and outside calls pass; those ach telephone whereby each user may select the line of any trunk line to a central office, and those having a local equip- switches of the step-by-step or of the relay type.

ject of the private exchange is to enable the telephones within cate with each other directly without using lines through all. A second object is to enable communication from tele- ate exchange through the central office by the use of fewer ere are telephones in the private group. A serviceable ratio cal telephones may be from one-tenth to one-fifth at a con- cost over the providing of a line to the central office from e.

RCUITS (Fig. 32.) — In Fig. 32, four wires join two offices. rs. They are designed to be efficient in transforming both currents. Currents from telephones connected to either es pass at any instant in opposite directions in the two wires hantom circuit uses one of the physical pairs as a wire of its by tapping the middle point of the line side of each of the

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transformers. The currents of the phantom circuit
circuit because they pass outwardly from the mid
in equal and simultaneous amounts and, therefore
netization in the core. The currents of the physi
the phantom circuit because the former can produ
in the phantom circuits, provided all four wires are
lation; under these conditions no difference of pot
middle points of the repeating coils at the two ends

Phantom circuits also are arranged with transfo
line and the phantom jack at each end of the circuit

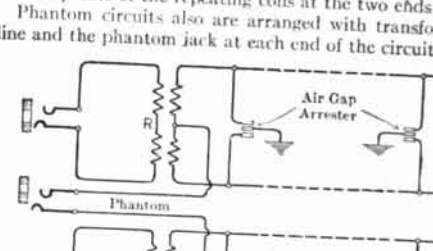


Fig. 32. Phantom Circuits

It is now possible to phantom loaded circuits and
The physical circuits, however, must be carefully
and well maintained, in order to get good results on b
circuits.

JOINT TELEPHONE AND TELEGRAPH C

lines may be equipped so as to permit speech and tel
same wires at the same time without interference wit
two ways of accomplishing this, being known respectiv
and the composite system.

Simplex Circuits (Fig. 33) are made from metall
as in Fig. 33. The principle is the same as that of

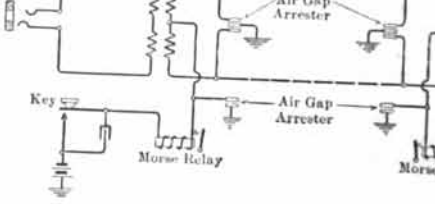


Fig. 33. Simplex Telephone and Telegraph

cuit. Nearly the same results can be obtained by usi
coil (i.e., a single winding with tap brought out from the
the telephone line instead of a transformer inserted in
such a line with a grounded generator the telegraph relay

Circuits (Fig. 34) depend upon a different principle. Imped- inserted to oppose alternating currents, and condensers to oppose ts. In Fig. 34 one telephone circuit forms two Morse circuits, so s form one telephone circuit and (with the earth) two telegraph h Morse circuit includes in series two 50-ohm impedance coils and e shunted to ground between the Morse sets and the impedance -ohm impedance coils are connected differentially and so offer low the Morse impulses, whose frequency is not high. The coils, how- eat impedance to voice currents, since they are not differentially h respect to the latter. Voice currents can pass through the con-

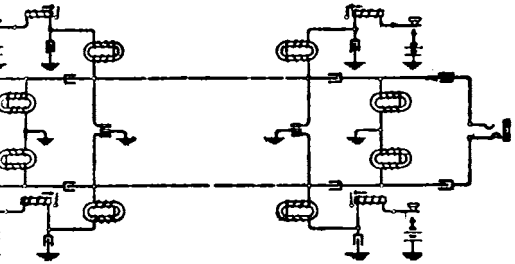


Fig. 34. Composite Telephone and Telegraph Circuit

telephone line, but direct currents cannot. Impulses due to dis- and capacities in the Morse circuit would make sounds in the hat they are choked off or led off by the 30-ohm impedance coils apacities connected to the Morse sets.

mposite Systems. — The principles of the respective imped- tances and capacities to direct and alternating currents, upon posite system depends, are applied to the conversion of series into combined telegraph and telephone lines. It sometimes is of modify a single-wire telegraph line so that telephones may be without abandoning its use as a regular telegraph circuit. gement is known as a railway composite system. Calls between ns on such a circuit are sent by means of high-frequency alter- such as are developed, for example, in an automobile spark coil. received at the telephone stations on "howlers," which are merely ers with special horn-shaped mouthpieces. These calling cur- high frequency as not to affect the telegraph relays. The paths equency currents in general are supplied by condensers and the wer-frequency currents for telegraphy in general are supplied

E REPEATERS. — A telephone repeater is an apparatus the voice currents flowing in the line. Repeaters are not within a city, but are useful in long-distance working. They amplify speech in both directions in the line, without requiring ments of the apparatus, so that the conversation may proceed line having no repeaters. Amplifications sufficient for around- ission are now possible, assuming a line to be available. of amplification exist. That of Shreeve uses an electromagnetic ate the movable electrode of a carbon-granule transmitter.

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The other method uses a three-electrode vacuum
parts whatever, unless electrons be called movin
there are associated transformers and condensers
requirements of the problem.

In the vacuum-tube method one of the tube's elec
as in an incandescent lamp; the other two electro
lated from each other and from the filament withi
Variations of potential on one of the insulated surf
rent in a circuit between the filament and the sec
current so varied may have many times the amplitu
the current causing the varying.

Repeaters are adaptable to other uses than in
possible to pick up at considerable distances stray
single wire or even two-wire telephones line, and
It is possible to repeat between radio-telephone
with such freedom that the conversation over the
lent to wire conversation. Speech originating in e
can be amplified and delivered to loud-speaking rec
enabling large groups of people to hear one speake
where the amplification desired is greater than on
two or more tubes can be used. The current deliv
by another, and so on in "cascade." As many as
cascade.

For a detailed discussion of the three-electrode va
Radio Communication.

MULTIPLEX TELEPHONY. — Vacuum tu
rents into high-frequency alternating currents, cap
electromagnetic waves through space or along con
of propagation a number of different frequencies ca
wires, each frequency being a carrier for one conv
capacitances properly related to the frequencies
the several conversations. The currents used in s
believed to be carried through space adjacent to
through the metal of the wires. This multiplex t
over wires that at the same time are being used fo
Morse telegraphy. See article on *Telegraph System*

COSTS (Pre-war figures). — The following
they are all f.o.b. factory. These costs are given
preliminary estimates. For accurate estimates qu
from the manufacturers.

Magneto wall set complete:

Series (80-ohm ringer).....
Bridging (1000- to 2500-ohm ringer).....
Magneto desk set complete:
Add 75 cents to above prices.
Common battery wall set complete:
Oak or walnut, 500-ohm ringer.....
Oak or walnut, 1000-ohm ringer.....
Hotel type, 1000-ohm ringer.....
Common battery desk set complete with cord:
500-ohm ringer.....
1000-ohm ringer.....
Automatic wall or desk set.....

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witchboards:

lines, 1-operator equipment	175–575
lines, 2-operator equipment	730–865
mon battery switchboards:	
ines	550–2500
nding cost per line	5.50–4.17

ommon battery switchboards, formerly standard for offices in anges, are so largely superseded by machine-switching equipments actice that prices will fluctuate widely among different types. hing equipment prices vary with the type; the amount of equip- on the amount of traffic and on the number of telephones in the eneral, however, machine-switching equipments cost more to s to operate than do manual equipments.

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TELEPHONE LINES. — (*See also Distribu Lines; Wires and Cables.*) The line always consist one of these may be the earth. The standard tel wires of the same size and of the same material. the earth forms the return the line is called a "gr two wires without earth return is called a "metalli

LINE CONSTANTS.—(*See also Transmission* efficiency of a telephone line depends upon its resis leakage and inductance.

Leakage. — High insulation, i.e., small leakag a line and from each wire to earth is possible in insulation is possible in open wire lines.

Resistance.— The resistance of the conductor telephone current, but does not distort it appreci to resistance are practically independent of the freq

Electrostatic Capacity. — The electrostatic ca the current and distorts it also, because the ch pendent of the frequency. As the voice current is posite frequency, the higher frequencies are reduce

There are two ways of expressing the important capacity in cables, i.e., in terms of the "mutual or in terms of the "grounded" or "regular capaci *ity and Charging Current.*) The mutual expressio the amount of mutual capacity which determines capacity in telephone cables is about two-thirds same wires. A given cable has higher capacity cable capacities should be referred to a standard te

Inductance. — The inductance of telephone lin small, since the wires are usually close togethe together for use as lines in cables have very small *Inductance and Inductive Reactance.*)

Pupin Coils. — In 1887 Oliver Heaviside po inductance would decrease the harmful effects of c Pupin made public (*Trans. A.I.E.E., Vol. XVII,* ing attenuation and distortion by inserting additio showed how to determine how much inductance t ideal method distributed inductance would offset capacity. In the Pupin method the inductance is at predetermined intervals. The coils ordinarily They are called "loading coils" because of physical the publication cited.

CHARACTERISTICS OF OPEN WIRE LIN lines hard drawn copper is now almost universally important lines, where iron wire may be employed employed range from No. 16 B. & S. to No. 8 B length and importance of the line. Where the te is unimportant, as when the wires are fastened alon ports close together, smaller sizes may be employe instead of hard drawn. Aerial wires are usually horizontally, and from 18 to 24 inches vertically, de the cross arms. For the resistance, capacity, and in *Wires and Cables, Bare.* The insulation resistan wires depends upon the types of insulator, pin an

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ndition of the weather. The following values are representative of good ctice: —

Very dry,	500 megohms per mile.
Average,	25 megohms per mile.
Very wet,	2 megohms per mile.

Three different gages are employed for specifying the size of telephone wire: B. & S., the B. W. G., and the N. B. S. (*See article on Gages, Wire.*) The lowing table gives the diameter, weight and resistance of the various sizes ployed in telephone practice.

TABLE I

Number	Diameter in mils	Weight per mile in pounds	Resistance per mile of wire in ohms, 60° F.	Resistance per mile of circuit in ohms, 60° F.
8 B. W. G.	165	435	1.97	3.95
6 B. & S. G.	162	419	2.05	4.10
8 N. B. S. G.	160	409	2.10	4.20
7 B. W. G.	148	350	2.45	4.91
7 B. & S. G.	144.3	331	2.59	5.19
9 N. B. S. G.	144	331	2.59	5.19
5 B. W. G.	134	287	2.98	5.97
8 B. & S. G.	128.5	262	3.28	6.56
5 N. B. S. G.	128	262	3.28	6.56
1 B. W. G.	120	230	3.73	7.47
1 N. B. S. G.	116	215	3.99	7.99
9 B. & S. G.	114.4	208	4.14	8.27
2 B. W. G.	109	190	4.52	9.05
2 N. B. S. G.	104	173	4.97	9.94
0 B. & S. G.	101.9	166	5.17	10.33
3 B. W. G.	95	144	5.96	11.91
3 N. B. S. G.	92	135	6.35	12.70
1 B. & S. G.	90.74	130	6.49	12.98
4 B. W. G.	83	110	7 80	15.61
2 B. & S. G.	80.81	105	8.19	16.39
4 N. B. S. G.	80	102	8.40	16.80

CHARACTERISTICS OF TELEPHONE CABLES. — Telephone bles are groups of pairs of paper insulated wire twisted together and en-sed in a lead sheath. Soft drawn copper is invariably used for the con-ctors. The size wire usually employed ranges from No. 19 to No. 22 B. & S. r long distance underground lines individual wires as large as No. 10 B. & S. ve been employed. For the resistance of the different sizes of conductors see *ires and Cables*. The capacity of any pair of wires and the capacity of any e wire to ground depends largely upon the way in which the cable is made up. hen the wires are twisted tightly together the capacity is greater than when ey are loosely assembled. The mutual capacity ranges from 0.067 to 0.090 icrofarad per mile, and the regular or grounded capacity from 0.10 to 0.12

microfarad per mile for tightly twisted wires, as
0.080 to 0.10 respectively for loosely twisted wir
capacity is usually referred to as "high" and the l

The effective insulation resistance between the tw
megohm per mile at 800 cycles per second in a w
figure includes the effect of dielectric hysteresis.
resistance measured by direct current would be a
per mile.

The inductance of a pair of wires in a telephone c
being less than 1 millihenry per mile of cable (2 mi

DISTORTION AND ATTENUATION. — (S
Corresponding to any vowel, syllable or word spok
rent wave of a definite shape is sent over the line.
number of simple sine waves of different frequen
placed with reference to one another, i.e., reaching
times. Each of the simple sine waves as it progress
amplitude or is "attenuated." Moreover, the sh
attenuated more than the longer ones, with the
reaches the receiver is made up of harmonics of rel
than the wave sent out from the transmitter, that i
receiver is "distorted." The sound produced by
differs from the word spoken into the transmitter, si
depends upon the relative magnitude of the const
also a displacement of the harmonics with referenc
placement, although it changes the shape of the re
if any, effect upon the quality of the sound.

Attenuation of a wave without distortion merely
since the wave form remains unchanged, only the
duced thereby, were it converted into a sound wa
alone, since it produces the same relative attenuation
fore the least troublesome of the line characteristics.
of the line is the controlling characteristic, since the a
depends upon the wave length, and therefore disto

In addition to the distortion produced by the line
tion in the transformation at the transmitter of the
wave, and again another distortion at the receiver
reconverted into a sound wave.

**DISTURBANCES DUE TO NEIGHBORIN
SION LINES.*** — (*See also Distribution Lines; T*
small voltage between the wires of the telephone
duce noise in the telephone apparatus comparable
produced by the voice currents. The noise is due
monics of the power system, especially to those be
At these frequencies induced currents in the tele
millionths of an ampere are sufficient to make conv

Balanced versus Unbalanced Power Circuits.
of neighboring power circuits on telephone circu
balanced and unbalanced power circuits must be cle
pletely balanced power circuit consists of two or mo
way that the vector sum of the currents in all the w
cally zero, and the vector sum of the voltages betwe
ground is practically zero. A *completely unbalanced*
or more wires with a ground return, the currents in

* By H. Pender.

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and the voltages between the several wires and the ground being ual and in phase. In practice power circuits are frequently etely balanced nor completely unbalanced, but the currents and be resolved into completely balanced and completely unbalanced Examples of such circuits are a three-phase circuit having one and a three-phase circuit with grounded neutral; in the latter al current may be of fundamental frequency due to an unbal- the system, or the neutral current may be of triple frequency harmonic in the voltage wave (*see Generators, Alternating Current*). e effects arising from unbalanced voltages or currents are very an the inductive effects arising from balanced voltages or currents agnitude, because with balanced voltages and currents the effect argely neutralized by the near presence of other wires of opposite

duced between Wires and between Wires and Ground. ircuits affect the telephone circuits by producing: (1) a voltage o wires of the telephone circuit; (2) a voltage between telephone nd.

between telephone wires and ground is usually large compared e between wires. Even though the telephone circuit is transposed oltages are induced between the two wires and ground, the volt- produces a voltage between wires because of the unavoidable ities in the constants of the two sides of the circuit. If the nd is high it endangers the users and operators of telephones e circuits and puts the circuits out of commission by operating evices.

or Inductive Disturbances in Telephone Lines. — It is in ible to perfectly realize any of the following remedies, and no ould be sufficient even though perfectly realized. In order to tive disturbances it is therefore necessary to carry out each of far as possible.

sposition of Power and Telephone Circuits. — The way in effects are affected by the transposition of the power and s is indicated in the following table:

EFFECT OF TRANSPOSITIONS

Line	Voltages Induced in Telephone Line	Affected by Transpositions in	
		Power Circuit	Telephone Circuit
.....	To ground	Yes	No
	Between wires	Yes	Yes
.....	To ground	No	No
	Between wires	No	Yes

lance as far as possible the inductive effects between a three- uit and a telephone circuit it is necessary to divide each uni- he exposure into six or a multiple of six equal sections in which f the six possible phase angles are induced. The methods of tions of a telephone line are described below in the section on *s;* methods of transposing power lines are described in the *ission Lines.*

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2. **Balancing the Power Circuit.** — Th
the telephone circuits and ground by small unb
power voltages and currents are relatively large ar
positions. In order to reduce the inductive interfe
ant to construct and operate the power circuit in s
possible balanced with respect both to voltage and

3. **Balancing the Telephone Circuit.** — I
by the voltage between the telephone wires and g
is necessary that the telephone circuits be carefull
two sides of the circuit be of the same resistance a
the same insulation resistance and the same capa
ancing due to unequal insulation and to unequal c
ductors and ground is frequently important and ev
minimize it. All apparatus connected to the cir
impedances inserted in the two sides of the circuit,
between the two sides of the circuit and ground, are
equal.

A Joint Committee on Inductive Interfe
mission of the State of California made a thorough s
interference between electric power and electric con
1911 and 1919, and its findings, reports and reco
the Commission's rules and orders, are a source of
ject. The matter is available in a volume issued
in bibliography.

**COMMERCIAL TRANSMISSION. — LIM
DISTANCES.** — Transmission is said to be "co
with normal ears and voices, using standard tra
converse with reasonable ease. The length of the
versation can take place is called the "limiting
limiting transmission distance of a pair of No. 19 B
insulated cable is about 30 miles, the resistance per
(2 miles of wire) being 88 ohms and the mutual ca
microfarad per mile. Such a line is taken as a sta
may be referred.

For ease in comparing various lines, the qualit
described are very closely imitated by assembling
sers in a portable case, the number of coils and co
artificial line thus made is equivalent to many mil
artificial line is usually referred to as a standard c

To determine the qualities of an unknown line
observer listens to a distant speaker alternately th
the standard cable set. He adjusts the latter unti
and similarly through both. The number of mil
gives the limiting transmission distance of the li
the limiting transmission distance by the actual l
of its transmitting ability.

The limiting transmission distances of various ty
manner explained above are given in Table II, be
allowance for switchboard and connection losses.

Effect of Bridging Telephone Set Across Li
a standard local telephone set across a non-loaded
the limiting transmission distance by approximately
bridging such a set across a cable circuit is cons

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er cent. These figures also apply roughly to each of several sets bridged oss the line, provided these sets are widely separated.

INE CONSTRUCTION. — In open country and small towns aerial lines n bare wires are almost invariably used. In large cities cables containing n 5 to 600 pairs of wires are usually employed. Cables may be run overhead nderground. Aerial telephone cables, on account of their low tensile strength, hung from steel messenger wires, the latter being supported from the cross

TABLE II

Gage of wire	Theoretical limiting distance, with no allowance for switchboard losses and without Pupin coils
	Miles
o. 8 B. W. G. copper, open wire line	900
10 B. W. G. copper, open wire line	700
10 B. & S. copper, open wire line	400
12 N. B. S. copper, open wire line	400
12 B.& S. copper, open wire line	240
14 N. B. S. copper, open wire line	240
8 B. W. G. iron, open wire line	135
10 B. W. G. iron, open wire line	120
12 B. W. G., iron, open wire line	90
16 B. & S. cable, copper	40
19 B. & S. cable, copper	30
22 B. & S. cable, copper	20

Wires smaller than those given in this table should not be used on pole lines, account of their lack of mechanical strength.

ns or fastened directly to the poles. Underground cables are usually run in : or other type of ducts. (*See Conduits and Conduit Lines, Underground; res and Cables.*)

Open Wire Lines. — With the exception of the smaller insulators, usually ss, and the larger number of wires carried on a single pole line (as many 100), the construction of open wire telephone lines differs but slightly from at of pole lines for power transmission. (*See Cross Arms; Distribution Circuits; Poles for Overhead Lines; Transmission Lines.*)

The size of poles and their spacing usually employed for various classes of es through level country are given in the following table:

Type of line	Ultimate number of wires	Height, feet	Diameter of top, inches	Number per mile
Short, local	6	22	5 to 6	30
Important routes	20	25	6 to 7	40
Long distance	30 to 40	30 to 35	7 to 8	40

Where special conditions arise the height and size of poles must be selected ccordingly. The depth to which a pole is set in the ground ranges from one-

fifth to one-eighth of its total height, the larger fig
(25 feet), the latter to tall poles (65 feet).

Hard-drawn copper wire is now used on all importa
iron wire is still employed on short unimportant li
steel wire has been proposed for telephone lines. S
properties of wires. The particular size to be emplo
upon the length of the line; see Table II above.
are usually spaced 1 foot apart horizontally and the
to 24 inches apart.

Transpositions to Prevent Cross-Talk. — which may thread the space between the two wires varying electrostatic field about the line, will set up a and if the frequency is such as to produce in the pitch, this sound will interfere with the proper fun noise produced in this manner by one telephone "cross-talk." Noise may be produced in a similar from other sources, such as railway or lighting (altern

To prevent such cross-talk or noise the wires of a transposed every quarter of a mile. Fig. 1 show scheme. The vertical lines represent the cross arm

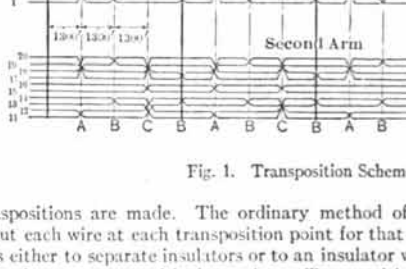


Fig. 1. Transposition Schem

transpositions are made. The ordinary method of to cut each wire at each transposition point for that ends either to separate insulators or to an insulator make the cross-overs with short wires. Transpositio out cutting the wire by using a single insulator with the other. This scheme, known as the "single cheaper than the ordinary scheme.

The transpositions for the first and second cross ar in Fig. 1; when there are more than two cross arms, bered arms are usually transposed in the same manne and the wires on the even numbered arms in the sa second arm. When phantom circuits are used the are not transposed alike.

Transposition systems become more comprehens with the growth of phantom circuit working and th technique in neutralizing inductive disturbances. of the principle of transpositions.

Telephone Cables for either aerial or under follows: Soft copper wires are insulated with dry such insulated wires then are twisted into a pair, t

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TABLE III. PROPERTIES OF STRANDED TELEPHONE CABLES

No. pairs	Gage B. & S.	Electrostatic capacity	Thickness of sheath, inches	Approximate external diameter, inches	Approximate weight per foot, pounds
5	22	High	1/12	0.48	0.55
10	22	High	1/12	0.59	0.71
15	22	High	1/12	0.66	0.83
20	22	High	1/12	0.72	0.93
25	22	High	1/12	0.77	1.02
50	22	High	1/12	0.97	1.45
50	20	High	3/32	1.10	1.88
100	22	High	3/32	1.32	2.36
100	22	Low	3/32	1.50	2.63
100	20	High	1/8	1.57	3.60
100	20	Low	1/8	1.81	4.11
200	22	High	1/8	1.84	4.43
200	22	Low	1/8	2.11	4.99
200	20	High	1/8	2.11	5.47
200	20	Low	1/8	2.46	6.19
200	19	High	1/8	2.24	6.08
200	19	Low	1/8	2.65	6.94
300	22	High	1/8	2.21	5.71
300	22	Low	1/8	2.51	6.32
300	20	High	1/8	2.53	7.09
300	20	Low	1/8	2.96	7.94
300	19	High	1/8	2.69	7.95
300	19	Low	1/8	3.20	9.04
400	22	High	1/8	2.51	6.84
400	22	Low	1/8	2.86	7.56
400	20	High	1/8	2.89	8.56
400	20	Low	1/8	3.43	9.37
600	22	High	1/8	3.20	9.21
90	16	Low	1/4	2.88	7.2
43	13	Low	1/4	2.88	7.17
50	10	High	1/8	2.88	8.95

Note. — High capacity, 0.067–0.090 mutual, 0.10–0.12 grounded. Low capacity, 0.054–0.067 mutual, 0.080–0.10 grounded.

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ent colored papers; a number of pairs are laid up s
core. The core then is wrapped spirally with pap
and a lead sheath molded on it in a lead press. M
cent of tin in the lead sheath.

The external diameter and **weight** of a cable co
pairs depend upon how closely the wires are wrapp
determines the capacity of the wires, the capacity
wires are wrapped together. Table III gives the
standard cables.

Telephone cables, if used in connecting subscr
offices, usually are formed of 22 B. & S. gauge w
when No. 19 B. & S. is generally used. For trunk
exchanges, cables are usually formed of No. 19 B.
coils are used in trunk lines, and successful operat
would be impossible without loading coils.

Cables for long distance purposes have large wi
mit the use of loaded cables between cities, the op
uniform. Chicago and New York are connected to
hundred miles by loaded underground cables, and
The principal advantages are that the cables are n
their insulation does not vary. The insulation res
tion and distortion of the waves sent over the wire.
coils are particularly sensitive to changes in insulat
age in wet weather greatly exceeeds the normal leak
more harm than good.

Installation of Cables. — (*See also Conduits
ground; Wires and Cables.*) It is of particular impo
nected with telephone cables to keep the core dry.
only by paper, which is useless if moist and is of v
dry air. As soon as the sheath is removed from a
nating, the paper absorbs molsture from the air
fore expose the core as little as possible and boil
hot paraffine over and through the conductors
cable.

Splicing. — To splice a telephone cable, a le
of the ends and the sheath cut off of each of the en
part at which the sleeve later is to be soldered with
is bound tight with dry muslin just at the end of
packed under slightly. The cable ends are boiled i
immersion. If white fumes arise from the paraffi
then are joined by stripping the paper from the en
together so as to include a little of the insulation,
sleeve previously placed over one wire.

When all the pairs are spliced, the conductors
paraffine. The lead sleeve is slipped into place, it
wipe joint made at each end. This gives the splic
the cable itself. A *Y-splice* is one in which one cab

Cable Terminals are devices in which the p
phone cable are made accessible to wires outside t
requirement is that the insulation of the conducto
by keeping moisture from the cable insulation and
which the wires outside the cable attach.

A standard form of cable terminal consists of a
iron and partly porcelain, wherein the end of the c

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mpound. Binding posts in the porcelain receive the cable wires inside the aled part and the outer wires on the outside.

Potheads are splices between rubber-insulated wires and paper-insulated ble wires. They are filled with bituminous sealing compound, so that moisre shall not lead to the paper insulation along the rubber-insulated wires. Potheads are less widely used than before the development of the porcelain rminal. They are necessary for places where more than 50 pairs of wires are be terminated. At the junction between aerial and underground cables, ses require to be inserted to complete the protective system. Potheads then e placed on both cables, and the rubber-covered wires led to the fuse terminals. is good practice to house the fuses and pothead ends in wood or metal proting boxes.

Drop Wires. — The wires used to connect open wire lines or aerial cables subscribers' premises are called drop wires and are of hard drawn copper inlated with rubber, covered with a braid, then twisted into pairs. Standard es are No. 16 B. & S. gage in regions where ice does not form, and No. 14 & S. gage in other regions. No. 17 B. & S. copper-clad steel wire is sucssfully used as a substitute for either.

ELECTROLYSIS of the sheaths of underground telephone cables takes ace when the sheaths carry stray direct current from one region to another the current leaves the sheath in the presence of moisture (*see Electrolysis of rounded Structures*).

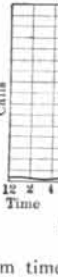
COSTS.—The cost of building a telephone line depends on so many varides that no data of any value can be given in the space here available. Useful st data on telephone lines will be found in J. C. Slippy's *Telephone Cables* and Clark's *Telephone Construction Methods and Costs*, Appendix A. Approxiate costs of the various constituent items will be found in the articles on *nduits and Conduit Lines, Cross Arms, Insulators, Poles for Overhead Lines, ire and Cables, etc.*

BIBLIOGRAPHY.—See *Bibliography* in article on *Telephone Instruments d Circuits.*

[S. G. McMeen.]

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TELEPHONE TRAFFIC AND RATES.—*ments and Circuits; Telephone Lines.*) For the pu phone users, the unit of telephone traffic is the "con of designing and using telephone equipment the t unit. A call does not always result in a conver subject to general variations closely linked with va Obviously, telephone traffic relative to business i working days; on all days telephone traffic vari fairly uniform from day to day. It is possible to p is a load curve representative of what happens each working day in most regular exchanges. The number of calls which subscribers originate depends on the kind of service rendered, whether residence, business, etc., and on the method of charging. Subscribers will call about twice as often under flat rates as under measured rates.



A knowledge of the amount of traffic in a system, of its distribution as to time and as to divisions of the exchange, is important. By that knowledge the equipment must be designed, modified from time tributed upon it as changing circumstances shall re

Methods of Counting Calls. — Amounts of t are observed in three general ways. A peg-coun operator actuating some counting device for each A second way is to determine a ratio existing, for t between the calls in a given period and the averag use in that period. Knowing these, the probable the cord circuit as counted. The third method is service meters on all lines and is to associate one with all the meters of that position, so that it will cou meter of the position is operated.

In machine switching systems, meters can be ar tabulate any desired part of the traffic automatica themselves are equipped with service meters for charging for the service.

Operator's Speed.— The number of calls an o hour depends on the percentage of total calls whi offices. With standard manual equipment, for exa calls in an hour if none have to be trunked, and 165 them have to be trunked. In machine switchin controlled type, an operator completes a much la per hour. All calls being handled alike, whatever station within the exchange system, the work of t may be as many as 1200 connections per busy ho are average and usual performance, as compared wi 165 per hour.

Prompt disconnection is of great importance. A nect signals shall be given prompt attention by so precedence over a call for connection. A flashing recall should be given precedence over all other calls systems disconnection is automatic and instantaneo

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NG. — Traffic studies enable the determination of the number uired for an anticipated traffic. The number of trunks required, central offices, or between a central office and a private exchange the number of calls which must be trunked per maximum or busy lement of the probable coincidence in the time at which the calls must be considered, and for this reason the more trunks installed ill be the number of calls which each trunk may be expected to following illustrate current manual practice:

unked calls per busy hour	35	90	1080
umber of trunks required	5	10	60
lls per trunk	7	9	18

ONE RATES. — Rates for telephone service are of two kinds, nd "measured service rates." Under flat rates, a fixed sum per ed and the subscriber may use his telephone as much as he pleases. ed service rates, the subscriber is charged a certain sum for each e originates. Ordinarily also the subscriber guarantees to pay certain minimum amount per month. Rates for private exchanges up by charging a rate per month for each local telephone, another for each section of local switchboard, another rate for each trunk l further rate for each outward call over the trunk lines leading te exchange, the monthly charge being the sum of all.

elephone service depends on the amount of use, though there is a ost of being prepared to furnish service. There is a tendency to e flat-rate to the measured-rate system. The latter is in opera- ge cities.

ystems. — In flat-rate systems there is no continuous effort umber of conversations. Counting is done from time to time urposes.

ate Systems. — In measured-rate systems it is necessary to ersations as they occur, so that each subscriber may be charged he receives. Sometimes this is done by hand on tickets, but nterferes with the operator's regular work, losing not only perating but wasting switchboard investment by not using it e best way is to equip each line with a meter under electrical uses it to count one unit for each completed conversation. Such xtensive use in the larger cities. In manual systems, when a kes place, the operator presses a meter key associated with the and this makes the record upon the meter. In automatic wering of the called station operates the meter.

ces in London usual calls are charged a penny each and certain wo-pence each. In trunking calls of the latter kind, the operator he higher charge by the lighting of a specially colored lamp as nk order key. Being so reminded, she presses the meter key n a conversation occurs, the result being that the calling sub- -pence for each such special call, because his meter records two

TANCE CALLS are those which occur between cities, as dis- within cities, no matter how large the latter may be. Long- ually are handled by special operators at special switchboards unks to the switchboards which handle city service. Long-dis- ly require that a particular person be found in the called city, such calls includes the name as well as the number of the called ticket is recorded the duration of the conversation in minutes.

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and fractions so that the charge may be computed recorded by a time-computing machine which prin

Two-number Method. — Where calls betwe number, it is found economical to provide for con stations of the subscribers who call frequently, number" method. Such connections generally ar ing to and from special long-distance switchbo multiple-switchboard positions make and comp ticketed only at the originating end.

COIN-COLLECTING DEVICES. — Measur or long distance, may be made over telephones devices. These are so arranged that the operator in advance of conversation that the proper amou in the machine. Machines of one type require th the central office can be signaled at all; the coin completed. Machines of the other type require after the order has been given but before the conv

DEVELOPMENT STUDIES — FACTORS A development study is an inquiry to determine w of construction or reconstruction is warranted by ties of a region. Some form of development st work. Economical construction and efficient ope provement in development-study methods and thei

Forecasting Requirements. — In cities a first development through a period of from 15 to 20 yea ing statistics of growth. Ratios of telephones to p for the past, and future ratios estimated. A taken. This means the counting of existing bu of the telephone-using abilities of the occupants. is made of the probable future development of e

Determination of Number of Central Office quire switchboards for more than 10,000 lines there office. The more switchboards there are in a town, shorter will be the average length of subscribers' the mileage of trunk lines. The more offices there owning and maintaining the buildings for them, operating the equipment in them. A balance for the

The economical number of districts having been district can be located so as to attain the greatest runs and pole lines then are laid out for the subscrib ing generally, it is good practice to provide a main office and having cross routes extending from it a alternate street or in alleys if they exist.

In machine-switching practice, it is possible fu districts and to place some of the apparatus in sm trunks leading to the district office, still other tr district offices. This lowers still further the co increases still further the cost of trunk lines.

BIBLIOGRAPHY. — See Bibliography in artic *and Circuits.*

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TURE AND THERMOMETERS. — (*See also Heat and rties; Pyrometers; Thermodynamics, Principles of; Units and Con-*.) The temperature of a body may be defined as its relative olness referred to some standard substance under standard con- change in some physical property of a standard substance must order to give a number to temperature. Any device which serves called a thermometer; if the device is applicable to the meas- y high temperatures it is also called a pyrometer, q.v.

TURE SCALES. — The standard* temperature-measuring onstant volume hydrogen thermometer, which consists essentially eceptacle containing a constant mass of hydrogen gas kept at e, viz., the volume it would have at a pressure of 1000 millimeters l at the temperature of melting ice, with means provided for variation that may be caused to take place in the pressure of

Scale. — The temperature of melting ice at a pressure of 760 ercury is arbitrarily taken as zero degrees, and the temperature eam at a pressure of 760 millimeters of mercury is taken as alling p_0 the pressure of a constant volume of hydrogen gas tacle is immersed in the melting ice and p_{100} its pressure when e saturated steam, and p_t its pressure when immersed in any (the pressure in each case being measured after the lapse of a or it to reach a constant value), the numerical value of the tem- given substance is defined as

$$t = \frac{p_t - p_0}{p_{100} - p_0} \times 100.$$

ade is abbreviated deg. cent. or °C.

Scale. — The Fahrenheit scale of temperature is derived in r, except that the temperature of the melting ice is taken as ling point of water (at 760 millimeters mercury) as 212°. A degrees Fahrenheit is then equal to

$$t_c = \tfrac{5}{9}(t_f - 32) \qquad \text{degrees centigrade.}$$

perature of t_c degrees centigrade is equal to

$$t_f = \tfrac{9}{5} t_c + 32 \qquad \text{degrees Fahrenheit.}$$

eit is abbreviated deg. fahr. or °F.

le. — This scale, which is used to some extent in Europe and his country, is defined in the same manner as the centigrade t the boiling point of water (at 760 millimeters mercury) is temperature of t_r degrees Réaumur is then equal to

$$t_c = 1.25\, t_r \qquad \text{degrees centigrade.}$$

e. — See article on *Pyrometers*.

TEMPERATURE. — Let p_0 = absolute pressure of a given ° C., p = absolute pressure of this same mass of gas at any as above defined. For all values of t between about $-150°$ e., for all values of t within the experimental range, it is found

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DEGREES FAHRENHEIT CORRESPON
CENTIGRADE

°C.	0	− 1	− 2	− 3	− 4	− 5
−40	−40.0	−41.8	−43.6	−45.4	−47.2	−49.0
−30	−22.0	−23.8	−25.6	−27.4	−29.2	−31.0
−20	− 4.0	− 5.8	− 7.6	− 9.4	−11.2	−13.0
−10	14.0	12.2	10.4	8.6	6.8	5.0
0	32.0	30.2	28.4	26.6	24.8	23.0

°C.	+ 0	+ 1	+ 2	+ 3	+ 4	+ 5
0	32.0	33.8	35.6	37.4	39.2	41.0
10	50.0	51.8	53.6	55.4	57.2	59.0
20	68.0	69.8	71.6	73.4	75.2	77.0
30	86.0	87.8	89.6	91.4	93.2	95.0
40	104.0	105.8	107.6	109.4	111.2	113.0
50	122.0	123.8	125.6	127.4	129.2	131.0
60	140.0	141.8	143.6	145.4	147.2	149.0
70	158.0	159.8	161.6	163.4	165.2	167.0
80	176.0	177.8	179.6	181.4	183.2	185.0
90	194.0	195.8	197.6	199.4	201.2	203.0
100	212.0	213.8	215.6	217.4	219.2	221.0
110	230.0	231.8	233.6	235.4	237.2	239.0
120	248.0	249.8	251.6	253.4	255.2	257.0
130	266.0	267.8	269.6	271.4	273.2	275.0
140	284.0	285.8	287.6	289.4	291.2	293.0
150	302.0	303.8	305.6	307.4	309.2	311.0
160	320.0	321.8	323.6	325.4	327.2	329.0
170	338.0	339.8	341.6	343.4	345.2	347.0
180	356.0	357.8	359.6	361.4	363.2	365.0
190	374.0	375.8	377.6	379.4	381.2	383.0
200	392.0	393.8	395.6	397.4	399.2	401.0

Example: − 12° C. = 10.4° F.; − 33° C. = − 27.4°

that, in the case of the so-called permanent ga
readily liquefied, such as air, hydrogen and nitr
exists between p_0, p and t provided there is no ch

$$p = p_0 (K + t),$$

where K is a constant, approximately equal to 2
in 300.* Consequently, assuming this relation
becomes zero, the value of t which would correspo

$$t_0 = - 273° \text{ C.}$$

This temperature is called the absolute zero. Tha
scale is 273° C. above the absolute zero.* Similar
scale is approximately 460° F. above the absolute

* For hydrogen Callendar gives the

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ature measured above the absolute zero is called the absolute
Let t_c = temperature in ° C. above the centigrade zero, t_f = tem-
above the Fahrenheit zero, then the absolute temperature in ° C.
o t_c is

$$T_c = 273 + t_c,$$

e temperature in ° F. corresponding to t_f is

$$T_f = 460 + t_f.$$

Thermodynamic Temperature. — (*See article on Thermo-
ciples of.*) The difference between the temperature scale as
onstant-volume hydrogen thermometer and the absolute thermo-
s less than 0.1° C. at ordinary temperatures, and is less than 1° C.
range from − 150° to 1000° C.

IETERS. — The standard constant-volume hydrogen ther-
om used except for standardizing purposes, and then only for
o to about 500° C. The constant-volume nitrogen thermometer
dardizing purposes for temperatures up to about 1500°. For
ures radiation pyrometers are used as standards (*see Pyrometers*).

Glass Thermometers. — For ordinary temperature measure-
about − 35° C. and 350° C., the ordinary mercury-in-glass
almost universally employed. The temperature may be read
e position of the end of the mercury column as given by a
ed scale on the stem, provided the 0° and 100° points have
cated and the stem has a uniform bore.
neasurements the scale on the thermometer should be checked
ether the 0° and 100° points are properly located and whether
rm. Unless the proper quality of glass is used the bulb does
actly the same volume after successive heatings. Even when
rmometer is employed, the zero should be frequently checked
er is used for high-temperature measurements.
alibrating mercury thermometers are described in text books
the present day it is more convenient to compare the ther-
secondary standard mercury thermometer which has been
entral standardizing bureau, such as the Bureau of Standards

ge Mercury Thermometers. — The mercury thermometer
ery hard glass and filled under pressure with the space above
mn containing some inert gas, like nitrogen, may be used to
tures up to about 550° C. If a considerable length of stem
air, a very considerable error, 25° C. or so, may be introduced
ures. This "stem correction" varies slightly with the kind
be represented very nearly by the formula

ection to be added to reading = $0.00016\, n(t_b - t)$,

atures are all in degrees centigrade and n = number of degrees
ath or furnace, t_b = temperature of bath and t = mean tem-
ent mercury column.

dinary mercury thermometers cost from 50 cents to $5.00 a-
upon the accuracy of their calibration. A 100° C. mercury
ciently accurate (error not over ½ per cent) for ordinary
costs about $4.00. A 400° C. mercury thermometer costs
550° C. mercury thermometer about $12.00.

HY. — See Bibliography in articles on *Heat* and *Pyrometers.*

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THERMODYNAMICS, PRINCIPLES (*istry, Principles of; Heat and Thermal Properti Temperature and Thermometers.*) "Thermodyn employed to include all problems involving t one body to another, and the transformations The word "energetics" is a better general term but the term "thermodynamics" is the one ord (Greek, "thermos") is developed in practicall e formation of energy. The transfer of energy f every known instance is found to be consistent w principles or laws:

FIRST PRINCIPLE OF THERMODYNA mental facts are in accord with the principle that given state or condition 1 to any other given state given out by the body is always the same, indepe place.

Intrinsic Energy. — Any given body in a may, therefore, be considered as having associate energy, which, in general, changes when the st changes. This energy is called the "intrinsic e pends solely upon the state or condition of the b in a given state or condition 1 is U_1, and in some U_2, then the total energy given out by the bo state 1 to the state 2 is $U_1 - U_2$, and this diffe initial and final states of the system and is in passes from one state to the other.

Heat and Work. — The energy given out by mechanical work, electrical, magnetic or other fo ience, all other forms of energy given out by the the "external work" done by the body. Hence, W the external work *done by* a body when it chan the total energy given out by the body may be exp the amount of heat evolved and the external w changes from a state 1 to a state 2 depend respecti the change takes place, but the sum of the heat always the same for given initial and final states, takes place.

Mathematical Expression of First Law. — sions given above for the total energy transferred from a state 1 to a state 2, gives the relation

$$U_1 - U_2 = Q_e + W,$$

which is the usual mathematical expression of the If, in the change from state 1 to state 2, heat i positive, while if the heat is absorbed Q_e is negat venient to consider the heat absorbed by the Hence, putting $Q = -Q_e$ the above expression ma

$$W = U_1 - U_2 + Q,$$

in which U_1 is the intrinsic energy of the body i energy in any other state 2, Q is the heat *absorbed* body when it changes from the state 1 to the state

PATH OF CHANGE. — Consider a body or condition 1 to another state or condition 2.

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l state the body passes through a series of successive states, ring but infinitesimally from the preceding. The given series of hich the body passes is called the "path" from state 1 to state a body may pass from a state 1 to a state 2 by an infinite paths; therefore, a change can be completely specified only path" of the change as well as the initial and final states. e work done and the heat given by a body when it changes from ate 2 depends only upon these states, i.e., upon the ends of the portions of the energy given out as work and heat respectively upon the series of successive states through which the body "shape" of the path), but also upon the relation of the given rnal bodies which may in any way affect it.

PROCESS. — Any process by which a change can be pro- under conditions such that the body neither absorbs nor gives other body is called an "adiabatic" process. Adiabatic pro- be completely realized, since no known substance is a perfect ut such processes can be closely approximated, e.g., the expan- ion of a gas in a cylinder with well-insulated walls when the pression is so rapid that no heat is conducted through the walls.

AL PROCESS. — Any process by which a change can a body without changing its temperature is called an "iso- s. For example, the melting of ice, when the ice and water are is an isothermal process.

E PROCESS. — Whenever a change takes place in a e also takes place in some other body or bodies *B*. If the ystem formed by *A* and *B* are such that the path of each versed in direction without changing by an appreciable amount of the system, then the process by which the change takes "reversible" process.

pass only from a hot to a cold body and never in the reverse on of heat), it follows that, if during any step of a process there it between bodies whose temperatures differ by a finite amount, is irreversible. Hence, a reversible process can take place ions only: either there must be no transfer of heat (adiabatic ransfer of heat must be between bodies which differ in tem- an infinitesimal amount.

g, the last type of process is absolutely reversible only in the n the bodies between which the transfer of heat takes place same temperature. This condition can be only approximated always be a difference in temperature, though this difference small, in order that a transfer of heat may take place.

W OF THERMODYNAMICS. — The so-called second amics involves three distinct principles, which may be stated

v changes from a state 1 to a state 2 by any *reversible* process, n 2 to 1 over the same path, but in the reverse order, then the the body during the change from 1 to 2 is exactly equal to the his body during the reverse change from 2 to 1.

changes from a state 1 to a state 2 by any irreversible process, during this change can never be greater than the heat which re the change from 1 to 2 over the same path produced under would render the process reversible. Similarly, if the body ring an irreversible change, the heat given out can never be

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less than the heat which it would give out were t
produced under conditions which would render th

3. The heat (Q) absorbed by a body during any
bears the following relation to the temperature (t)

$$Q = MK\ (t + T_0)$$

where M is the mass of the body, T_0 is a constant
scale on which the temperature is measured, and K
solely upon the nature of the body and its initial and

Absolute Thermodynamic Temperature. —
any known means to produce a negative temperat
perature scale, numerically greater than the cor
T_0 in the above expression (equation (2)). Hence t
of any given scale equal to this constant T_0 is ca
namic zero" of this scale, and the temperatures
called "absolute thermodynamic temperatures."
be written

$$Q = MKT,$$

where $T = (t + T_0)$ is the absolute temperature c
ture t. The value of the absolute thermodynam
as that temperature, as measured on the consta
mometer, at which the pressure of the gas would
in pressure per degree ($= 1/273$ of the pressure
at all temperatures.

On the centigrade scale the absolute zero is, the
and on the Fahrenheit scale $-460°$ (approximat

Entropy. — Since the factor K, in equatio
upon the nature of the body and its initial and
looked upon as representing a change in a proper
ing this property of the body for the initial state
then K may be put equal to $N_2 - N_1$, and equatio

$$Q = M\ (N_2 - N_1)\ T.$$

This equation, which represents the relation betw
temperature, for a reversible isothermal process
adiabatic process, if the property of the body re
assumed to remain unchanged during such a proc
the heat absorbed is zero, by definition, and this, c
in N during such a process, is consistent with equa

In general, the temperature of a body during a
the process may be considered as made up of a
and adiabatic steps, and the above definition of t
to each step. That is, the change in N for each
isothermal "tread" and an adiabatic "rise" is

$$dN = \frac{dQ}{MT},$$

where M is the mass of the body, dQ is the heat a
temperature of the body during this step.

This property N, whose increase during any
equal to the heat absorbed per unit mass divide
of the body during this step, is called the "entro
Since entropy is defined in terms of its change, it

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of a body may be arbitrarily taken as zero. In steam tables, water at 32° F. and at atmospheric pressure is usually taken as ropy of a body can in many cases be calculated from the other he body. (*See article on Steam.*)

ce with the above definition of entropy the heat absorbed by a hanges from a state 1 to a state 2 by any *reversible* process is then

$$Q = M \int_1^2 T dN, \tag{3}$$

mass of the body, T its absolute temperature during any step of d dN the increase in its entropy per unit mass during this step.

le of the Increase of Entropy. — It can be shown, from the e stated, that the only possible changes which can take place in lies to which no energy is added or subtracted are changes which ase in the total entropy of the system. Reversible changes may ke place without increasing the total entropy, but reversible take place in nature nor can they be realized *absolutely* by any ental means.

I WORK. — The maximum external work which a body changes from a state 1 to a state 2 along a given path (i.e., by a given series of states) is equal to the decrease in its intrinsic maximum amount of heat it can absorb when it changes along maximum external work which a body can do in changing from ate 2 along a given path is therefore

$$W_{\max} = U_1 - U_2 + M \int_1^2 T dN. \tag{4}$$

e last term in this expression depends upon the temperature at change, and this temperature depends upon the "path" along e takes place. If the path is such that *all* the heat is absorbed nperature T, then

$$W_{\max} = U_1 - U_2 - TM(N_1 - N_2). \tag{4a}$$

e written

$$W_{\max} = U_1 - U_2 + T\frac{dW_{\max}}{dT}, \tag{5}$$

the rate of increase of the maximum work done by the body

ture at which the heat is absorbed.

. — The maximum work which a body can do in changing a state 2 is sometimes referred to as the "free energy" of the ing to this change. This free energy depends not only upon nal states of the body itself but also upon the temperature of nal body available as a source of heat; this is apparent from

OCESSES. — In the theory of the steam and other heat ion arises as to what is the maximum amount of external work ained from a body by alternately heating it to a high tempera- ing it do work (e.g., by expanding), thereby cooling to a lower cycle of operations being repeated over and over again. That working substance" changes from a state 1 to a state 2, then then changes again to 2, and so on for any number of cycles. rgy of the body at the beginning and end of any cycle is then erefore, the net work done by the body during any cycle is

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the difference between the heat actually absorbe
during the cycle.

Thermal Efficiency. — The ratio of the
absorbed during the cycle gives the proportion
converted into external work, and is called th
cycle.

Carnot's Cycle. — From the principles stat
heat absorbed will be a maximum when this hea
manner under conditions such that the tempera
is the same as that of the hottest body availal
the heat given out is a minimum when this hea
manner under conditions such that the temperatu
the same as that of the coldest body available
"path" along which the body changes (*see* Fig.
thermal change at temperature T_1, an adiabatic c
to a lower temperature T_2, an isothermal chan
this temperature T_2, and then a second adia
change to T_1. Such a path is called a "Carnot's c
The figure represents such a path for a perfect
the ordinates being pressure and volume.

From the general expression for maximum work,
tion (4), it follows that the efficiency of this cy

$$\frac{W}{Q_1} = \frac{T_1 - T_2}{T_1}.$$

For a given amount of heat added to a workl
change, the maximum possible work which the
that done when the cycle is a Carnot's cycle, and
proportional to the difference between the temp
the working substance absorbs heat and the tem
it gives out heat, and is inversely proportional t
the body from which it absorbs heat.

APPLICATIONS OF THE LAWS OF

The laws of thermodynamics serve as the basis fo
of the performance of the steam engine, steam
engines, refrigerating machines, air compressors,
In many important electrochemical relations (s
of). It is beyond the scope of this book to go
the treatises listed in the following bibliography.

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neers;* Hicks, R. C., *The Steam Engine and T
Engine Theory and Practice;* Peabody, C. H.,
Engine; Carpenter and Diederichs, *Experimental
cal Engineers' Handbook.*

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AIL, OR CONTACT-RAIL, SYSTEMS. — (*See also Bonding; Rails, Track and Third; Standardization Rules of the rolley Systems, Overhead; Trolley Systems, Underground.*) The brief table of contents of this article:

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rail, or third rail, is a conductor supported on insulators near the resenting a continuous contact surface to a collector or shoe ne rolling stock. In its commonest form it is a rail of standard ted at intervals of a few feet by substantial insulators, electrical veen adjacent lengths being obtained by copper bonds across the

LOGY. — The following terms and definitions are used in con- ird-rail systems. See also Standards of the A.I.E.E.

oe. — A third-rail contact shoe is a conductor, fastened to the hich is designed to make electrical contact with the third rail. ter referred to as the "shoe."

face. — The contact surface of a third rail is the surface against presses.

ack. — The minimum clearance between the inside surface of two track rails, i.e., the distance *A* in Fig. 17. The track gage s 4 feet 8½ inches.

age. — The distance measured parallel to the plane of the tween the gage line of the nearer track rail and the inside gage ct surface of the third rail, i.e., the distance *B* in Fig. 17 of this

Third rail locations will be described in terms of the third-rail evation or vertical distance (*C* in Fig. 17) between the normal and the normal top of the track rail. See also Table II below.

Rail. — A top-contact third rail is one on which the contact upper side of the rail.

ct Rail. — An under-contact third rail is one on which the s on the under side of the rail.

sulator. — A third-rail insulator is that portion of the third- h forms the principal electrical insulation.

se or Bracket. — A third-rail insulator base or bracket is a pport the third-rail insulator.

incline is a portion of third rail sloped to gradually bring the e position into contact with the normal surface of the third

— An end incline is an incline at the end of a run of third rail ceive shoes moving in line with the third rail.

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Offset-end Incline. — An offset-end incline of third rail and is made to receive shoes movi rail.

Cross Incline. — A cross incline is a combin inclines from adjacent third rails which meet at

Side Incline. — A side incline is an incline a made to receive shoes moving laterally towards t

Offset-side Incline. — An offset-side incline standard third rail in order to gain clearance b maximum equipment line of the rolling stock.

Maximum Equipment Line. — The maximun ary which encloses the cross-sectional outlines o all normal operating conditions.

Third-rail Protection. — A third-rail protecti third rail which affords some degree of protectio accidental contact with foreign bodies.

Third-rail Anchorage. — A third-rail anchora third-rail creeping longitudinally.

Tie Motion. — Unless otherwise specified, tie r mean the vertical play of the ties caused by the pa

TYPES OF CONSTRUCTION. — Third-rail fied into the top-contact and under-contact types, of important variations in design, especially with reference to the type of protection.

Interborough Top-contact Type (Fig. 1). — One of the most commonly used types is illustrated in Fig. 1. It is often called the "Interborough Type" on account of its use in the subways of the Interborough Rapid Transit Co., of New York. The rail is a standard T-section and rests on reconstructed granite insulators. A board protection is attached to the rail itself by means of clamps and uprights and is thereby kept in perfect alignment.

Pennsylvania Top-contact Type (Fig. 2). — Another type has the protection supported on separate brackets independent of the third rail itself. It is claimed that this reduces the amount of labor w live rail, when repairs are being made, but it cannot the Interborough type to keep the rail and protectio

London Tube Type (Fig. 3). — The mounting rail and the negative contact rail of the London Tub Fig. 3.

Under-contact Types (Figs. 4, 5, 6 and 7). — W have given first-class service, they are considered to h for exposed locations as they cannot be wholly prot sleet. The lower part is only a few inches from th generally reduce this clearance, increasing the danger o lation of wet snow and ashes and from flooding. Th traffic during sleet and snowstorms and floods, on railr type of third rail, led to the idea of an under-contact

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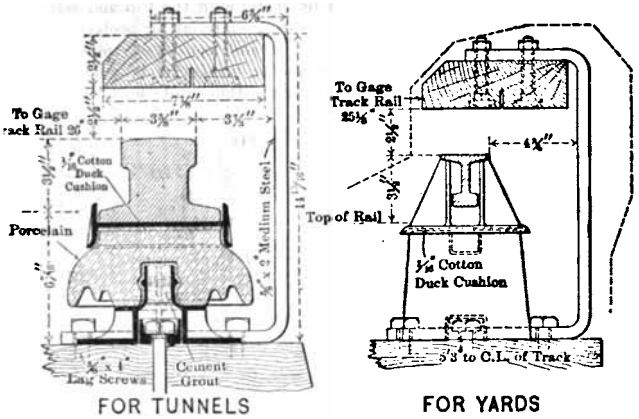


Fig. 2. Pennsylvania Top-contact Type

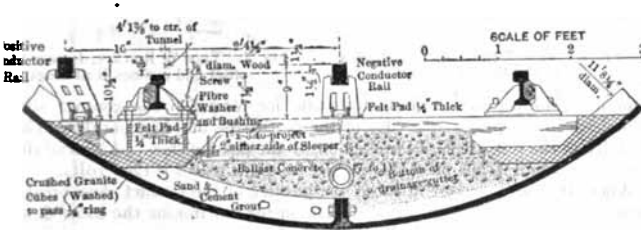


Fig. 3. London Tube Type

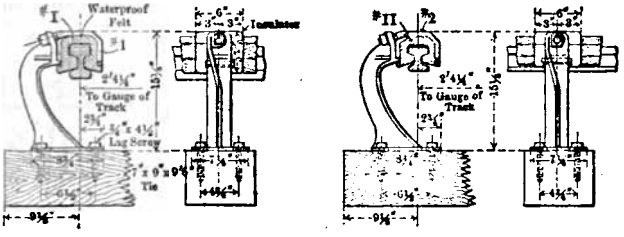


Fig. 4. Type X Bracket, for use on Straight Work

Fig. 5. Type Y Bracket, Applied to End Incline

in insulators by hook bolts hung from brackets, with the top and sides of t rail completely sheathed in a flexible insulating material for protecting the from accidental contact with man and beast, and from sleet, snow and sp With this type of rail (Figs. 4, 5, 6 and 7) the protection is of such chara that there is no packing of snow between the sheathing and the contact rail, a

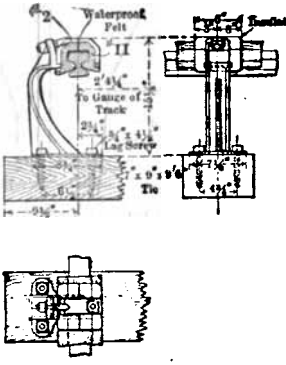


Fig. 6. Type Z Bracket, for use with end inclines A at frogs

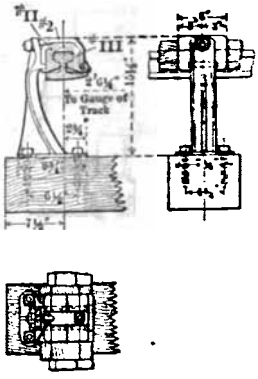


Fig. 7. Type W Bracket, for use with offset end inclines B at frogs

some other forms, and in sleet storms no ice forms on the contact surfa some icicles may form at the edge of the petticoats, but hanging down clear the edge of the rail, are easily broken off by the passing shoe. A special desi using a standard T-rail, is shown in Fig. 8, and is used for 1200 volts.

Where the rail is buried in snow, the passage of the contact shoe breaks snow away, leaving the rail surface clear, instead of ironing the snow down the rail, as may happen with the top-contact type.

Sheathing and Special Work. — The sheathing between the insula blocks, depending upon local conditions and the price of materials, as wel the potential used, is usually formed of three wooden strips, one grooved on under side and inclosing the head of the rail, and the other two, attached to and dependent from it, reaching in toward the web of the rail. Where good wood is not available, an alternative protection costing about the same and having a higher electrical resistance, although not so good mechanically, is a semi-flexible shell of indurated fiber conformed to the rail sections.

The special work, i.e., inclines, jumpers, etc., used with the under-contact rail, is shown in Fig. 9.

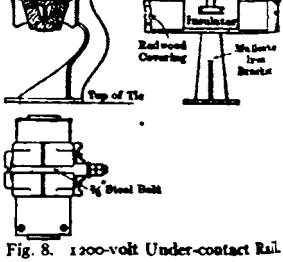
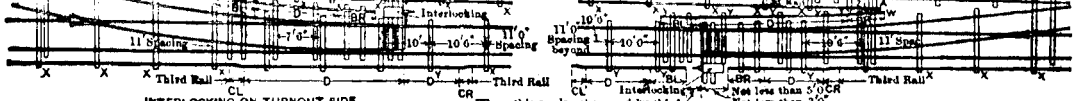


Fig. 8. 1200-volt Under-contact Rail.

Combined Top- and Under-contact Shoes. — The employment of collecting shoes on rolling stock so constructed as to press upwards on the und contact rail and downwards on the top-contact type solves the question interchange between railroads not using the same type.

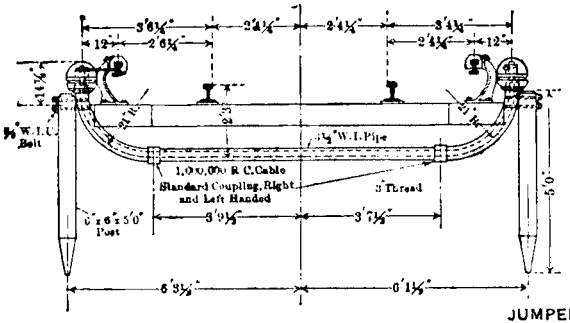


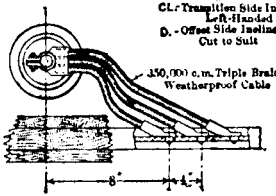
ASSEMBLY SKETCH FOR SWITCH WORK

No Scale

A.- End Incline
BR:Offset End Incline, Right-Handed
BL:- Offset End Incline, Left-Handed
CR:-Transition Side Incline, Right-Handed
CL:-Transition Side Incline, Left-Handed
D.- Offset Side Incline, Cut to Suit

X:-Bracket for Straight Work with Insulator I and Hook Bolt 1
Y:-Bracket for End Inclines A and F and Offset Side Incline D, with Insulators II & III & Hook Bolt 2
Z:-Bracket for End Incline A, at Frogs with Insulator II and Hook Bolt 2
W:-Bracket for Offset End Incline Data Frogs with Insulators II and III and Hook Bolt 2





JUMPER

Fig. 9. Special Work used with Under-contact Rail

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CONTACT RAILS VERSUS OVERHEAD TROLLEY. — The conta
ail is used as a part of the positive conductor system whenever the current
e collected by each collector exceeds the amount which can be taken safe
rom a trolley wire, or whenever the total current taken by a train exceeds
mount that can economically be carried by conductors of such expensive met
s copper or aluminum.

Positive Contact Rails. — Considered as a part of the positive conduc
ystem, the contact rail and overhead trolley possess the relative qualifica
ions given in Table I.

TABLE I. — RELATIVE QUALIFICATIONS OF THIRD RAIL AND OVERHEAD TROLLEY SYSTEMS.

(*Adapted from Table by C. E. Eucleth.*)

I Protected third rail	II Overhead high-tension bridge, catenary construction	III Overhead side bracket, catenary construction
Interference with track maintenance.	Entirely clear of road bed.	Same as II.
Can be maintained by section gang.	Requires special tools, crews and work trains.	Same as II, but not as important.
Easily cleared up and insulated when derailment occurs.	In the way of boom of derrick car — liable to be knocked down and put all tracks out of service.	Same as II.
Hindrance to coupling freights, etc. With protected rail this is not very serious.	Dangerous to freight brakemen on account of parts hanging down and small bridge clearance. Very difficult to install satisfactory ticklers to warn trainmen when approaching bridges.	This point is of less importance.
Interference with clearing snow between tracks.	Not affected.	Not affected.
Ease of satisfactorily collecting current on account of location, where relative motion between track and rail is small. Collectors may be safely replaced on the road.	Difficult to collect current, as a more complicated mechanism is required on account of the grade of the wire due to low clearances at bridges and high clearances at road crossings.	Similar to II.
May be readily inspected by track walker.	Requires a man with special training.	Similar to II, but of less importance.
Ease of sectionalization. Jumpers may be disconnected at the nearest adjacent road crossings.	Difficult of sectionalization.	Sectionalization not of so much importance.

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TABLE I. — RELATIVE QUALIFICATIONS OF THIRD-RAIL AND OVERHEAD TROLLEY SYSTEMS — *Continued*

(*Adapted from Table by C. E. Eveleth.*)

I Protected third rail	II Overhead high-tension bridge, catenary construction	III Overhead side bracket, catenary construction
May be worked on while alive to make track changes or repairs, making system very flexible.	Requires that current be shut off no matter how slight repairs are, making system inflexible.	Similar to II, but not of such importance.
No interference with visual signals.	Signals located and seen with difficulty, as they must be lower than the bridges and even then have the distant bridges as a background. Dangerous to maintain signals in this location, as it must be done from ladders.	Not affected.
Danger of wreck from burning off track rail due to arcing current. This is a possible contingency, but one not very likely to occur.	Danger from dangling overhead work when messenger cable is burned off at a defective insulator.	Same as II.
Little interference with fire-extinguishing apparatus in the car storage yard.	Difficulty in removing cars on account of high-tension wires interfering with firemen.	Will probably have low-tension wires for this type of construction.
Absolute freedom from lightning disturbances.	Very much exposed to lightning.	Same as II.
Entire freedom from telephone and telegraph disturbances, also inductive effects on signal wires.	Difficult problem in connection with these interferences, affecting not only the railroad company's wires, but those belonging to other interests.	Same as II.
No trouble at grade crossings with crossing trolley wires.	Probably trolley crossings will have to be avoided by overhead or undergrade crossings.	Troubles similar to II.
Can add sidings or more tracks with little difficulty.	Can make such additions only at considerable expense.	Difficulty not very great.

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Negative Contact Rails. — Negative contact
negative-feeder system when the drop of potential i
such a small amount that it is cheaper to use an
force the track rails with feeders. Considered as
system, the contact rail possesses the following ad
return system. If used in connection with a positi
rail is placed between the track rails.

(I) When properly insulated, it eliminates every
(II) It gives the block-signal system complete in
traction system. Among the advantages which thi
of signal circuits, saving the cost of reactance bo
and increased economy in signal circuits.
(III) It gives greater safety to passengers.
(IV) It reduces the probability of short circuits.
(V) It decreases the cost of track-rail mainter
bonds.
(VI) It halves the first cost of bonds, as one b
usually replaces two track rails.
(VII) It reduces the wear of bonds by saving th

These advantages are usually offset by the first
rail, by the complications it introduces at special tra
bility of protecting a central rail from snow and i
clearance for any kind of covering.

ELECTRICAL DESIGN. — The calculations
resistance, etc., are treated under *Trolley Systems*,
weight, dimensions, resistance and reactance of rail
on *Rails, Track and Third*.

Selection of Suitable Rail. — When the vari
consideration it is well to arrange a table with the
to compare the relative economy of the different
copper equivalent to rail; (2) Additional circular
equal the rail of highest conductivity; (3) Cost of
(4) Cost of additional copper for entire railroad;
additional copper for entire railroad.

MECHANICAL DESIGN. — The general de
been settled, the next step is to secure a set of tra
the special work. When an entirely new railway i
designer and the third-rail designer can work tog
line is being converted, the general track plans ca
dom sufficiently accurate for the electrical engine
the contact-rail engineer has to take measurements
to make drawings of the cross-overs and other com

Location and Weight of Third Rails. — The
contact rails, corresponding to the standard tra
condition arises from lack of uniformity in the clear
and in the maximum equipment lines of variou
standard clearances have been recommended (191
Railway Engineering Association:

The clearance lines for third-rail and permane
ing equipment to be as shown in Fig. 10, thus rese
AT, BT, CT, DT, ET, FT and *AT, JT, KT, LT,*
rolling equipment not to encroach upon the third-r

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l deflection beyond the line *AE*, *BE*, *CE*, *DE*, *EE*, *FE*, -way structures not to encroach upon the third-rail space S, *JS*, *KS*, *LS*, *MS*; this leaves a clearance space or ıe inch both horizontally and vertically upon which il structures nor equipment shall encroach. On curves 800 feet, the third rail must be moved back and the

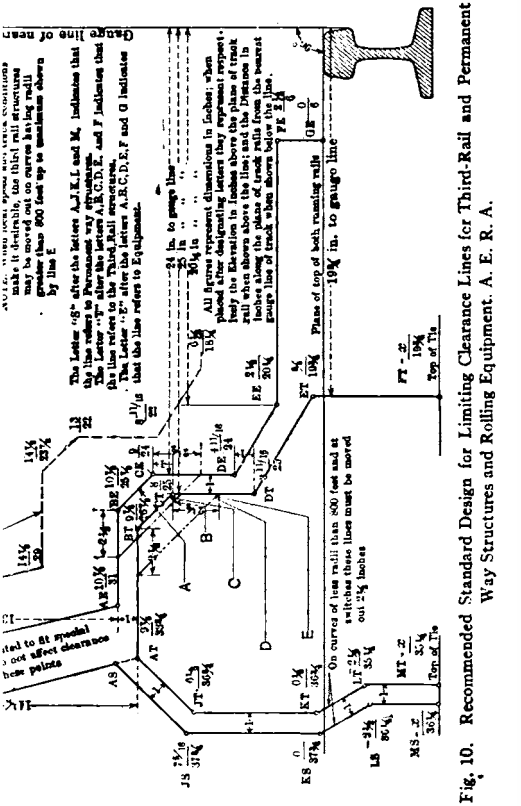


Fig. 10. Recommended Standard Design for Limiting Clearance Lines for Third-Rail and Permanent Way Structures and Rolling Equipment. A. E. R. A.

allowed to swing outward as indicated by the lines and

l construction of new rolling stock to be used in interance must be made for such horizontal and vertical varia- reasonable probability occur in combination at one time as for deflections on curves. Encroachments on normal :flection of springs and wear vary with the type of con- the practice of the respective roads as regards permissible before repairs and adjustments are made. For the general ads, in designing equipment, but not as a standard, there-

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TABLE II. — LOCATION AND WEIGHT OF THIRD RAIL

Name of railroad	Center of third rail to near gage line, inches	Contact face above top of running rail, inches	Weight lb. per yard
Albany & Hudson	27	6	...
Aurora, Elgin & Chicago	20⅛	6⅝₁₆	100
Baker St. & Waterloo Ry.	....	....	90
Baltimore & Ohio	30	3½	...
Berlin Elevated and Subway	14⅝	7	....
Boston Elevated and Subway	20⅝	6	85
Brooklyn Rapid Transit	21¾	6	70
Camden & Atlantic City R.R.	26	3½	100
Central London Ry.	Center	1½	...
Columbus, London & Springfield	27	6	...
Columbus & Newark	27	6	...
Fayet-Chamounix	23	9	...
Grand Rapids, Gd. Haven & Muskegon	20⅝	5¾	60
Great Northern Ry., England	19¼	....	80
Hudson Tunnels, New York	26	4	75
Interborough Rapid Transit	26	4	153
Kings County El., Brooklyn	19½	5¼	....
Lackawanna & Wyoming	20⅝	3	75
Lake St. El., Chicago	20⅛	6½	....
Lancashire & Yorkshire Ry.	19¼	3	70
Liverpool Elevated	Center	1½	....
Long Island R.R.	27	3½	100
Manhattan Ry., New York	20¾	7½	100
Mersey Ry.	22	4½	....
Metropolitan & District, London	16	3	100
Metropolitan Elevated, Chicago	20⅛	6¼	45
Milan Gallerate	26⅝	7½	...
*New York Central R.R.	28¼	2¾	70
Northeastern Ry., England	19¼	3¼	80
Northwestern Elevated, Chicago	20⅛	6½	45
North Shore R.R., Cal.	27	6	50–60
Paris Orleans Ry.	25⅝	7⅛	...
Paris Versailles	25⅝	7⅞	...
Pennsylvania R.R.	27	3½	150
*Philadelphia & Western	27	3⅝	...
*Philadelphia Rapid Transit	27	6	70
Seattle & Tacoma R.R.	20	7½	....
South Side Elevated, Chicago	20⅛	6½	....
Wamseebahn (Berlin)	33½	12⅝	....
Waterloo & City Ry.	28¼	0	....
West Jersey & Seashore	26 †	3½	100
*West Shore R.R.	32	2¾	70
Wilkesbarre & Hazleton	28	5	80

* Bottom contact surface. All others have top-contact surface.
† Gage, as defined under Terminology.

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t, a dotted line is shown on the diagram located 2 inches distant horizontally and 4 inches distant vertically from the limiting clearance line for uipment.

Turnouts. — (*See also Railways, Location and Permanent Way for.*) A typical nout is shown diagrammatically in Fig. 11 which shows the lengths which uld be measured; *F* is the distance from the point of the switch the point of the frog, and is led the "frog distance"; *D* is the gth between the adjacent frogs, d *Z* the distance apart of the ck centers. In such a diagram- tic view the lines represent the ge lines of the track rails. When, however, a contact rail is represented by ine, it is the center line that is given. Having measured the four distances ecified above, the radius of the turnout curve may be calculated from the following formulas:

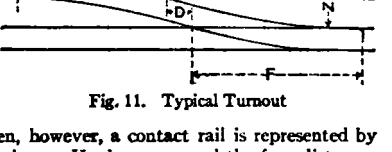


Fig. 11. Typical Turnout

$R = 0.127\ F^2$, when the turnout is from a straight track.
$R = 0.271\ F^2$, when the turnout is from a track of equal radius to the turnout.

Graphical Method of Locating Contact Rail. — The track plans having en drawn from the field sketches, to a scale of say ¼ inch to the foot, the ntact rail may be drawn in, as outlined below. An aid in this work is an oute plan of the electric car or locomotive to the same scale as the track work awings — say ¼ inch to the foot. Such a plan is shown in Fig. 12, in which e points *W* represent the wheels, *S* the contact shoes and *K* the king-pins. This d better be made of celluloid with a large pinhole at ch point *S*. In order to lay out the contact rail the is drawn along the tracks with the points *W* on rails and a pencil stuck in one of the pinholes. The e traced by the pencil represents the center line of the e path, and therefore that of the contact rail. Such a e should be made on each side of the car. In cases ere there are sharp curves, it will not do to run the wheel points *W* along tracks, as an error will arise due to the truck rotation not being represented. such a case the king-pin points must be run along a track center line.

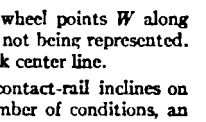
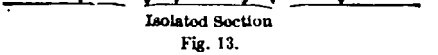


Fig. 12.

Location of Inclines. — The exact location of the contact-rail inclines on ch side of a track-rail intersection depends upon a number of conditions, an portant one of which is the extent to which the equalizer bar and journal box ject outward. If there is a train-bus line connecting all the cars, the end lines may be situated many feet back from the switch point or frog, but if re is no such bus line, the contact rail will probably have to be terminated a cross incline extending near as possible to the itch point or frog.



Isolated Section
Fig. 13.

Sectionalizing the Contact Rail. — Where a train- s line is not used, it is customary to break the third rail in front of substaons and use an isolated section of third rail between the two main sections, as own diagrammatically in Fig. 13. The length of this isolated section and the gaps which bound it should be such that both gaps are never spanned cars at the same time.

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Let L = car length, feet,
T = distance between shoe centers (usually truck centers),
S = shoe length.

Then,

Total space must be $> L + T$
Rail section must be $< 2L$
Length of each gap must be

For example, on the Manhattan Railway, New was adopted, a short isolated section was used.

$L = 46.37$, $T = 32.27$, S

Total space > 79.64, actually
Section of rail < 59.47, actu
Gap length < 31.27, actually

Cross and End Inclines. — Inclines serve contact shoes to rise (or fall) from their free posi with the rail. They should, therefore, have sufficient slope to prevent any undue shock either to the rail or to the shoes. Low-speed lines and sidings may therefore have shorter inclines than high-speed lines. The usual length of straight slope (i.e., without end nose and flat surface at top) is from 60 to 70 inches for high-speed work and 30 or 40 inches for sidings. The slope ranges from 1 in 45 for high-speed work to 1 in 30 for urban railways. made of cast iron. A typical design is shown in



Fig.

Third-rail Insulators. — Third-rail insulator qualifications. Strength to withstand weight and to moisture; resistance wet shall not be less th drip edge; shall allow free motion of rail laterally to allow for expansion, contraction and tie motion and quick removal without disturbing the rail.

Spacing of Insulators. — A spacing of recommended by the American Street & Interurb rails and represents present day practice.

INSTALLATION OF CONTACT RAIL. railway being electrified, the first step is to replac vals by long ones. A man then proceeds along marks on them the location of the screw holes o followed by an augur gang which drills the holes the case of an under-contact rail) or the stool a top-contact rail) are distributed along the line. gang screws the brackets or stools to the ties.

Where the rails rest on tie plates which hav it is not unusual to place shims under the brack have reached their normal position.

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se of under-contact rails the brackets must be accurately checked for mensions before being distributed.
and fish-plates, etc., are next distributed along the line on that side where they are to be installed and a gang follows which installs the the case of an under-contact rail, attaches the insulators and hook ne case of a top-contact rail, another gang follows, attaching the ıtever is used to fasten the rail to the insulators. Another gang ıstall the fish plates, expansion joints and anchorages, if any. If o anchorages or expansion joints, expansion and contraction are ıinst by making an allowance at all joints, depending on the temper-ch the rails are installed. This is done by inserting an "expansion e the rails are l together. The shim for different on a 30-foot rail ig. 15.

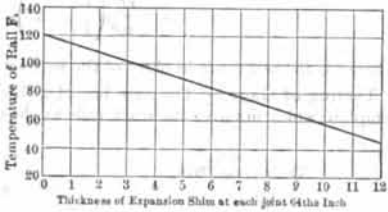


Fig. 15. Thickness of Expansion Shims for 30-ft. Rail

rails are being materials for the are distributed e and a gang fol-g them. A last the protection ɔriming and then ıg paint.

ve to be carefully located to make sure that the shoes will ride n them.

ON AND MAINTENANCE OF CONTACT RAIL. — The ird rails is negligible and even without painting the deterioration very slow. The principal items of maintenance are the insulators, l bonds. Unless the supports are carefully designed, insulators by "tie motion," i.e., by the depression and rebound of the ties ass over them. Every time a wheel passes over a tie carrying an latter is pounded against the rail and is likely to be broken unless is provided.

ffects due to large currents sometimes causes the third-rail voltage 3 times its normal value. (D. D. Ewing, E. R. J., 1917, Vol. 56,

f Sleet. — The best protection against sleet is undoubtedly the third rail and the next best is a top-contact third rail with a wide rd. Where these are impracticable the deposit of ice on the rail ented and means for its removal have to be adopted. The two ıs are scrapers and hot water. Electrical heating of the rail uggested but found to require too much energy. When the hot-is used, some salt such as calcium chloride, or some other sub-lowers the freezing point of water must be added to the water. ous objections to the hot-water method, especially on elevated e saline solution not only rusts the metal of the structure but chloride is used in the water, damage also occurs to the roofs of , underneath.

OF CONTACT RAILS. — Contact rails have to be tested for ontinuity at the joints, (2) conductivity, (3) insulation from gage.

ntinuity at Joints are described in the article on *Bonds, Rail-*

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The Conductivity Test is best performed by passing a considerable current through a length, measuring the drop with a milli-voltmeter and calculating the resistance by Ohm's law.

The Insulation Test is best performed by means of a pair of voltmeters, as shown in Fig. 16. The rail A to be tested is connected to a live rail B through a voltmeter, and the voltage V_1 between the two noted. At the same instant the voltage V_2 between the rail B and ground is also read. Let L be the length in miles of the rail A. Then the insulation resistance of the rail A in megohms per mile is

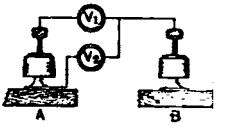


Fig. 16.

$$\frac{rL}{10^6}\left(\frac{V_2}{V_1} - 1\right),$$

where r is the resistance in ohms of the voltmeter on which V_1 is read.

Testing of Gage. — The gage line of a third rail is measured by means of a template which fits over the track rails as shown in Fig. 17.

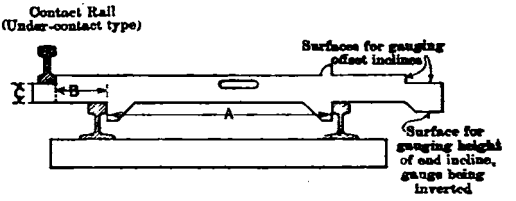


Fig. 17.

COST OF CONTACT-RAIL CONSTRUCTION. — The estimates in Table III include the cost of (1) handling and distributing the material from the storehouse to the place where it is used; (2) the solder, gasoline, etc., used in bonding contact rail; (3) putting three coats of paint on the protection; (4) bending rails on curves; (5) 5 per cent for breakage; (6) foremen's and engineers' salaries. They do not include the cost of tools or of jumpers.

These estimates are approximately correct where existing traffic does not materially impede the work. Under less favorable conditions, the cost may rise 50 per cent or more over the figures given.

The estimate on the top-contact type is based upon the Interborough Rapid Transit Co's. construction, New York (Stillwell-Slater patent), the weight of rail, however, being slightly less than on that railway. The estimate of the under-contact type is based upon construction similar to that used by the New York Central Railroad (Wilgus-Sprague patent). Little third-rail cost data having been published since the Great War, the data from the 1914 edition are reproduced.

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I.—COST PER MILE OF CONTACT-RAIL CONSTRUCTION

Item	Top contact		Under contact	
	Amount	Cost	Amount	Cost
.....	55 tons	$1815	55 tons	$1815
ial.....	....	....	1.2	40
standard.....	11	47	11	47
special.....	511	92	1000	165
r pedestals.....	....	....	25	13
special.....	515	62	500	250
.....	....	....	15	7
.....	515	10	515	90
.....	1030	20	1515	30
.....	1030	41	.....	....
ws.....	....	....	80 gross	24
onds.....	350	168	350	168
s and bolts.....	350	53	180	31
.....	....	793	....	642
.....	....	49	....	82
tor.....	....	....	....	2
xcess only*.....	505	177	505	177
rial.....	....	$3327	....	$3583
oonding and protection of				
.....	....	$ 800	....	$1000
ng ties.....	....	101	....	101
.....	....	$ 901	....	$1101
.....	....	$4228	....	$4684

includes only the *difference* in cost between the long ties which ators and the cost of the same number of standard ties. The es of third rail on the West Jersey and Seashore R. R. is given 5 as $4, 235 per mile, and the average cost of maintenance, as ear.

APHY. — (*See also Railways, Systems of Electric Traction for; Grounded Structures; Endosmose; Trolley Systems Overhead.*)

m Protected Third Rail Systems Street Ry. Jour., 1906, Vol. 27, J. A., *Tests of Steel for Electric Conductivity*, Trans. A.I.M.E. p. 400; Fortenbaugh, S. B. *Conductor Rail Measurements*, ., 1908, Vol. 27, p. 1215; Duer, J. V. B., *Third Rail and Trolley 'est Jersey and Seashore R.R.*, Trans. A.I.E.E., 1915, Vol. 34–2, n, C. J., *Contact Conductors and Collectors for Electric Railways*, ., 1915, Vol. 34–2, p. 1547; Jones, C. H., *Top Contact Unpro- Rail for 600-volt Traction Systems*, Trans. A.I.E.E., 1915, Vol.

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TIMBER. — (*See also Structures, Simple; Poles for Overhead Lines.*) The standard names for structural timbers as adopted by the Am. Soc. for Test. Mat. and the Am. Ry. Eng. Assoc. are reprinted below by permission from the present (1913) board of the Am. Soc. for Test. Mat.

Fir, Douglas. — The term "Douglas Fir" is to cover the timber known likewise as yellow fir, red fir, western fir, Washington fir, Oregon or Puget Sound fir or pine, norwest and west coast fir.

Hemlock, to cover Southern or Eastern hemlock; that is, hemlock from all states east of and including Minnesota.

Hemlock, Western, to cover hemlock from the Pacific coast.

Larch, Western, to cover the species of larch or tamarack from the Rocky Mountain and Pacific coast regions.

Pine, Norway, to cover what is known also as "Red Pine."

Pine, Southern Yellow. — This term includes the species of yellow pine growing in the southern states from Virginia to Texas, that is, the pines hitherto known as longleaf pine (*Pinus palustris*), shortleaf pine (*Pinus echinata*), loblolly pine (*Pinus taeda*), Cuban pine (*Pinus heterophylla*), and pond pine (*Pinus serotina*).

Under this heading, two classes of timber are designated: (*a*) dense southern yellow pine and (*b*) sound southern yellow pine. It is understood that these two terms are descriptive of quality rather than of botanical species.

Pine, Western, to cover the timber sold as white pine coming from Arizona, California, New Mexico, Colorado, Oregon and Washington. This is the timber sometimes known as "Western Yellow Pine," or "Ponderosa Pine," or "California White Pine," or "Western White Pine."

Pine, White, to cover the timber which has hitherto been known as white pine, from Maine, Michigan, Wisconsin and Minnesota.

Pine, Idaho White, the variety of white pine from western Montana, northern Idaho and eastern Washington.

Redwood, to include the California wood usually known by that name.

Spruce, to cover Eastern spruce; that is, the spruce timber coming from points east of and including Minnesota.

Spruce, Western, to cover the spruce timber from the Pacific coast.

Tamarack, to cover the timber known as "Tamarack," or "Eastern Tamarack," from states east of and including Minnesota.

A fuller description of the timbers used for transmission line poles is given in the article on *Poles for Overhead Lines.*

DEFECTS IN TIMBER. — The standard names for defects in structural timber as adopted by the above association are the following:

Encased Knot. — An encased knot is one whose growth rings are not intergrown and homogeneous with the growth rings of the piece it is in. The encasement may be partial or complete; if intergrown partially or so fixed by growth or position that it will retain its place in the piece, it shall be considered a sound knot; if completely intergrown on one face, it is a watertight knot.

Large Knot. — A large knot is a sound knot, more than 1½ inches in diameter.

Loose Knot. — A loose knot is one not firmly held in place by growth or position.

Pin Knot. — A pin knot is a sound knot not over ½ inch in diameter.

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— **A pith knot is a sound knot with a pith hole not more than** meter in the center.

ot. — A rotten **knot is one not** as hard as the wood it is in.

ot. — A round knot is one which is oval or circular in form.

t. — A sound knot is one which is solid across its face and which he wood surrounding it; it may be either red or black, and is so h or position that it will retain its place in the piece.

t. — A spike knot is one sawn in a lengthwise direction; the mean lth shall be considered in measuring these knots.

Knot. — A standard knot is a sound knot not over 1½ inches in

ets. — Pitch pockets are openings between the grain of the wood e or less pitch or bark. These shall be classified as *small, standard* pockets.

tch Pocket. A small pitch pocket is one not over ½ inch wide.

Pitch Pocket. A standard pitch pocket is one not over ⅝ inch es in length.

tch Pocket. A large pitch pocket is one over ⅝ inch wide, or n length.

k. — A pitch streak is a well-defined accumulation of pitch at e piece. When not sufficient to develop a well-defined streak, or between grains, that is, the coarse-grained fiber, usually termed ' is not saturated with pitch, it shall not be considered a defect.

Shakes are splits or checks in timbers which usually cause a ne wood between annual rings.

. — An opening between the annual rings.

ake. — A shake which extends between two faces of a timber.

nd Red Heart. — Any form of decay which may be evident red discoloration not found in the sound wood, or the presence rotten spots, shall be considered as a defect.

ane is bark, or the lack of wood from any cause on edges of

ID PRESERVATION. — Decay is due usually to a fungus revented by cutting off the air by immersing the timber in water, is known is a sure preventive. Decay is retarded by thorough naturally or in the kiln, or by poisoning the food supply of the ical treatment. The latter method usually consists in impreg- with creosote or zinc chloride, the former being more commonly e methods used for preserving timber poles are described in the *for Overhead Lines.*

ESSES FOR STRUCTURAL TIMBER. — The values of structural timber given in the following table are recommended tee on Wooden Bridges and Trestles of the American Railway ociation. See *Manual* of the Association, Chicago, 1911. For vable in various cities of the United States see article on *Build- Unit Stresses in.*

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UNIT STRESSES FOR STRUCTURAL TIMBER IN POUNDS PER SQUARE INCH

(See Note under table)

Kind of timber	Compression						
	Perpendicular to grain		Parallel to grain		Working strength of columns		Ratio of length of ... to diameter
	Elastic limit	Working strength	Average ultimate	Working strength	Length under 15 diameters	Length over 15 diameters	
Cedar, Red.....	470	230	2800	900	680	$900\left(1-\frac{L}{60\,D}\right)$	
Cypress, Bald.....	340	170	3900	1100	830	$1100\left(1-\frac{L}{60\,D}\right)$	
Fir, Douglas.....	630	310	3600	1200	900	$1200\left(1-\frac{L}{60\,D}\right)$	1:
Hemlock, Western.	440	220	3500	1200	900	$1200\left(1-\frac{L}{60\,D}\right)$	..
Oak, White.....	920	450	3500	1300	980	$1300\left(1-\frac{L}{60\,D}\right)$	1:
Pine, Longleaf.....	520	260	3800	1300	980	$1300\left(1-\frac{L}{60\,D}\right)$	1:
Pine, Norway.....	....	150	2600*	800	600	$800\left(1-\frac{L}{60\,D}\right)$	..
Pine, Shortleaf....	340	170	3400	1100	830	$1100\left(1-\frac{L}{60\,D}\right)$	1:
Pine, White.....	290	150	3000	1000	750	$1000\left(1-\frac{L}{60\,D}\right)$	1:
Redwood.....	400	150	3300	900	680	$900\left(1-\frac{L}{60\,D}\right)$	..
Spruce.....	370	180	3200	1100	830	$1100\left(1-\frac{L}{60\,D}\right)$	..
Tamarack.....	....	220	3200*	1000	750	$1000\left(1-\frac{L}{60\,D}\right)$	..

* Partially air dry.

L = unsupported length in inches. D = least side in inches.

NOTE. — These unit stresses are for a green condition of timber and are to be ... without increasing the live-load stresses for impact.

The working units given in these tables are intended for railroad bridges and trest... For highway bridges and trestles the unit stresses may be increased twenty-five (25) ... cent. For buildings and similar structures in which the timber is protected from ... weather and practically free from impact, the unit stresses may be increased fifty ... per cent. To compute the deflection of a beam under long-continued loading instea... that when the load is first applied, only fifty (50) per cent of the corresponding mod... of elasticity given in the table is to be employed.

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RESSES POR STRUCTURAL TIMBER IN POUNDS PER SQUARE INCH

(See Note bottom of p. 1589)

ıber	Bending			Shearing			
	Extreme fiber stress		Modulus of elasticity	Parallel to grain		Longitudinal shear in beams	
	Average ultimate	Working strength	Average	Average ultimate	Working strength	Average ultimate	Working strength
.....	4200	800	800,000	....	....	....	....
l.....	4800	900	1,150,000	500	120	....	....
.....	6100	1200	1,510,000	690	170	270	110
stern.	5800	1100	1,480,000	630	160	270*	100
.....	5700	1100	1,150,000	840	210	270	110
f.....	6500	1300	1,610,000	720	180	300	120
.....	4200	800	1,190,000	590 *	130	250	100
lf....	5600	1100	1,480,000	710	170	330	130
.....	4400	900	1,130,000	400	100	180	70
.....	5000	900	800,000	300	80	....	....
.....	4800	1000	1,310,000	600	150	170	70
.....	4600	900	1,220,000	670	170	260	100

* Partially air dry.

D SIZES. — The commercial sizes of spruce and yellow pine part of the United States are as follows:

Cross-sectional dimensions in inches are:

, 2 by 5, 2 by 6, 2 by 7, 2 by 8, 2 by 10, 2 by 12
, 3 by 8, 3 by 10, 3 by 12
, 4 by 8, 4 by 10, 4 by 12
, 6 by 10, 6 by 12
o, 8 by 12.
ft. are ordinary lengths.
ft. are less common.
ft. are obtained with difficulty.

. — Same cross-sectional dimensions as spruce and also the fol-ons in inches):

by 16	6 by 14, 6 by 16	12 by 14, 12 by 16
by 16	8 by 14, 8 by 16	14 by 14, 14 by 16
by 16	10 by 14, 10 by 16	16 by 16

icks are commonly longer than spruce sticks, frequently exceed.

F TIMBER BEAMS. — Timber beams may be designed by of the ordinary beam formulas (*see Design of Beams in article mple*). Timber is especially weak in longitudinal shear which ng factor in many cases as shown by the preceding tables. It , be noted that the projection of the end of a beam over the en gives the timber a greater resistance to shear than would be strict application of theory and the designer must often use cretion in applying the shear formula.

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ALLOWABLE LOADS (POUNDS) ON BE
YELLOW PINE

(See Note below table)

Allowable uniformly distributed load in pounds
in excess of weight of beam, for end-supported
laterally at intervals of 12 times their thickness or
plied by width of beam in inches to get carrying capacity

Span in ft. = distance c. to c. end bearings	Depth of beam in inch					
	4	5	6	7	8	10
5	91	142	190	221	253	316
6	63	98	142	184	210	263
7	46	72	104	142	180	224
8	35	54	79	108	141	196
9	27	43	62	85	111	177
10	22	34	50	68	90	141
11	18	28	41	56	73	116
12	15	23	34	47	61	96
13	12	19	28	39	52	82
14	10	16	24	33	44	70
15	9	14	21	29	38	60
16	....	12	18	25	33	53
17	....	11	16	22	29	46
18	....	....	14	19	25	41
19	....	....	....	17	23	36
20	....	....	....	....	20	32
21	....	....	....	....	....	29
22	....	....	....	....	....	26
23	....	....	....	....	....	23
24	....	....	....	....	....	21
25	....	....	....	....	....	19
26	....	....	....	....	....	18
27	....	....	....	....	....	16
28	....	....	....	....	....	15
29	....	....	....	....	....	....
30	....	....	....	....	....	....

NOTE. — The tables pp. 1688 and 1689 are for
timber and require no allowance for impact.

For highway structures add 25 per cent to tabul

For buildings and other structures where timbe
add 50 per cent to tabular values.

Bold-faced type is used for lengths where shear

Values below zigzag line cause a deflection unde
of 1/1000 of span.

For actual deflection in inches, except where
divide deflection coefficient by depth of beam in i
manent load will ultimately equal double this valu

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OWABLE LOADS (POUNDS) ON SPRUCE BEAMS

(*See Note, bottom p. 1688*)

niformly distributed load in pounds per inch width per lineal foot, eight of beam, for end-supported spruce beams, supported laterally 12 times their thickness or less. *Tabular values to be multiplied m in inches to get carrying capacity of beams per lineal ft.*

Depth of beam in inches									Coefficient of deflection
4	5	6	7	8	10	12	14	16	
70	92	111	130	147	185	221	258	296	0.57
48	76	92	108	122	154	184	215	246	0.82
35	56	79	92	105	131	157	184	210	1.12
27	42	62	81	91	115	137	160	184	1.47
21	33	48	66	81	102	121	142	163	1.85
17	27	39	54	69	91	109	128	146	2.29
14	22	32	44	57	83	99	116	133	2.77
11	18	27	37	47	75	90	106	121	3.30
10	15	23	31	40	64	83	98	112	3.87
8	13	19	27	34	55	77	90	104	4.49
7	11	17	23	30	47	68	84	97	5.15
...	10	15	20	26	41	60	79	90	5.86
...	9	13	18	23	36	52	72	85	6.62
..	....	11	16	20	32	46	64	80	7.42
..	....	....	14	18	29	41	57	76	8.27
..	....	....	....	16	26	37	51	68	9.16
..	....	....	....	....	23	33	46	62	10.10
..	....	....	....	....	21	30	42	56	11.08
..	....	....	....	....	19	27	38	50	12.12
..	....	....	....	....	17	25	35	46	13.19
..	....	....	....	....	16	23	32	43	14.31
..	....	....	....	....	14	21	29	39	15.48
..	....	....	....	....	13	19	27	36	16.70
..	....	....	....	....	12	17	25	33	17.96
..	....	....	....	....	....	16	23	31	19.26
..	....	....	....	....	....	15	21	29	20.61

ues used in the tables are:

ellow Pine		*Spruce*	
	Lb. per sq. in.		Lb. per sq. in.
		Fiber stress :	
	1,300	Bending	1,000
ear	120	Longitudinal shear	70
city	1,500,000	Modulus of elasticity	1,310,000

lues used are the same as given in the table on pp. 1686 and 1687. ulus of elasticity for Yellow Pine, which is taken as 1,500,000 For other values of stress modify tabular values in proportion t stresses.

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WEIGHT OF TIMBER. — This is variabl
ture in the timber and whether it has been che
common to assume yellow pine at 4½ lb. per b
per board foot in estimating the strength of bea
ume and Weight of Poles in article on *Poles for Or*

COST OF TIMBER (Pre-war figures). —
and depends for ordinary stock upon the size an
New York in June, 1913, gave the price of spruc
board feet. Similar quotations on longleaf yellow

COST OF YELLOW PINE IN DOLLARS
AT YARD IN NEW Y

Cross section	20 feet and under
2 in. thick by 8 in. wide, and under..	$36
10 in. thick by 10 in. wide, and under..	42
12 in. thick by 12 in. wide, and under..	42
14 in. thick by 14 in. wide, and under..	47.50
16 in. thick by 16 in. wide, and under..	50

For regular quotations on timber see the firs
Engineering-News Record.

The cost of hauling timber and putting in plac
$10 per 1000 board-feet for fairly heavy yellow pi
labor.

BIBLIOGRAPHY. — U. S. Dept. of Agricu
(These give much valuable information conce
classification, etc., of timber.) Snow, *The Princ*
Diseases of Trees; Johnson, *Materials of Constr*
Its Strength, Seasoning and Grading; Am. Soc. of
of Am. Ry. Association; Yellow Pine Manual, p
Manufacturers' Association, St. Louis.

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FOR TRANSMISSION LINES. — (*See also Distribution ators for Transmission Lines; Poles for Distribution Lines; Struc- ; Transmission Lines.*) Steel towers are often used instead of for supporting electrical circuits. They have the advantages over ey can be of as large size as desired and are much more perma- owers are especially advantageous for high voltages (over 50,000) ire spacing is necessary; for long spans, such as river crossings, chanical stresses are exceptionally heavy; and in localities where r forest fires occur.

. FEATURES OF DESIGN. — Towers are composed of two er proper and the foundation. Towers are usually built of stand- steel shapes. Angles are used for most members. Channels are rger members of some towers, usually the cross arms, or for posts wers. Flat pieces are sometimes used for the minimum-sized ht towers. Round rods are used for tension members in some rincipal members of a tower are the corner posts or legs, which approximately vertical, and are usually the heaviest members roper, and the horizontal and diagonal web members which con- together in vertical planes which constitute the sides or faces

of a tower at the base is generally between one-fourth and one- eight. The greatest economy in cost of tower plus foundation es a little wider base than that which gives the least cost for the one.

usually designed for either one or two three-wire circuits, usually wo ground wires above and sometimes with a telephone circuit two circuits are on one tower they are usually located on op- reduce the hazard of repairing the line. The three wires of a asionally arranged to form an equilateral triangular prism, but in a single plane which is usually horizontal for single-circuit rtical for two-circuit towers.

owers. — There are two general types of towers, viz., (1) the only two legs and (2) the rigid, having three or more legs.

Towers (Fig. 4). — The flexible tower is set with face at right e so as to rigidly resist any transverse force, such as a wind blow- line, while bending if necessary to relieve any stress in the direc- e. The stability of the tower in the direction of the line is the conductors which it supports acting as guys. Where con- perform this function, due to being attached by suspension in- ound wires are used as the guys. The flexible tower is especially the smaller sizes, where the line conditions approximate those oles would otherwise be used. On lines of flexible towers, rigid re set at intervals.

owers. — These are usually triangular, square (Fig. 2) or rec- 3). The square tower is probably the most common. Square have the four faces framed with the same size members (even sses in the longitudinal and lateral faces rarely figure the same), economy of manufacture and erection which results from the is feature has an advantage in design in that the torsional e simply determined. Rectangular (including square) towers vantage that the unequal settlement of the foundations may ternal stresses not allowed for in the design. Triangular towers tresses from unequal foundation settlement, but present diffi-

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culties in the joining of standard structural shapes,
cult to calculate.

Connections of Members. — The members of
by bolts. By using no rivets the members may
handled even in rough country, erected by less sk
ing can be done after all shop work is complete
should be of one diameter (⅝ inch is suitable for
and of as few different lengths as possible. Bolt
than the bolts (1/16 inch is a usual amount). By
so that friction between the surfaces develops th
members, the play in the bolt holes with changin
the members is eliminated.

Clearance Between Conductors and Tower. —
ductor and tower should be sufficient so that the
tower at a lower voltage than is required to arc
usually determined approximately by making the
length of the string of suspension insulators. A
for change of position of conductor with swing c
amount of swing will not ordinarily exceed 45 d
should be determined for each case with and wit
mission Lines. The angle of swing will be greate
ductors and will be more for aluminum than for
Clearance to the cross arm will require special c
of swing exceeds 45 degrees from the vertical an
insulators are used which do not have an arc-ove
to the working voltage.

Foundations for Towers (Figs. 5 and 6). —
enforced) concrete, reenforced concrete or piles
dations. Rock footings are also used in special k

Structural Steel Foundations are cheap a
their durability has been questioned, they have b
trouble on this account yet apparent.

Concrete Foundations have an advantag
they can more easily be varied in depth, spread,
selves to local conditions of soil. This is especially
or irregular ledges interfere with the use of a stan
Mass-concrete foundations are advantageous in
sary or desirable to have a foundation of such w
uplift with little reliance on the holding power of
be conveniently attached to anchor bolts imbedded
tension in the concrete the bolts must extend to t
for distributing the stress. The anchor bolts and
system of reenforcement.
Reenforced concrete foundations are durable
mass concrete, thereby facilitating transportation.

Piles are used under or for foundations i
the holding power of other foundations is unreliab

Rock Footings for towers standing on l
bolts grouted into holes drilled in rock and ext
plates grouted to the rough rock surface at the pr

FORCES ACTING ON TOWERS. — The st
(1) The weight of tower, insulators, clamps, cabl

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ires) and ice loads on them; (2) The wind pressure on above;* alanced tension in cables when dead ended or broken on one side; alanced resultant due to cable tension at angles in the line; ds imposed when erecting towers, stringing wire or repairing line. study should be made of all the combinations of these loads which or probable. Often no single combination can be found which will maximum stress in all tower members, and therefore several com- ist be used to determine the design.

e anchor tower carrying six wires, three on each side, the maximum e expected in the corner posts when all six wires are pulling in the on; the maximum stress in the web members will probably be pro- ce wires pulling on one side in one direction and the three on the the opposite direction. In the first case the tower is subject to a s and in the second to a torsional stress. In each case the stresses t and wind are to be superimposed. The wind may act as a force e or across the line, but generally its longitudinal effect is negligible al effect is important.

n Tower Members. — The stresses in the several members of a ually determined graphically from the assumed loadings by means grams; see section on *Trusses* in the article on *Structures, Simple.* gns the distribution of stress is not fully determinate.

tal Assumptions. — Certain assumptions are, however, commonly ive a determinate distribution for the purposes of design. Among ions are:

alanced stress on the tower (say a broken wire pulling on one resolved into an equal stress at the axis of the tower and a tor- t.

uivalent stress at the axis of a ower can be considered as bal- n the two faces parallel with it, ng one-half the stress.

rsional moment can be consid- ed between all four faces of a wer.

ower is square each face takes he torsion.

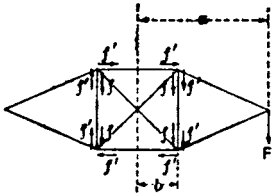


Fig. 1.

relations may be expressed as ig. 1):

alanced force in pounds applied at end of cross arm,
ance, in feet, from *end of cross-arm* to axis of tower,
ance, in feet, from *side of tower body* to axis of tower;

anced force in pounds applied at each corner post equivalent

to F in bending effect on body of tower,

ssure on a tower is assumed to be uniformly distributed per square foot t which the wind blows, one-half of it consequently being on the wind- windward face and the other half on the windward side (inside) of the or simplicity in calculation this uniformly-distributed force is replaced ncentrated forces, one at each panel point equivalent to the total dis- ending over a half panel above and a half panel below the panel point. is meant a point of intersection of principal members, for example, mbers with vertical members in Fig 4; and by panel is meant the between panel points, a panel usually being bounded by two vertical al members as in Fig 4.

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$f' = \frac{Fa}{8b}$ = torsional force in pounds applied at each corner post equivalent to F in twisting effect on body of tower.

(5) In a tower framed with a double system (i.e., diagonals in duplicate and suitable for compression as well as tension) each system may be considered as taking one-half of the stress as far as possible.

Approximations Made in Calculating Tower Stresses.—The stress diagrams are usually simplified by employing certain approximations:

(a) Faces of towers are usually battered so that they deviate slightly from a true vertical plane, but the stress diagrams usually neglect this inclination and are based on the vertical projection of the face.

(b) Where the face of a tower does not lie in one plane (i.e., has a change batter as occurs frequently at bottom cross arm where a prismatic cage joins pyramidal base) the change of inclination is neglected and the diagrams are based on a single vertical projection as before.

Subject to the limitations of the assumptions and approximations given above, the four faces of the tower can be regarded as four cantilevers, supported at the base and loaded at the top, which are independent except that the four corner posts are each common to two faces and must contain the resultant of both stresses.

Where a face of a tower or any part of a face has any considerable inclination the above approximations may not be used without danger of serious error.

Unstressed Members.—A tower usually contains members no stress in which is shown by the stress diagram, viz.:

(1) Diagonal members in a horizontal plane do not usually appear in the stress diagram when located below the lowest cross arm. These members play an important part in the distribution of torsion among the faces. In a rectangular tower the torsion will usually redistribute between the four faces at each level where there are horizontal diagonals, therefore the failure of the stress diagram to show stresses in them may be taken to indicate that the assumed distribution of torsion is not quite correct rather than a true absence of stress.

(2) Redundant members are braces which carry no determinate stress but perform the important function of supporting the compression members which do carry stress. The unit stress allowable in a compression member diminishes as the unsupported length increases. The weight of compression members is therefore diminished by dividing their unsupported length by braces applied at one or more intermediate points.

Unit Stresses in Towers.—The factors of safety and unit stresses used in tower design have not been standardized. In some cases it has been assumed that the combination of loading taken for tower design represents conditions which would happen so rarely that a tower which would stand these loadings in test without failure would be sufficient. This is equivalent to taking a severe combination of loads and designing for a factor of safety of but one. The result, however, may be as good a tower as one designed for the same conditions individually (but not in combination) with a factor of safety of two or four. It is probable that few towers are designed for the combination of all loadings, each taken at the most severe condition reasonably possible with an actual factor of safety exceeding two.

For a factor of safety of from 2½ to 1½ (as determined by test of complete tower, not of individual members) the following unit stresses have been used:

Tension: 12,000 to 20,000 lb. per sq. in.
Shear: 12,000 to 20,000 lb. per sq. in.
Bearing: 16,000 to 30,000 lb. per sq. in.
Compression: $12{,}000 \div K$ to $20{,}000 \div K$ lb. per sq. in.

$\frac{}{R^2}$,
orted length of member, in inches,
adius of gyration of section, in inches,

so limited that for main members $L + R$ does not exceed 125 to
econdary members $L + R$ does not exceed 150 to 220.

tricity in Stresses at Joints. — As tower members are ordinarily
ether the stresses in them are slightly eccentric, thereby prevent-
rength of the members being developed. The eccentricity should
or reduced as much as possible by having the center of gravity
members at each connection meet at one point as exactly as

ACTING ON TOWER FOUNDATIONS.—Foundation stresses
ses: first, the foundations resist the tendency of the tower to slide
due to the external forces on it considering the tower as a self-
cture; second, the foundations resist certain stresses which would
wer stresses were the tower framed as a complete self-contained
which become external stresses because the ground is depended
tion of certain omitted members. The weight of the tower can
educed by thus substituting the ground for certain members, but
ndation is thereby increased. The amount of these latter stresses
e outline and framing of the tower and their effect should not be
letermining loadings on foundations.
ude and direction of the forces acting on the tower foundations
ated by taking the case of a rectangular tower, and considering
line which runs north and south.

(feet) of base of tower (east and west);
(feet) of base of tower (north and south);
eight (pounds) of tower, insulators, fittings and one span of all
wires, including ice load, if any;
eight (pounds) of any unbalanced load, such as a wire c feet off
r;
nt force (pounds) of the wind on the tower and a complete
of all the wires (with ice coat, if any), acting at a distance of d
above the foundation, wind assumed blowing across line from
to east,
ounds) of any unbalanced force toward the south applied at a
ace of e feet above the foundation and f feet to the west of axis
wer, as for example, a dead-ended wire or when a wire on the
side of the tower is broken.

that the forces divide equally among the four foundations and
al forces are in a circumferential direction, the relations given
table hold. These assumptions are reasonably correct for a
four legs joined at the bottom with a horizontal strut in each
s and with horizontal ties across the diagonals, unless the
usually provided in the other faces is inadequate. Probably
s fully meet these requirements. Therefore, there are usually
s of large magnitude due to the foundations performing the
ng or inadequate members, as pointed out in the notes ap-
ble.

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FORCES ON TOWER FOUND

Magnitude of force on each of the four foundations	Direction at ea	
	N. E. corner	S. E. corner
$\frac{W}{4}$	Down	Down
$\frac{cW'}{a}$	Down	Down
$\frac{F}{4}$ (Note 1)	East	East
$\frac{dF}{a}$	Down	Down
$\frac{P}{4}$ (Note 2)	South	South
$\frac{eP}{b}$	Up	Down
$\frac{afP}{4(a^2+b^2)}$ (Note 3)	North	North
$\frac{bfP}{4(a^2+b^2)}$ (Note 3)	West	East

NOTES. — Where there are no struts between the bott where the bottom panel is framed on the single system, usual:

(1) The force of the wind F will give a greater force th on the two west foundations and a correspondingly less fo in addition produce four new forces tending to force the side and draw them together on the tension side.

(2) Similarly the pull of the wire P will give a greater direction on the two north foundations and a correspon two, and will in addition produce a westerly force at the N easterly force at the S. E. and N. W. corners.

(3) Similarly, the torsional forces due to P will increas direction, and the unbalanced pull P may develop new for nally-opposite legs and depress the other two.

Resultant Forces on Foundations. — From t sultant force on each of the four foundations may will be on each foundation: (1) a downward pres (3) a horizontal overturning force, producing a tend on one side of the foundation and a downward pres

Downward Pressure. — The downward pre portance in determining the size of the foundation a for uplift and overturning is unnecessarily safe agai

Direct Uplift. — The uplift is very import and foundation is rarely sufficient to provide more holding-down power required. The excess uplift is in which the foundation is buried. Not only is the over the foundation effective but there is an addition or cohesion of the earth which may be several ti are usually computed on the assumption that they a the earth in a frustrum of an inverted cone or py

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tending to the surface of the earth. The face of this cone is as making an angle of 30° with the vertical.

ontal Overturning Force, Sliding and Indirect Uplift. — The erturning force is also important. Its effect on the base may be two components, one a horizontal force tending to slide the foun- he other a moment tending to rotate the base about a horizontal sistance of the earth to these forces is an obscure subject, especially tion is of irregular shape. The following discussion which neglects able elements may be considered as a conservative view of the earth

nce to sliding may be considered as due to the friction of the base on the earth, and it may further be assumed that any base to resist uplift will also furnish sufficient friction to prevent slid- n of the overturning force is then the same as the height of the ottom of base to top where tower is attached), and the over- nt is equal to the horizontal force multiplied by this arm. The ent may be considered as due entirely to the vertical reaction of the top and bottom of the foundation. These vertical pressures as varying uniformly from zero at a horizontal neutral axis through the base, to a maximum at the edges of the base most remote from e moment of resistance is calculated as for a beam subject to aving a cross-section identical with the area of the base. It may at any unit pressure allowable on the uplift edge will be amply posite edge where the pressure is downward, so that calculations y are necessary. The maximum allowable unit stress on the y be taken as equal to the average unit resistance to uplift of dation, determined as described above under *Direct Uplift*.

g Conditions. — Usually the most severe condition that a tower required to meet consists of a combination of uplift and over- this condition the unit stress of uplift proper must be added to unit stress of uplift due to overturning and the sum must be wable average unit resistance to uplift.

Foundations. — (*See also article on Strength and Elasticity.*) A ubject to stresses from the tower tending to move it and from the he earth preventing motion. The foundation should of course gh not to break when subject to these opposing forces. As the cation of the resistance of the earth and the magnitude of the ransmitted by the earth at any point are subject to great un- foundation should be designed for strength for the distribution nce which is most severe, considering for example that while the is calculated on a uniformly-distributed earth resistance, it may practice by concentrated pressure from stones or timber located edge of the base.

Points Regarding Design of Foundations. — The following are lusions which follow from the above discussion:

erted cone theory of resistance to uplift gives a calculated re- increases at a rapid rate with the depth (eventually increasing as the cube of the depth). It would however be unsafe to ap- for foundations differing much from those of usual dimensions, much exceeding six feet and for foundations where the spread of less than the depth to which it is buried.

of the tower (top of foundation) should be brought as close to he ground as possible to reduce the overturning moment.

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he tower diagonals of the bottom panel of the tower should intersect
osts as low as possible, because this is the actual point of application
rturning force to the foundation and if this intersection is above
ion this extra length must be added to the arm of the overturn

ly inclining the axis of the foundation approximately in line with
tower leg (i.e., to bring it as near as possible into line with the result
iorizontal overturning force and the vertical pressure or uplift) a
ical use of material may be made to resist the combined uplift and

TING OF TOWERS. — Since towers are generally indeterminate st
iew designs are usually tested. Test loads proportional to the
l for the design are applied until the required factor of safety has
or failure occurs. Towers are usually mounted on a rigid base for
his gives the strength which the tower would develop on an "id
ion. In practice the tower must be expected to develop somewhat
ı, as unequal movement of the foundations will ordinarily overst
members. Test loads may be applied by means of weights suspe
at proper points for vertical loads and applied by means of pulle
to a tower-testing structure ("test tower") for horizontal loads. T
of application makes the determination of the test loads easy, but
nient to have the weights fall any considerable distance if the tow
o failure.

ng of Foundations. — Foundations are occasionally tested, but t
usually more for determining the holding power of the soil than
ı of the foundation. For the former purpose the test result will dep
on the character of the soil and its condition (dry, wet or frozen). Te
ling power are only necessary for uplift and overturning forces. In te
important that the testing machine should not press down on the surf
oil near the foundation. The machine should rest on the ground o
the base of an inverted cone of angle of 45° from the vertical and
g the base of the foundation under test.

CIFICATIONS, CONTRACTS AND PROPOSALS. — Differ
.cturers of towers use different details of construction so that specifi
ritten for the purpose of obtaining proposals should contain only
and requirements. These should state the loadings, factors of saf
ım allowable stresses, and show outline dimensions of the tower as de
from clearances required.

specifications should state whether towers are bolted or riveted, g
l or painted, shipped assembled or partly assembled, tested or not tes
sides containing the usual structural steel specifications; see *Steel*.

proposals should show the arrangement and sizes of members and typ
of connections.

racts are oftentimes let on the basis of furnishing an approximate nu
towers when the exact number required cannot be determined in a
and a unit price per pound is included to cover extensions, spec
tions and modifications that may be required.

galvanizing and sherardizing of towers and parts are usually specified t
ıe American Telephone and Telegraph Co's. Specification for galva
on wire (*see Galvanising for Iron or Steel*). All members of towers th
too heavy, so that there is danger of their buckling in the process, ma
ified to be galvanized by the hot dip process. All bolts, nuts, threade
id turnbuckles may be specified to be sherardized.

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ATION AND ERECTION. — Towers are generally shipped en-
mbled, all of the members for one tower being bundled together.
usually assembled lying on its face on the ground adjacent to the
When assembled it is temporarily braced when necessary (usually
ween the legs at the base of the tower) and up-ended onto the foun-
r the latter operation temporary hinges connecting the two legs
ground to the two adjacent foundations are convenient. Towers
up-end and towers in inaccessible places are built up in place.
d connections the nuts should be prevented from working loose by
ads on bolts, riveting over the end of the bolt, or by lock-nut or

r member should have a number which should be shown on the
ings and marked on the corresponding member of each tower.
rs should be cut, bent and punched to template so that the parts
nangeable and the assembled tower will fit the foundation prepared

n of Foundations. — Foundations should be set with their bases
st line. The hole should not be excavated deeper than necessary,
undation may rest on undisturbed earth. If any of the several
f a tower rest on loose backfill, unequal settlement may be ex-
may greatly weaken the tower. The hole should not be larger
y, as the backfill will be less effective than undisturbed earth in
t. The resistance of concrete foundations can sometimes be in-
gging a hole smaller in diameter than the base and undercutting
om, while with structural steel foundations large stones can some-
ed against the steel to increase its resistance to motion, either
eral. The backfill should be well tamped in place and especial
used if it is probable that the foundation will be subject to heavy
he earth has had time to settle. On sloping ground filling may be
e low side to give the designed weight of earth against uplift. In
the floating power of hydrostatic pressure beneath the foundation
ed for. Where towers are raised on extensions the increased
esses due to increased moment must not be overlooked.
foundations of a tower should be set accurately by template
ls spacing and elevation so that towers stand trully vertical and
stresses due to distortion.

ANCE OF TOWERS. — All bolted connections on towers
ully watched and kept tight, and the galvanizing or paint should
gularly and towers must be repainted before any deterioration
ccurs. Foundations are the most likely source of trouble in
ese should be kept properly backfilled and should be watched
tlement of legs.

ONS, WEIGHTS, COSTS. — Data on these items for a number
given in the following table. Galvanized towers cost from 2½
pound, f.o.b. factory. Galvanizing costs from ½ to 1 cent per
t of galvanizing is included in the figures just given.

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DATA ON TYPICAL STEEL TOWERS

Use (a)	Conductors (b)		Number and diam. of ground wires, inches	Kilovolts between wires	Pin or suspension insulators	Height, feet		Base, feet		Weight, pounds
	Number	Size, cir. mils or B. & S.				To lowest cross arm	Over-all	Across line	Along line	
L (2)	6	300,000	1–½	110	*S*	55	79	20	20	6,800
A	6	300,000	1–½	110	*S*	50	75	24	24	10,500
L (3)	3	683,000 (*c*)	1–½	150	*S*	43	47	18	20	4,335
A	3	683,000 (*c*)	1–½	150	*S*	37	41	24	24	6,985
L (4)	3	0000	1–⅜	50	*P*	42	53	9.5	(*d*)	2,150 (*e*)
A	3	0000	1–⅜	50	*P*	42	53	9	9	3,750
L	3	0	2–⅜	102	*S*	43	45	14	13	1,800
L	6	000	1–⅜	32	*S*	51	76	17	17	4,560 (*f*)
L	6	000	1–⅜	100	*S*	51	77	17	17	.....

L = straight-line or suspension tower, *A* = anchor or angle tower; numbers ets refer to accompanying cuts, Figs. 2, 3 and 4 respectively. (*b*) All conducte ded. (*c*) 605,000 circular mils of aluminum with a 78,000 circular-mil steel co lexible tower. (*e*) Including foundation. (*f*) Average for 197 towers, includi r towers and hardware.

DATA ON TYPICAL TOWER FOUNDATIONS

(Used in connection with the first four towers listed in above table, respectively)

Type	Fig. No.	Number per tower	Height, in.		Base, in.	Lb. of steel	Cu. yd. of concrete
			Over-all	Projection above earth			
Reënf. concrete.	5	4	78	6	60 by 60	500	4.4
Reënf. concrete.	..	4	96	6	96 by 96	1584	14.4
Steel.....	6	4	90	6	44 by 45	1285	.....
Steel.....	..	4	88	6	52 by 52	1865	.....

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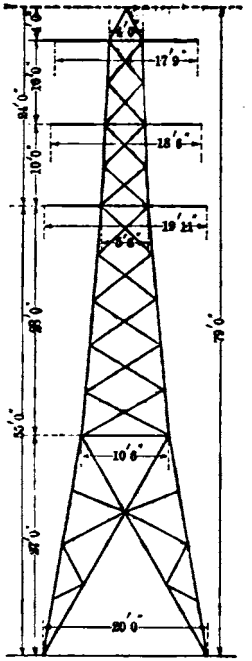


Fig. 2. Square Two-circuit Tower

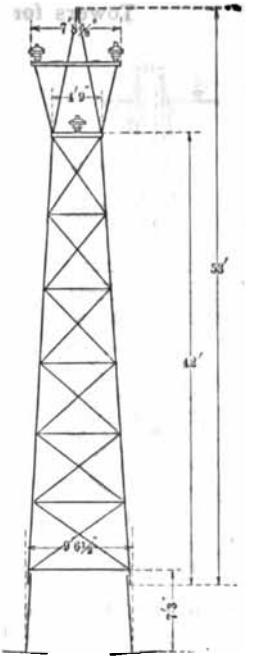
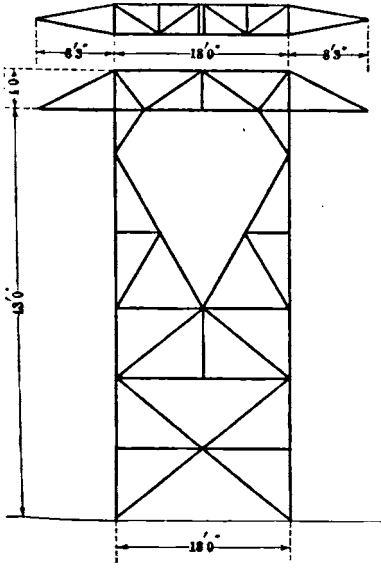
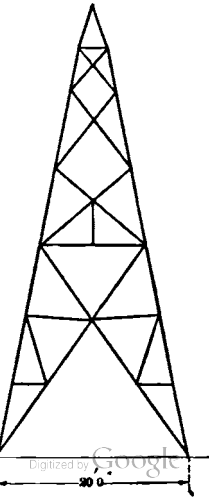


Fig. 4. Flexible Tower with Steel Foundations





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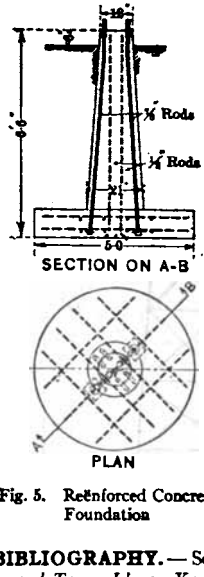


Fig. 5. Reënforced Concrete Foundation

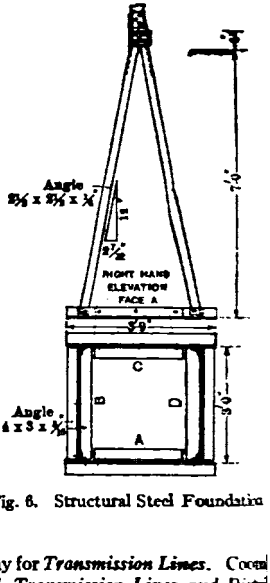


Fig. 6. Structural Steel Foundation

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ANSFORMERS. — (*See also Alternating Currents; Auto-transformers; ctricity and Magnetism, Principles of; Standardization Rules of the A.I.E.E.; nsformers, Instrument.*) The following is a brief table of contents of this cle:

Classification	p. 1703
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Transformer Connections	1709
Three-phase Transformers	1713
Design	1714
Predetermination of Performance	1719
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Testing of Three-phase Transformers	1728
Examples of Performance	1729
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General Description. — The electrical transformer, commonly called the tic transformer, is a piece of stationary apparatus used to transform alter- ting-current energy at one voltage to some other higher or lower voltage. e single-phase transformer consists of two electrical circuits, usually of a ge number of turns, interlinked with a common magnetic circuit of iron. ice the power is approximately the same in both windings, the currents in e two windings are inversely proportional to the voltages in the windings. e polyphase transformer is essentially two or more single-phase transformers ide into a single piece of apparatus, but so designed that at least a part of e magnetic circuit is common to all the phases. A three-phase transformer s three high-tension and three low-tension windings arranged on a single n core; see Figs. 1 and 2. The auto-transformer is treated in a separate ticle, viz., *Auto-Transformers.*

Terminology. — The winding by which the energy enters the transformer logically the "primary" and the one by which the energy leaves the trans- rmer is called the "secondary." Since either winding of the transformer ay be connected to the source of energy, these terms are not definite unless e manner of connection is also stated. When referring to the transformer as separate piece of apparatus the terms "high-tension" winding and "low-ten- on" winding are used to distinguish the two windings, the high-tension winding ing the one with the greater number of turns. When the high-tension winding connected to the source of supply it is the primary, and the transformer is id to be used as a "step-down" transformer; when the low-tension winding connected to the source of supply, the high-tension winding is the secondary, id the transformer is said to be used as a "step-up" transformer.

CLASSIFICATION. — Transformers may be classified according to their perating characteristics, to their construction, or to the method of cooling.

Constant Potential and Constant-current Transformers. — Transformers ay be either constant potential, such as are intended to give an approximately onstant potential on the secondary side, or constant current, intended to give n approximately constant current on the secondary. Both types are intended o operate on a supply circuit of a constant potential.

Series Transformers are connected in series with the main circuit and re- ceive a variable voltage and current in the primary. The secondary circuit is

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closed through a path of low impedance and thus the secondary current will be proportional by the ratio of turns to the load current flowing in the primary or supply circuit. They are usually used to supply low-reading ammeters and wattmeters from circuits carrying very heavy currents.

Auto-Transformers or Compensators, sometimes called single-circuit transformers, consist of one electric circuit interlinked with the magnetic circuit and a tap brought off from some part of the winding. The voltage between the tap and either terminal of the electric circuit will be a fraction of the total voltage and thus a fractional voltage may be secured from this piece of apparatus. It is customary to proportion the windings on each side of the tap in accordance with the current to be carried. Auto-transformers are generally used where the ratio of voltages is quite near to unity as in this case they can be constructed with much less copper than the regular transformer. See article on *Auto-transformers.*

Potential Regulators are a form of transformer in which the voltage of one member may be varied from zero to a fixed maximum either by changing the direction of the magnetic flux or by changing the phase of the electromotive force of the secondary with respect to the electromotive force of the primary.

Core and Shell Types.—Two methods of arranging the electric and magnetic circuits are in use, the corresponding construction being designated as the "core type" or the "shell type." At present a large number of lighting transformers of small and medium capacity are constructed in a manner which is a composite of the core and shell types.

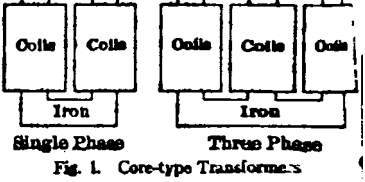


Fig. 1. Core-type Transformers

Core Type (Fig. 1).—The single-phase core-type transformer consists of a single magnetic circuit interlinked with two electric circuits, each consisting of a group of coils as shown in Fig. 1. The three-phase core-type transformer is also shown in Fig. 1.

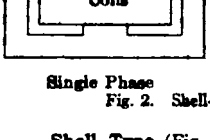




Fig. 2. Shell-type Transformers

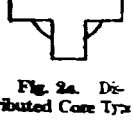


Fig. 2a. Distributed Core Type

Shell Type (Fig. 2).—In the shell type of transformer each electric circuit is interlinked with two magnetic circuits having a common path inside the coils but branching outside of the coils as shown in Fig. 2.

Distributed Core Type (Fig. 2*a*) is a compromise between shell and core type and is much used for small lighting transformers because it economizes in iron and distributes the heat. It consists of the two electric circuits wound concentrically about one central core which divides at the top and bottom into four radiating magnetic circuits surrounding the coils on four sides. It is shown in Fig. 2*a* in plan view.

Comparison of Core and Shell Type.—The core type of construction is best adapted for high-voltage low-capacity transformers and the shell

e for low-voltage high-capacity transformers. This arises from the fact that most economical disposition of material in the core type demands a large ıber of turns and small cross-section of iron, while in the shell type a large ıs-section of iron and small number of turns may be used to advantage. In shell type the coils are usually wound in flat "pan-cakes," this type of struction being particularly well suited to the use of heavy copper rib- or straps. In the core type the coils usually consist of two or more ›ls, long in comparison with their diameter. The use of the core type is easing both in number and size of transformers as it is found possible to nge the coils so they will better withstand the mechanical strain due to 't circuits.

lassification According to Method of Cooling. — (*See also below.*) nsformers may be subdivided into classes in accordance with the method l for dissipating the heat due to their internal losses. As a transformer is a compact piece of apparatus the problem of carrying away the heat is important and various ingenious means have been devised for the purpose.

Naturally Cooled Transformers. — As this name implies this type of sformer has no special means of cooling but relies upon the ordinary circu- ın of the air. It is only used in transformers of very small sizes, such as ıe intended to supply meters.

Oil-cooled Transformers. — In this type of transformer the core and lings are submerged completely in oil in a tank and the windings and core subdivided by ducts in order that the oil may circulate and carry off the from the internal parts. The heat is carried to the surface of the tank ch contains the transformer and from there carried off by the surround- air. The tank is specially designed to provide large air-cooling surfaces, provided with deep corrugations, or with projecting vanes or tubes.

Air-blast Transformers are designed with special passages through ch a current of air is forced by means of a blower, the heat being carried off he atmosphere in this manner.

Water-cooled Transformers consist of a construction similar to that he oil-cooled type and in addition a coil of pipe carrying running water is nerged in the oil.

Forced-oil Transformers. — Transformers artificially cooled by cir- tion of oil are used when the size is too great for the self-cooling oil type no cooling water is available. The oil circulates through external coils or cs which give a greater cooling surface.

IETHODS OF RATING. — The *Standardisation Rules of the A.I.E.E.* ify that the continuous rating of a transformer is that load in kilo-volt- ıeres which when applied continuously will cause a rise in temperature of C. as measured by a thermometer, or 55° as measured by resistance of the dings. The iron of transformers takes a long time to reach a constant perature, that of oil-cooled transformers in particular requiring from 10 to 12 rs. Thus a transformer will stand a considerable overload for a short time ›out overheating, the principal danger being excessive mechanical stresses.

'RANSFORMER PRINCIPLES. — (*See also Electricity and Magnetism, nciples of.*) The essential features of a transformer consist of a primary ding having a number of turns interlinked with a magnetic circuit, and a ›ndary winding also interlinked with the same magnetic circuit, as shown ig. 3.

Simple Theory, Neglecting Leakage Reactance. — In the following dis- sion the assumption will first be made that all the flux links both primary l secondary windings; the effect of the leakage flux will be discussed later.

In Fig. 3, S_1 is the primary winding, M the magnetic circuit (of iron) and the secondary winding. If an alternating current is caused to flow in S_1 it will set up a flux in M which at any instant is proportional to the current i_1. Thus

$$\phi = \frac{4\pi S_1 i_1}{10 R},$$

where S_1 is the number of turns, i_1 the instantaneous value of the current and R the magnetic reluctance of the path in M.

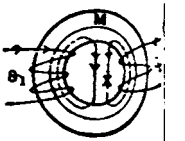


Fig. 3. Elementary Transformer

Thus ϕ alternates with i_1 and since it interlinks with S_2 it will induce a voltage in S_2 at any instant equal to

$$e_2 = -S_2 \frac{d\phi}{dt} 10^{-8} \quad \text{volts}$$

in which S_2 is the number of turns. The negative sign means that any current due to e_2 will tend to diminish ϕ.

No-load Conditions. — When there is no current in the secondary the vector relations are as shown in Fig. 4. Let E_1 be the voltage impressed on S_1, then the maximum value of the alternating flux will be

$$\phi = \frac{10^8 E_1}{4.44 f S_1},$$

where f is the frequency of alternation of E_1. Strictly, the numerator is $10^8(E_1 - r_1 I_\omega)$, where I_ω is the exciting current and r_1 the resistance of the primary, but the term $r_1 I_\omega$ is practically negligible. This flux will lag 90° behind E_1 or 90° ahead of the counter electromotive force E_c which it induces in S_1. The true magnetizing current I_m will be in phase with the flux and the hysteresis component of current I_H will be in phase with E_1. Hence the total no-load current I_ω will assume some phase a little less than 90° behind E_1.

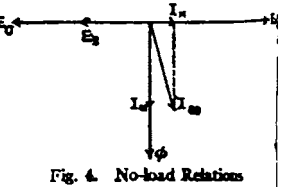


Fig. 4. No-load Relations

The flux ϕ will induce in the secondary turns S_2 an e.m.f. 90° behind the flux, hence 180° behind E_1 or in phase with the primary counter e.m.f. The effective value of this e.m.f. is

$$E_2 = 4.44 f S_2 \phi \, 10^{-8}.$$

Load on Secondary. — When the secondary is closed through a non-inductive external circuit a current will flow. This current will tend to demagnetize the iron, that is, to reduce the flux and hence the counter e.m.f. of the primary. This action, however, allows the current in the primary to increase until the secondary m.m.f. is balanced and there is left an excess m.m.f. in the primary to give sufficient flux to induce the counter e.m.f. E_1'. The vector relations are as shown in Fig. 5, again neglecting the leakage flux.

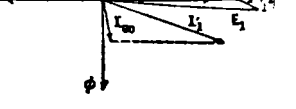


Fig. 5. Full Load, No Leakage

Leakage Reactance. — Due to the fact that a part of the lines of induction set up by the currents in the two windings pass through the air space (Fig. 3), the m.m.f.'s set up by the secondary current and the load current

(the current I_1' in Fig. 5) cannot neutralize each other, since the es established by the two currents are in the same direction, and ition as are the fluxes in the iron. The primary leakage flux is in he total primary current and the secondary leakage flux is in phase condary current; these leakage fluxes are therefore not in phase eful flux (i.e., the flux which links both primary and secondary). that the leakage fluxes cause a decrease in the secondary voltage ifting of its phase with respect to the primary voltage.

wo leakage fluxes are in phase with the total currents in the primary ry respectively the voltages induced by the alternation of these quadrature with the cur- quotient of the voltage he primary by the alter- ary leakage flux divided ary current is called the kage reactance," and the he voltage induced in the

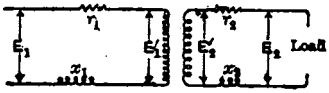


Fig. 6. Diagram of Circuits

the alternating secondary leakage flux divided by the secondary led the "secondary tance." These re- practically con- the major portion ge path is in the

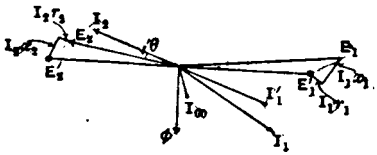


Fig. 7. Complete Vector Diagram

Vector Diagram

ner.—Fig. 6 shows ally the primary windings of the transformer and Fig. 7 the vector diagram.

secondary terminal e.m.f.;
er factor of load;
ndary current, lagging by angle θ behind E_2;
ndary resistance drop in volts; in phase with I_2;
ndary reactance drop in volts due to ½ of leakage flux, at 90° to I_2;
ced e.m.f. in the secondary (hypothetical);
. necessary to overcome counter e.m.f. in primary; opposed and roportional to E_2' by ratio u;

of transformation $= \frac{S_1}{S_2}$;

ary load current; opposed and proportional to I_2 by ratio $\frac{1}{u}$;

al or useful flux;
ary no-load current;
or resultant primary current;
ary resistance drop; parallel to I_1;
ary reactance drop, at 90° to I_1;
quired voltage on the primary, that is, the impressed e.m.f.

t " Circuit of Transformer. — In practice it is not possible to ately the primary and secondary reactances. They must be ther and treated as one quantity, called the total reactance x_t rmer, which may be expressed in terms of either the primary condary turns.

proximate method which is sufficiently accurate for all practical ed on the equivalent circuits shown in Fig. 8. This method is

used in calculating the characteristics of a transformer from constants obtained from tests.

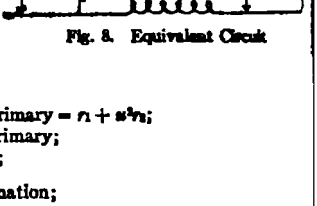


Fig. 8. Equivalent Circuit

Let E_2 = terminal e.m.f. of secondary;
$\cos\theta_2$ = power factor of load;
I_2 = secondary current;
u = ratio of transformation = $\frac{S_1}{S_2}$;
E_2' = uE_2;
I_2' = $\frac{I_2}{u}$;
R = total resistance in terms of primary = $r_1 + u^2r_2$;
X = total reactance in terms of primary;
I_M = primary magnetizing current;
I_H = $\frac{\text{core-loss}}{uE_2}$, to a close approximation;
E_1 = primary impressed e.m.f.;
I_1 = total primary current;
$\cos\theta_1$ = power factor of transformer with load, i.e., power factor at primary terminals;
P_1 = watts input at primary terminals;
η = per cent efficiency.

Then

$$E_1 = \sqrt{(E_2'\cos\theta_2 + RI_1)^2 + (E_2'\sin\theta_2 + XI_1)^2};$$
$$I_1 = \sqrt{(I_2'\cos\theta_2 + I_H)^2 + (I_2'\sin\theta_2 + I_M)^2};$$
$$P_1 = E_2I_2\cos\theta_2 + R(I_2')^2 + E_2'I_H;$$
$$\cos\theta_1 = \frac{P_1}{E_1I_1};$$
$$\eta = \frac{100\,P_2}{P_1};$$
$$P_2 = E_2I_2\cos\theta_2;$$
$$\text{Per cent regulation} = \frac{100\,(E_1 - uE_2)}{uE_2}.$$

Constant-current Transformers are used for supplying current to arc lamps connected in a series circuit which requires from 4 to 10 amperes and about 2000 volts. The principle of operation for this type of transformer is based on the existence of the leakage or useless flux which causes a repelling force between the primary and secondary windings. One winding is arranged so that it may move with respect to the other. As the current in the windings increases the repelling force increases and the windings move apart. This allows more flux to leak or pass between the windings and less to thread the secondary. Therefore the voltage induced in the secondary decreases as the current tends to increase. A counterweight is attached to the movable winding to regulate the amount of movement. The current in the primary remains fairly constant but the power factor decreases with decreasing load on the secondary so that power in the primary is approximately proportional to the output of the secondary.

Series Transformers operate under conditions similar to those in a constant-potential transformer with short-circuited secondary. Under operating conditions the flux is small as the only voltage to be induced in the secondary is that required to overcome the impedance drop in that winding and the instrument which it supplies. The only counter e.m.f. in the primary is that due to impedance drop. The series transformer must be operated with the secondary

rt circuited by a low impedance. If the secondary circuit is open there is counter m.m.f. to balance the primary turns, which, being in series with the in line, carry a current irrespective of the secondary circuit. The primary pere-turns would then set up a magnetic flux of considerable magnitude. the transformer is not designed for this condition, the density would become y high in the magnetic circuit of small cross-section, and the transformer is ble to burn up from the heat due to core-loss.

TRANSFORMER CONNECTIONS. — The various transformer connecns which are commonly used in lighting and power services are described ow; see also section on *Operation* below.

Single-phase System with Three-wire Secondary (Fig. 9). — Standard ictice in residence lighting with the a-c. system involves grounding the neuwire on the low-tension side, the primary side not being grounded. Lamps motors operating at 110 volts are connected between the neutral and either

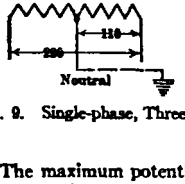


Fig. 9. Single-phase, Three-wire

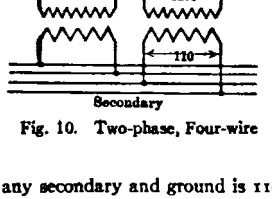


Fig. 10. Two-phase, Four-wire

le. The maximum potential between any secondary and ground is 110 volts it if either of the outside wires becomes grounded it constitutes a short-circit on that half of the transformer.

Two-phase or Quarter-phase Four-wire System (Fig. 10). — The standd two-phase or quarter-phase system is essentially two independent singlease systems which are usually independent electrically throughout. When e two phases are not electrically connected inside the generator, either wire one phase may be connected to either wire of the other phase, without any ow of current resulting. In certain two-phase generators, however, the windgs are interconnected, in which case any interconection of the wires coming from the generator will ause a flow of current through this connection.

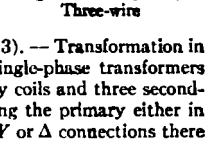


Fig. 11. Two-phase, Three-wire

Two-phase Three-wire System (Fig. 11). — his connection is occasionally used for the distriution of power in small systems. There is a possiility of a slight saving in copper, but the chances f unbalanced voltage and bad regulation, particlarly with an inductive load, render it objectionable.

Three-phase Y and Δ Connections (Figs. 12 and 13). — Transformation in three-phase system with either three independent single-phase transformers r with a three-phase transformer, having three primary coils and three secondry coils on one iron core, is accomplished by connecting the primary either in *Y* or in Δ and the secondary either in *Y* or in Δ. With *Y* or Δ connections there re the following relations between voltage per transformer winding and voltge between lines, and between current in transformer windings and current n lines. The power in the three transformers in any case is $3 \times 0.58 \times EI = 1.73\,EI$.

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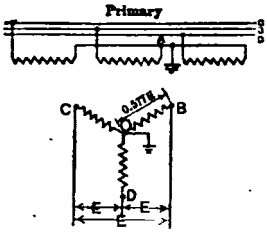


Fig. 12. Three-phase Y

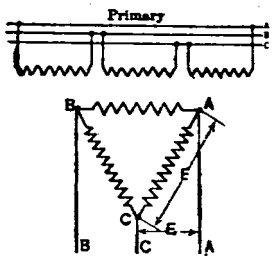


Fig. 13. Three-phase Delta

Connection	Volts bet. lines	Volts per winding	Current per line	Current per winding
Y	*E*	0.58 *E*	*I*	*I*
Δ	*E*	*E*	*I*	0.58 *I*

There are four combinations of these connections which may be used on any bank of transformers. These connections are given in the following table, and also the ratio of the voltage between lines for the low-tension and high-tension sides for a given ratio (u) of transformation in each individual transformer connection.

Connection		Low-potential volts bet. lines	High-potential volts bet. lines
Low pot.	High pot.		
Δ	Δ	*E*	*uE*
Y	*Y*	*E*	*uE*
Δ	*Y*	*E*	1.73 *uE*
Y	Δ	*E*	0.58 *uE*

Parallel Connection of Three-Phase Banks. — If there are several banks of transformers in the same system connected in parallel on one side, then to connect the other sides in parallel the connections must be such that the voltage between any two lines on this side will have the same phase in all the banks. From this relation result the following rules:

With ΔΔ on one bank, the other bank must be ΔΔ or *YY*.
With *YY* on one bank, the other bank must be ΔΔ or *YY*.
With Δ*Y* on one bank, the other bank must be Δ*Y* or *Y*Δ.
With *Y*Δ on one bank, the other bank must be *Y*Δ or Δ*Y*.

Even when these relations are satisfied a short-circuit will result unless the three phases of each bank are connected in the proper sequence. This can be

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ermined by the polarity test described below in the section on

tive Advantages of Y and Δ Connections. — There has been ssion as to the relative advantages of *Y*- and Δ-connected trans- high-tension transmission and as to the value of a grounded neu- eneral and fundamental arguments may be summed up as follows: Δ-system the advantages are that if one transformer becomes dis- stem may be operated from the other two, operating on open delta If the load is unbalanced the voltages do not become unduly un- Resonance cannot occur. On the other hand, each transformer ulated for full line voltage as there is no neutral to ground, and if omes grounded the voltage strain on the rest of the system becomes he normal strain, and this strain may extend to the low-tension the generator which is connected to the transformers.

Y-connection there is a very unstable neutral and a possible ex- ge strain on one phase, unless the neutral is grounded.

Y arrangement for step-up transformers, the neutral on the high- may be grounded. The voltage strain on any transformer is then 3 per cent of the line voltage. There is a possibility of operating g two transformers, if one becomes damaged, by using the neutral conductor. However, there is the possibility of resonance under mstances and the danger of causing disturbances in nearby tele- elegraph circuits. Any accidental ground on the system makes a t-circuit on one phase.

gement of *Y*Δ for step-up transformers is not desirable on account ble neutral with unbalanced load, but is permissible with a balanced a good connection from neutral of transformers to neutral of genera- onnection, however, is frequently used for step-down transformers when connected to a balanced load.

nded Neutral vs. Ungrounded Neutral. — In any system rounded neutral there are numerous possibilities of disturbances a high voltage strain on the various parts of the insulation of the th the high voltages now in use for transmission systems these may give a great deal of trouble by breaking down the insulation, always possible to employ a large margin of safety and lightning not always protect from these disturbances. On the other hand, l is grounded, most of these disturbances will merely result in an rent, and if the circuit breakers are installed in the proper places n the circuit, so that the only adverse result will be a temporary of service.

e is then between a system with ungrounded neutral and a large fety in the insulation, and a system with grounded neutral, mod- ion and the possibility of occasional interruption of service.

t of Higher Harmonics. — Many alternators generate an e.m.f. shape contains higher harmonics (*see Wave Analysis*) and the mag- ent of transformers operating at high magnetic densities has a ve shape which contains a prominent third harmonic. If these re present in a *Y*-connected machine they cause the voltage be- ine and the neutral to vary so that there exists an unstable neu- voltage strain on any one phase is indeterminate. If the neutrals s of apparatus in which these harmonics exist are grounded or ier, a high-frequency current will flow in the neutral connection. er hand these pieces of apparatus are Δ-connected a third harmonic circulate inside the apparatus. This may be measured by con-

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necting an ammeter in the Δ between two phases. This current heats the apparatus, does no profitable work, and is therefore to be avoided. High frequency current in the line will cause high voltages to occur at certain points if a large amount of capacity is present, as is the case in any underground line even of moderate length, and also in long overhead lines. All possible means both in the design of the generators and the connection of the apparatus should be taken to prevent the occurrence of, or to diminish the effect of, these higher harmonics.

Three-phase Open Δ or V Connection (Fig. 14). — This system consists in omitting one transformer from the delta connection, and is used to save expense, particularly in temporary installations or in new installations where the load is not great at first but is expected to increase in time. Thus the

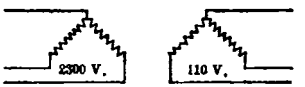


Fig. 14. Three-phase, Open Delta

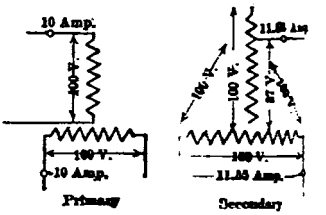


Fig. 15. Two-phase to Three-phase

purchase and installation of the third transformer is postponed until the load requires it. This connection can only be recommended for low voltages, such as 2300, as it is liable to produce dangerous potentials due to electrostatic unbalancing. The regulation and efficiency are also poor, as one phase of the load receives its power from two transformers in series. The aggregate capacity of the two transformers should be 15 per cent greater than the load.

Two-phase to Three-phase Transformation (Fig. 15). — The Scott or T connection, the standard method of transforming from two-phase to three-phase, consists of two transformers which on the two-phase side may be connected in the normal two-phase manner either independently or interlinked. On the three-phase side one transformer has a tap at the middle point and the other a tap giving 87 per cent of full-transformer voltage. Fig. 15 shows the method of connecting and the currents in primary and secondary with balanced loads. Since the total power is $2 E_2 I_2 = \sqrt{3}\, E_3 I_3$, it follows that $I_3 = \frac{2}{\sqrt{3}} \frac{E_2}{E_3} I_2$, or the three-phase current is 16 per cent greater than it would be for straight single- or two-phase transformation. Thus one of the windings of one transformer must carry 16 per cent more than its share of the volt-amperes of the load and is overloaded in that proportion.

In commercial practice it is customary for the sake of interchangeability to make the capacity of both transformers 16 per cent greater than the load and to put both a 50 per cent and 87 per cent tap on both transformers. For this connection of transformers each half of the main transformer winding must be distributed over both legs of the core in order to prevent flux (and therefore voltage) unbalancing. If this precaution is taken both the primary and secondary voltages are balanced if the load is balanced. Any unbalancing of the secondary causes a like amount of unbalancing on the primary; thus if this connection is used to transform from 3-phase to 2-phase and all the load comes on one phase of the secondary it will also come on one phase of the primary.

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Transformer Connection for Synchronous Converters.—For a tv
onverter the connections are simple as shown under *Converters*. For
hase converter there is a choice between Δ or *Y* secondaries, which is
ecided in deference to the conditions in
he high-tension line. The delta connection
s customary in railway substations. A
iagram of the connections is given in the
rticle on *Converters, Synchronous*. When
ie converter is to supply a three-wire d-c.
ghting system, the "distributed" *Y* con-
ection for the secondary should be used
s shown in Fig. 16. By this arrange-
ient the unbalanced current from the d-c.
eutral is divided, and sent through the two
alves of each transformer in opposite di-
ections. Thus it does not increase the magnetic densities in the tr
rs, and avoids the excessive core-loss which would occur with a s
onnection.

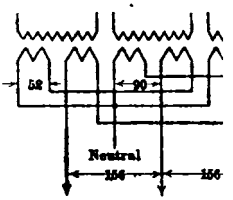


Fig. 16. Distributed Y for T
Converter

For six-phase converters there is the choice between the "diametri
double delta" connections as shown in Figs. 17 and 18. The diam

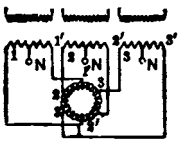


Fig. 17. Six-phase Diametrical

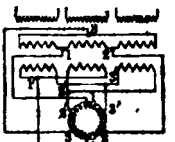


Fig. 18. Six-phase Delta

ommon with railway converters, or where the conditions are such
elta is not needed to prevent an unstable neutral.

For regulating pole or split-pole converters certain special conditions
orne in mind in choosing between the diametrical and the doubl
ections. With the variation of the direct voltage of the converter t
ape of the alternating e.m.f. is distorted and this introduces harm
ther the counter e.m.f. or current waves, among which the third
ominent. If the delta connection is used a local harmonic current c
the converter armature and transformer secondaries, which incre
sses and heating and lowers the efficiency. If the diametrical conn
ed the higher harmonic voltage gives an unstable neutral, and in
tra potential strains in the high-tension windings and line if *Y*-co
his may be obviated by grounding the neutral, but then a consider
nt may flow in the neutral connection, which may interfere with nel
rcuits. The best solution is to use the diametrical connection in the
y and ungrounded *Y* in primary, and use transformers having a gooc
safety in the insulation of the high-tension side.

THREE-PHASE TRANSFORMERS. — Considerable space, wi
st cost may be saved by the use of a three-phase transformer in
ree single-phase transformers. This saving is warranted in large inst
it not in small installations where the convenience of having one inte
le single-phase transformer as a spare for several banks of three tran
ch is an important item.

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Core of Three-Phase Transformer. — Three-phase transformers may have of the core type as shown in Fig. 1, in which case all the magnetic paths are of the same cross-section, or of the shell type shown in Fig. 2. In the latter type the horizontal cross pieces and outside vertical pieces may have one-half the cross-section of the central vertical core, providing the coil on the central leg is connected with a definite polarity with respect to the other two coils in order to have the fluxes differ in phase by 60 degrees.

Operation of Damaged Three-phase Transformer. — In a shell-type three-phase transformer if the primary and secondary are delta-connected it is possible to operate with only two phases in open delta at reduced capacity in case of trouble in the third phase of the system. This is accomplished by separating the third phase entirely from the system and short-circuiting both the primary and secondary windings.

DESIGN. — (*See also section below on Cooling of Transformers.*) The methods of design for single-phase and polyphase transformers are similar, the chief difference being that of the magnetic circuit. In the design of polyphase transformers each leg is treated as an independent single-phase transformer. The number of turns is adjusted to the voltage per phase and the cross-section of the conductors to the current per phase. All legs are wound alike and the phases are connected up as described in the preceding section.

The alternating-current transformer is the most efficient piece of electrical apparatus. Its efficiency at full load is usually better than 95 per cent and frequently better than 98 per cent. For this reason it is very small in volume and light in weight for a given output compared to other pieces of electrical apparatus and hence the chief difficulty in design is the necessity of providing sufficient surface and a proper means to carry off the heat developed.

The difference in mechanical construction between the core and shell types is that the winding of the core type usually consists of two or more long spools (in which the length is considerably greater than the diameter) surrounding each leg of the transformer. The shell type consists usually of large flat "pancake" coils, laid alongside of each other on the central core with proper separating devices to permit ventilation. See Figs. 1 and 2.

The following discussion applies alike to both core and shell types except where specific mention to one or the other is made.

Preliminary Calculation of Main Dimensions. — Let

E_1 = primary voltage, effective value;
I_1 = primary full-load current, effective value;
E_2 = secondary voltage, effective value;
I_2 = secondary full-load current, effective value;
f = frequency in cycles per second;
S_1 = number of primary turns;
S_2 = number of secondary turns;
ϕ = maximum value of flux;
$C = \dfrac{\phi}{S_1 I_1}$ = ratio of total flux to full-load primary ampere-turns;
e = volts per turn, effective value;
B = maximum value of magnetic flux density in lines per square inch;
A = cross-section of core in square inches;
f_1 = space factor of winding space;
D = total section of copper in square inches;
U = current density in amperes per square inch;
σ = ampere-conductors per inch length of core.

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ermination of Flux (ϕ) and Number of Primary Turns (S_1).— estimate a desirable value of the flux to be used there is employed which is defined by the relation

$$C = \frac{\phi}{S_1 I_1}. \qquad (1)$$

value of this factor C depends upon the type, capacity and voltage former, and the relative weights of copper and iron.* Usual values the accompanying table.

VALUES OF C

f transformer	Voltage	Core type	Shell type
		Value of C	Value of C
ft.....	0–6000	55–70	500–700
	6000 up	70–75	500–700
.....	0–10,000	75–100	
	10,000 up	100–150	
water-cooled...	0–10,000	110–160	600–1000
	10,000 up	160–240	600–1000

n between the effective value of the primary voltage and the ue of the flux is

$$E_1 = 4.44 f S_1 \phi \times 10^{-8}. \qquad (2)$$

equations (1) and (2) the proper values of the primary voltage ncy f, the constant C and the primary full-load current I_1, and o equations for ϕ and S_1, reasonable values for the flux ϕ and primary turns S_1 are obtained.

minary estimation of the full-load primary current I_1 it is suffi- e to ignore the efficiency and power factor and to take the current utput divided by primary voltage.

per Turn (e). — The above value of ϕ should be checked by ts per turn,

$$e = 4.44 f \phi \times 10^{-8},$$

it with values used in practice. In large transformers a greater n turns is permissible than in ners. The accompanying table transformers is based on the t double-cotton-covered wire is ndings. With special insulation ay be used. For the shell type es as great are customary.

Kilowatt rating of transformer	Allowable volts per turn for core type
10	2.5
20	3.5
50	5.5
100	7
200	9
500	13
1000	18

of Secondary Turns (S_2). — ned in a preliminary way the ry turns, the number of turns in $S_2 = \frac{E_2}{E_1} S_1$. It will considerably anical arrangement of the coils if 4. The nearest multiple of 4 is l value of S_2 and then S_1 and ϕ correspond to this value of S_2.

f this factor C will be found in Arnold's *Transformers* and in S. P. *mo Electric Machinery*, Vol. II.

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Cross-section of Core (A) and Magnetic Flux Density (B). — The cross-section is determined by the magnetic density which it is desirable to use, which in turn is determined by the core-loss. It is found that in average practice a loss of one watt per pound of iron can be dissipated without excessive rise in temperature. The corresponding flux densities in iron having a thickness of 14 mils are given in the following table. These values are approximate only since the quality of the steel used is exceedingly variable. It should also be noted for a transformer intended for supplying a load of low power factor that the iron loss should be less than 1 watt per pound for the best distribution of material.

VALUES OF FLUX DENSITY

Size of transformer	Kind of steel	Lines per sq. in.	
		25 cycles	60 cycles
Small	Ordinary transformer sheet	50,000	40,000
Small	Special; silicon-steel	70,000	60,000
Large	Ordinary transformer sheet	75,000	65,000
Large	Special; silicon-steel	90,000	75,000

The proper cross-section of core in square inches is then

$$A = \frac{\phi}{B}.$$

In the core type this cross-section may be assumed as a square whose side is d. Since the core is made up of laminations whose effective length one way is 0.9 d, the value of d is

$$d = \sqrt{\frac{A}{0.9}}.$$

In the shell type this cross-section is a rectangle whose length is from 2 to 3 times its width.

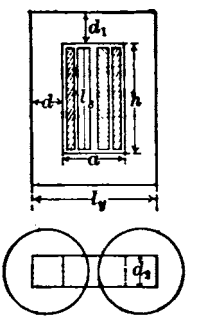


Fig. 19. Dimensions, Core Type

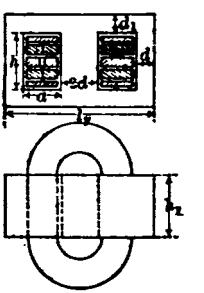


Fig. 20. Dimensions, Shell Type

Dimensions of Winding Space (Figs. 19 and 20). — The area or cross-section of the "window" or winding space depends upon the amount of copper

sulation and ventilating space. The first can be determined accurately by e chosen current density in the copper. The second and third are allowed : by a space factor (f_1) which gives the ratio of the actual total cross-section copper (D) to the cross-section of the window. Usual values of f_1 are given the following table.

SPACE FACTOR IN TRANSFORMERS (f_1)

Size of transformer, Kw.	Core type		Shell type		
	Up to 10,000 volts	33,000 volts	Up to 2000 volts	2000 to 10,000 volts	33,000 volts
0–50	0.22	0.15	....	....	....
50–1000	0.33	0.25	0.40	0.33	0.18
Above 1000	0.38	0.33	0.45	0.36	0.21

In the core type there is one window and it contains $S_1I_1 + S_2I_2$ ampere conctors; in the shell type there are two windows and each contains $S_1I_1 + S_2I_2$ ipere conductors. The cross-section of copper in one window in either case is

$$D = \frac{S_1I_1 + S_2I_2}{U} = \frac{2\,S_1I_1}{U},$$

here U, the current density in amperes per square inch, has the following lues:

Condition of transformer	U = amperes per sq. in.
Poorly cooled	850–1200
Ordinary oil cooled, air blast, etc.	1100–1600
Large, well cooled	1500–1900

Then the height h and width a of the window, see Figs. 19 and 20, must be ich that

$$ha = \frac{D}{f_1}.$$

Height of Core. — In the core type this depends upon the ampere-turns or npere-conductors per inch length of core, which in turn is related to the heatg. The ampere-conductors per inch length of core is

$$\sigma = \frac{S_1I_1 + S_2I_2}{2h} = \frac{S_1I_1}{h},$$

here h is the height of core.

For a maximum rise in temperature of 50° C. σ will have values as given in he accompanying table. A reasonable value of h can then be found.

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Form of transformer	σ = amp. conductors per inch of core
Natural cooled	500–750
Oil cooled or air blast	750–1250
Water cooled	1250–2000

In the shell-type transformer the practice is to make the height (h) from 1.5 to 3 times the width of window (a) and the width of window from 0.75 to 1.25 times the width of the central iron core, $2d$ in Fig. 20. See also paragraph above on *Cross-section of Core.*

Details of the Winding.—

$$\text{Cross-section of primary conductor in square inches} = \frac{I_1}{U}.$$

$$\text{Cross-section of secondary conductor in square inches} = \frac{I_2}{U}.$$

For minimum loss the copper density should be the same in both members but to save space the copper density in the high-potential winding is sometimes greater than that in the low-potential winding.

The low-potential winding is usually placed between the high-potential winding and the iron.

Each coil is now laid out in detail, placing as many turns in a layer as the height and insulation will allow. The voltage per layer must not exceed 150 to 200 volts. A space of 10 mils is to be allowed for insulation between layers when insulated wire is used and 8 mils when insulated strip is used. The space between coils is from 0.04 to 0.30 inch, depending upon the voltage per coil. Space for the air or oil ducts is also provided. Each duct is from ¼ to ⅜ inch wide and there should be one on each side of each coil. No part of the winding should be more than ⅝ inch from the surface of a duct.

Insulation of Windings.— The insulation of each turn usually consists of the cotton covering if the coils are wound with wire, or mica paper if the coils are wound with strip copper. This is proportioned to withstand the potential between turns as given above. The voltage between conductors on adjacent layers may be equal to twice the voltage per layer. To prevent breaking down between layers, a layer of Fuller board is used as a separator and this should project beyond the windings at the ends to prevent creepage. The maximum voltage between layers should be kept below 400 and to accomplish this it is customary to limit the voltage per coil to about 5000 volts. Between the windings and the core a layer of pressboard and sometimes wood is placed while between primary and secondary windings a layer of pressboard and micanite may be used. For very high voltages the end turns of the high-tension winding for about 75 feet from the terminals is given a special insulation to withstand the sudden high potentials which occur when there is a sudden change in the potential applied to the transformer. These high potentials result from the distributed capacity of the transformer, between the high-tension winding and the core, frame and other winding.

Terminal Bushings. — At the point where the high potential leads pass through the case there is a very great dielectric stress which must be taken care of by the use of a proper kind of insulation and a proper disposition of the

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o prevent a concentration of the dielectric flux at a few points. For ow 40,000 a porcelain bushing is customarily used.
r voltages it is necessary to supply a large creepage distance and to face submerged in oil to prevent corona effect. This is accomplished of bushing, known as the "condenser type," by surrounding the th layers of insulation and putting sheets of tinfoil between the is arrangement is equivalent to a series of condensers. By properly ig the area of the successive layers of tinfoil the drop in potential nsulation is kept uniform. The whole terminal is inclosed in an ng. Another form of bushing known as the "oil-filled type" consists ylinder of composition insulation which surrounds the lead and is oil. The cylinder is divided into compartments to keep the oil tributed, and disks or collars project outward from the outside to creepage distance.

Coils of Shell Type. — With the flat coils customarily used in e transformer the subdivision of the windings is usually such that lf coil of the low-potential winding at each end of the winding space). This is to reduce the leakage flux. In order to further reduce flux all coils may be divided into halves with a ventilating duct ves. The space between a primary and secondary coil is then iat necessary for the insulation.

nt of Core Dimensions. — After the final details of the windings the cross-section and length of core is finally settled. Sometimes tion of core in the core type is made cruciform instead of square se more effectively the area inside of circular coils.

ERMINATION OF THE PERFORMANCE OF A TRANS- — From the above calculations a drawing to scale of the trans- e laid out. The next step is to calculate its performance, i.e., to the values of the efficiency, regulation and temperature rise. ture is treated in the following section on the *Cooling of Trans-*

ng Current (I_M). — The final flux density will probably differ a from the value assumed earlier in the calculation. The cross- e is usually proportioned to give the same magnetic density in all condition gives minimum core-loss for a given weight of iron. ength of path in the iron is measured or calculated. If H (found netization curve of the iron, see article on *Magnetic Properties of* ampere-turns per inch for the given density the magnetizing transformer will be

$$I_M = \frac{H \times (\text{length path})}{\sqrt{2}\, S_1}.$$

it is desired to allow for the minute air gaps at the joints of the rnold finds that under practical conditions each joint represents 2 inch. Thus if there are n joints (usually 4) there should be in amount

$$\frac{0.313 \times 0.002\, Bn}{\sqrt{2}\, S_1}.$$

— The core-loss consists of hysteresis and eddy losses in the s. These losses have been considerably reduced in recent years

by improvements in the manufacture and quality of the steel (*see article Magnetic Properties of Iron*).

$$\text{Core-loss} = k_1 f V \left(\frac{B}{1000}\right)^{1.6} 10^{-6} + k_2 V \left(t f \frac{B}{1000}\right)^2 10^{-6} \text{ watts,}$$

where f = frequency in cycles per second;
V = volume of iron in cubic inches;
B = magnetic density in lines per square inch;
t = thickness of laminations in inches;
k_1 = a constant, ranging from 8 in ordinary transformer steel to 4 silicon-steel;
k_2 = a constant, ranging from 4 in ordinary transformer steel to 1.5 silicon-steel.

The core-loss may be calculated more easily by the method and curves given in the article on *Magnetic Properties of Iron*.

Copper Loss. — The mean length of turn of both primary and secondary windings is obtained from a sketch to scale. The direct-current or ohmic resistance of each member at 60° C. is obtained by substituting the proper values in the formula

$$R = \frac{0.0093\, lS}{12{,}000\, as},$$

where l = mean length of turn of primary or secondary respectively in inches
S = number of turns in series,
a = cross-section of conductor in square inches,
s = number of conductors or coils in multiple.

To allow for eddy currents caused by the leakage flux, the above resistance is increased by 15 per cent to give the effective resistances r_1 and r_2. The total copper loss is then $I_1^2 r_1 + I_2^2 r_2$.

Transformer Reactance. — As explained in the section above on *Transformer Principles*, the leakage of flux between the primary and secondary windings of a transformer causes a component of voltage in each member which is out of phase with the current; if the current lags very much this voltage may have a considerable component opposed to the useful voltage and cause a loss of voltage or poor regulation. It is, therefore, necessary in designing to estimate the amount of this flux and calculate the voltage it would produce. In practice empirical formulæ are usually used, but a logically deduced formula is desirable as it is more easily adapted to unusual cases.

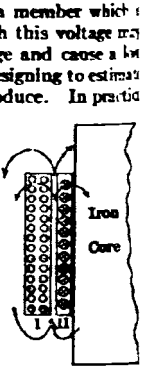


Fig. 21. Leakage Flux

The phase of the current in the secondary coil is nearly opposed to that in the primary and may be assumed to be exactly opposed without any great error. The result as shown in Fig. 21 is that all these ampere conductors, both primary and secondary, tend to set up a flux in the same direction in the space between the windings and to a lesser degree in the windings themselves. A part of the flux in the intervening space interlinks with the primary turns and another part with the secondary turns. In addition the flux in the windings themselves interlinks with some of the turns. The flux in each part is proportional to the ampere turns producing it and to the permeance of the path. In this case since the path is in air, the permeance is the area divided by the length, where the length is the average length of the flux lines.

he leakage flux passes between the windings and one part closes its path he iron inside the inner coil and the other part in air outside the outer coil the core type). The reluctance of the path between the two coils is large ıpared to that of the other two portions, because the inside path has a high neability and the outside path has a large cross-section. The reluctance he path between the coils is therefore accurately (and easily) calculated and ınstant used to allow for the rest of the path.

ı order to calculate the inductance it is necessary to have a cross-section he windings showing their thickness, length and arrangement, as in Figs. 19 20.

wo cases must be considered:

A) Where there are as many primary coils as secondary coils, and all coils are full size (usual core type).

B) Where there is a "half" secondary coil at each extremity of the group of windings (the usual arrangement in the shell-type transformers).

ırnold's Method of Calculating Reactance. — Arnold calculates the intance of a single primary coil and its secondary mate or mates, and multiplies by the number of primary coils in series or divides by the number in mul-. This gives the total "short-circuit" inductance of the transformer in ns of the primary voltage or turns.

eferring to Figs. 19 and 20 for the core and the shell type respectively, let various quantities be represented as follows, all dimensions being in inches:

q = number of primary coils in series,
p = number of primary coils in parallel,
s_1 = number of turns in one primary coil,
s_2 = number of turns in one whole secondary coil,
l_a = height of coils in cylinder type,
l_a = depth of coils in flat type,
t_1 = thickness of a whole primary coil,
t_2 = thickness of a whole secondary coil,
t = distance between coils,

l_1 and U_2 = mean length of primary and secondary turns respectively,
U_m = average of U_1 and U_2,
k = an empirical constant, varying from 0.95 with flat coils to 1.06 with cylinder coils.

Reactance of Core Type (Fig. 19). — In a core-type transformer with ndrical coils and an equal number of full-sized primary and secondary coils, permeance of the path of the flux in the duct which interlinks with a primary is $\frac{tU_1}{2l_a}$ and the permeance of the path in the winding itself is $\frac{t_1U_1}{3l_a}$.

: inductance of one primary coil is

$$L_1 = \frac{3.2\,ks_1^2U_1}{l_a}\left(\frac{t_1}{3}+\frac{t}{2}\right)10^{-8}.$$

: inductance of one secondary coil is

$$L_2 = \frac{3.2\,ks_2^2U_2}{l_a}\left(\frac{t_2}{3}+\frac{t}{2}\right)10^{-8}.$$

lucing the latter to terms of the primary turns by multiplying by $\frac{s_1^2}{s_2^2}$, adding ether and multiplying by $2\pi f$, the total reactance of the transformer in ns of the primary is

$$X = 2\pi f\,\frac{3.2\,qks_1^2U_m}{pl_a}\left(\frac{t_1+t_2}{3}+t\right)10^{-8}.$$

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Reactance of Shell Type. — If, as in the
in Fig. 20, there is a half secondary coil at each en
mixing, then

$$X = 2\pi f \frac{3.2\, qks_1^2 U_m}{2\, pl_g}\left(\frac{l_1 + l_2}{6} + \right.$$

Efficiency and Regulation. — The efficiency a
lated as described above under "*Equivalent*" *Cir*
or by the following method, which is sufficiently
purposes.
Let

E_2 = secondary terminal voltage,
I_2 = secondary current,
$\cos\theta_2$ = power factor of load on secondary,
$P_2 = E_2 I_2 \cos\theta_2$ = secondary output in watts,
A = core-loss in watts = input for no-load on
u = ratio of number of primary to number of
$R_2 = \frac{r_1}{u^2} + r_2$ = total resistance in terms of se
actual resistances of primary and seco
$X_2 = \frac{X}{u^2}$ = total reactance in terms of secon
reactance in terms of primary.

Then the per cent efficiency is

$$\eta = \frac{100\, P_2}{P_2 + A + R_2 I_2^2}.$$

Secondary voltage at no load is

$$E_{20} = \sqrt{(E_2\cos\theta_2 + R_2 I_2)^2 + (E_2 \sin$$

and the regulation is then

$$\frac{100\,(E_{20} - E_2)}{E_2} \text{ per cent.}$$

All-day Efficiency. — The all-day efficiency is
between the readings of a watt-hour meter connec
similar meter on the primary. It is of importance
formers, particularly for lighting, operate at full lo
day, but the core-loss or iron losses are just as grea
or when there is no load at all. Hence these tran
deal of energy, although their efficiency at full load
To calculate the all-day efficiency multiply each
for efficiency by the number of hours per day that

$$\text{All-day eff.} = \frac{100\, P_2 \times h}{P_2 \times h + h_1 A + h R_2}$$

where h = hours per day of secondary load; h_1 = ho
is on line, and the other symbols as above. Since
a day and P_2 only 2 or 3 hours, the importance of
transformer for this class of service is apparent.
However, there is another side to the question, si
as much during the day when there is little dema
in the evening when the demand is great.

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XAMPLES OF DESIGN. — In the following table are given the chie
ign characteristics of four different transformers.

EXAMPLES OF SINGLE-PHASE TRANSFORMER DESIGN

American or foreign	Foreign	Foreign	American	American
rm (cooling)	Oil	Air	Oil	Air
pe	Core	Shell	Distributed	Shell
equency	50	50	60	25
-a. rating	40	100	20	75
gh-tension voltage	3120	2200	2200	2500
w-tension voltage	230	110	220	320
(design constant)	56	670	222	1550
gh-tension Winding:				
Current at rating, amperes	12.8	45.5	9.1	30
Total turns in series	1408	130	640	219
Coils in series	8	4	2	3
Coils in multiple	1	1	1	1
Size of conductor, inches	d=0.183	0.79×0.059	0.105×0.09	0.34×0.03
Resistance at 25° C., ohms	1.13	0.24	1.43	0.492
w-tension Winding:				
Total turns in series	104	9	64	23
Coils in series	4	1	4	4
Coils in multiple	1	3	1	1
Size of conductor, inches	0.59×0.13	0.87×0.1	2, each 0.23×0.155	6, each 0.34×0.09
Resistance at 25° C., ohms	0.009	0.00059	0.0204	0.0095
ux density in core, kilolines per square inch	38.6	52	63	67.5
ore dimens., inches, length	(26 sq. in.)	5.1	4.6	8
ore dimens., inches, width	.....	22.8	4.6	21
ndow dimens., inches, height	35.5	5.9	9.2	5.5
ndow dimens., inches, width	5.45	9.9	3.1	8
gnetizing current, amperes	0.21	2.12	0.432	1.82
re-loss, watts	490	1320	164	1520
-load current, per cent	2.04	4.85	4.8	6.9
re-loss, per cent	1.22	1.30	0.80	1.96
imary, RI^2, per cent	0.50	0.52	0.59	0.57
condary, RI^2, per cent	0.68	0.48	0.81	0.67
ficiency, per cent	97.6	97.7	97.8	96.8
tal XI drop, per cent	1	2	2.84	1.36

COOLING OF TRANSFORMERS. — It is necessary to keep the tem
ature of the various parts of a transformer within such limits that the ma
ials of which it is constructed do not become damaged and deteriorate to
idly. When subjected to too high a temperature the insulating materia
integrate and lose their mechanical and dielectric strength, and the iro
eriorates in its magnetic qualities so that the core-loss becomes greater fo
iven density. This so-called ageing of the iron may cause an increase of a
ich as 50 per cent in the loss in the iron. The effect varies with the charact
the iron and is practically negligible in silicon-steel.

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Maximum Rise in Temperature.—The maximum rise in temperature above a room temperature of 25° C. at which the various materials of a transformer should be operated are given in the table.

To guard against this possibility of damage the Standardization Rules of the A.I.E.E. recommend that the windings shall not increase in temperature more than 50° C., as measured by resistance, above the surrounding air, and the other parts shall not increase more than 50° C. as measured by thermometer.

Material	°C
Iron	70–75
Cotton	60
Paper	75
Mica, asbestos	90

Means of Dissipating Heat.—The problem is to provide a path of low thermal resistance by which the heat energy may pass to the surrounding air. To accomplish this it is necessary, first, to provide sufficient surface in the subdivided transformer to transfer the heat to the cooling agent, air or oil, without too great a difference in temperature; second, to so subdivide the transformer that no part of the iron is more than one inch, and no part of the copper more than ⅝ inch, from a cooling surface; third, to provide a sufficient quantity of the cooling agent, air, oil or water to carry away the heat at the same rate as it is generated; and fourth, to provide sufficient surface of the containing case or tank to transfer the heat from the internal oil to the external air without too great a difference in temperature.

Calculation of Exposed Surface of Transformer.—The practical method of estimating the rise in temperature consists in calculating the drop in temperature in the successive media through which the heat must pass to be dissipated. The first step is to calculate the exposed surface of the transformer coil, core ducts, coils and coil ducts. In accordance with design practice the surface in the ducts is only rated at half the effectiveness of the outside surface (*Generators, Alternating-current*), and therefore only half the duct surface is included in the figure for "Effective Radiating Surface, A_t." Having found a value for A_t in square inches, the following criteria apply to the respective types.

Naturally-cooled Transformers should have from 4.75 to 5.3 square inches of surface (A_t) for each watt loss for 50° C. rise in temperature.

Oil-cooled Transformers.—(*See also Oil, Transformer.*) The transformer is submerged in oil in a tank so that the level of the oil is from 2 to 3 inches above the top of the transformer. The quantity of oil is from 6 to 10 pounds per kv-a. rating, or in small sizes 500 pounds per kilowatt loss. There should be from 1.5 to 2.3 square inches of transformer surface (A_t) per watt loss. The oil ducts should be ¼ inch wide and run vertically. If the tank is smooth there should be from 4 to 8 square inches of tank surface (not including top or bottom) for each watt loss. For sizes greater than 25 kilowatts it is customary to use fluted or corrugated sides to the tank. In this case there should be from 6 to 10 square inches of radiating surface per watt loss because the air does not circulate as rapidly in the grooves as over a smooth surface and consequently radiation is poor.

For a rise of 50° C. of the transformer there is an average rise of 30° of the oil. The maximum rise of the oil is 1.3 to 1.5 times the average.

The rise in temperature of the windings by resistance or of the iron by thermometer is

$$T = \frac{2W}{A_t} + \frac{fW}{S} + h,$$

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otal watts lost;
adiating surface of transformer in square inches;
adiating surface of tank in square inches;
om 160 to 200 with smooth tanks.
o to 270 with corrugated tanks;
aximum difference of temperature in oil, usually 40 to 45° C., depending upon circulation.

Transformers. — This type of transformer is usually set over a in the floor which is supplied by a blower with air at a pressure of ounce (¼ to 1 ½ inches of water). The air enters the transformer at nd is divided into two streams, one passing vertically through the the other transversely through the iron. There is a damper or stream so that the proper amount of air is provided to each part . Ducts ½ inch wide are provided every 3 to 4 inches. For 50° g surface of the transformer (A_t) should be from 1.5 to 2.3 square t loss. A liberal amount of air for 50° C. rise is 150 cubic feet per owatt loss. The air is expected to rise from 15° to 20° C. in its gh the transformer. The theoretical quantity of air in cubic feet

$$Q = \frac{1.65W}{Ta},$$

e rise in temperature of the air, which is usually about half as e of the transformer.

d Transformers. — The cooling coils are suspended in the il near the top, usually above the transformer, and carry a ulating stream of water. It is customary to provide ⅓ gallon inute for each kilowatt of loss and to allow the outgoing water above the incoming. Other requirements are from 1 to 1.5 f surface (A_t) per watt loss for 50° C. rise and 1 square inch coils per watt loss. This assumes a temperature drop of 20 to ulation and oil, 2 to 3° between oil and water and 20 to 25° in

SINGLE-PHASE TRANSFORMERS. — The customary s on transformers and the best order of making them are: cold ity, ratio and checking of taps, impedance, core-loss and exciting run, heat run, insulation tests. The efficiency and regulation om the results of these tests.

nsformers should never be tested or subjected to potential unless filled with oil from which all moisture has been removed.

est results are given below.

ce Measurement. — The cold resistance must be very care- t is used as a basis of calculating the temperature after the r the transformer has been standing in one place long enough arts to have reached the same temperature as the surround- current of from 10 to 15 per cent of the rated current of hrough the windings and the drop measured with a volt- ame time the temperature of the windings is measured by a

ity. — This test gives information necessary for connecting ers in a bank and have them operate in parallel or on poly- Direct current is sent through one winding of a transformer eter connected across the other winding. If the current is

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stopped, the voltmeter will give a deflection either positive or negati For similar connection and direction of current on all the transformers o bank the deflection should be of the same sign. A small current should used as otherwise the throw of the voltmeter needle may be sufficient bend it.

Ratio of Turns. — With no load on a transformer the ratio of voltage the same as the ratio of the turns. Thus, with a known voltage applied to low-tension winding, the ratio of turns of the two main windings and of sections between taps can be checked up by connecting across the other minals another voltmeter of proper range (using a potential transforme necessary).

Impedance Test. — This test is important in order to calculate the regula and in order to determine whether transformers will run in parallel with e other. One winding of a transformer is short circuited and a voltmeter, amme and wattmeter are connected in the circuit of the other winding. A voltag from 1 to 8 per cent of the rated voltage of this winding and of the proper quency is impressed. The voltage is regulated so that readings are take values of current from 50 to 125 per cent of the rated current of the windi The wattmeter reading will be in the neighborhood of 2 per cent of the ratin the transformer. The total impedance of the transformer will be $Z = \frac{E}{I}$. T total effective resistance will be $R = \text{Watts}/I^2$, which will include the effec eddy currents, and the total reactance will be $X = \sqrt{Z^2 - R^2}$. This reac cannot be separated into primary and secondary reactance. The results o test are usually plotted in two curves, one between volts and amperes and other between volts and watts.

Core-loss and Exciting Current Test. — The alternator supplying the po for this test should give a sinusoidal e.m.f. wave, as any distortion in the sha may cause a variation of from 5 to 10 per cent in the core-loss. A peaked wa gives a lower core-loss than a sine wave. For this test the high-tension win ing is left open and rated voltage at the proper frequency is impressed on t low-tension winding. A voltmeter, ammeter and wattmeter are connected i the low-tension circuit, the voltmeter having a range including the rated vo age of the transformer and the ammeter a range of approximately 15 per ce of the rated current of the machine. Readings are taken with a voltage from 50 per cent to 125 per cent of the rated voltage of the transformer. Bo ampere-volt and watt-volt curves are then plotted. If extreme accuracy desired, the RI^2 loss should be subtracted to give true core-loss.

Separation of Eddy and Hysteresis Losses. — In certain special ca it is desired to investigate the iron of a transformer by separating the hysteres from the eddy loss. Let

W_1 = the core-loss at normal voltage and frequency.
W_2 = the core-loss at half voltage and half frequency.
W_e = eddy-current loss at normal voltage and frequency.
W_h = hysteresis loss at normal voltage and frequency.

Then

$$W_e = 2W_1 - 4W_2$$
$$W_h = 4W_2 - W_1$$

Parallel Run Test. — The test for polarity and ratio having sho nothing wrong in the transformers, they are connected two at a time. T

windings being connected in parallel to a generator and the
n windings in parallel with each other with an ammeter of about
t the capacity of the transformer connected in one lead between
voltage of the alternator is gradually increased from zero and the
he ammeter noted. This current should not be greater than 5 per
rated current of that winding at rated voltage. If a transformer
vindings in either member the same test should be made on these
parallel.

n. — The heat run is made at the rated load of the transformer
nes at an overload of 25 per cent or 50 per cent, depending
uarantees. The run may be made by connecting the trans-
oad such as a water rheostat (*q.v.*) but as there are other equally
ls, avoiding the waste of so much energy, this dead load is
The other methods require two or three transformers to be
aneously.

'ransformers "Bucking" (Fig. 22). — The low-tension windings
›rmers are connected in multiple to a voltage of rated value and
'he high-tension windings are
so that their e.m.f.'s oppose
:h other, and are in series with
source of e.m.f., of rated fre-
; a value of from 2 to 5 per
ited voltage of the windings.
›ply" may be either an alter-
nsformer, or a potential regu-
tage of this source is adjusted
ad current circulates in the
indings and thereby induces
nt in the low-tension wind-
d be realized that although
cent of the rated voltage is
l the current through the

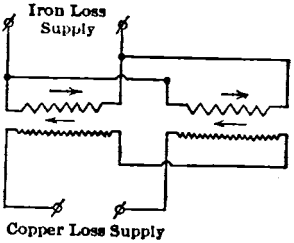


Fig. 22. Connections for Heat Run by Bucking

ach primary is generating its rated voltage and if there should be
here a dangerous potential strain or shock might result.

ransformer Arrangement (Fig. 23).— Three single-phase trans-
connected with their low-tension windings in delta to a three-
supply of proper volt-
e high-tension wind-
ted in delta with one
:o which the "loss
ected preferably by
uxiliary transformer
ngerous potential of
The "loss-supply"
adjusted so that the
ows in the primary winding.

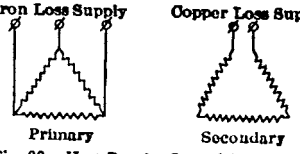


Fig. 23. Heat Run by Open-delta Method

Heat Run. — The time required for a heat run may be con-
ed by operating at an overload for a short while, or, if the trans-
blast transformer, by operating without the blast until a rea-
perature has been attained. Then the proper load is adjusted
inued until all temperatures remain practically constant, that
re than 1° C. in two hours. The voltage should be cut off once
resistance measurement quickly made to determine the tem-
indings.

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Temperature Rise by Resistance is calculated from the formula

$$T = (234.5 + t)\left(\frac{R_h}{R_c} - 1\right),$$

where T = temperature rise in ° C.;
t = temperature in ° C., by thermometer, at which the cold resistance is measured;
R_c = resistance in ohms at temperature t;
R_h = "hot" resistance in ohms at end of heat run.

The number 234.5 is the reciprocal of the resistivity temperature coefficient referred to 0° C.), of 100 per cent conductivity copper, i.e., the reciprocal of 0.00427. For any other conductivity, C per cent say, divide 234.5 by C. (*See article on Resistance and Conductance.*)

Temperature Rise by Thermometer.—In an air-blast transformer it is desirable to measure by thermometer the temperature of the incoming air and the outgoing air (from iron and coils), of the primary windings, and of the secondary windings. Spirit thermometers and not mercury thermometers should always be used for measuring the temperature of transformer windings.

In an oil-cooled transformer the temperature, by the thermometer, of the tank at top and bottom and of the oil in two or three places near the top should be taken.

Insulation Tests.—To test the insulation between turns and sections of coils double the rated voltage per section is impressed on each section for one minute. This test should be made at a high frequency, preferably at double the rated frequency. After this one and a half times normal voltage at rated frequency is applied for five minutes, to discover the effects of the double voltage test. These voltages should be applied and removed gradually.

High-potential Test on Complete Transformer.—To test the dielectric strength of the insulation as a whole the following high-potential test is made. Connect both terminals of the high-tension winding to one terminal of the high-potential transformer. Ground both ends of the secondary winding to the core and frame and connect to the other terminal of the high-potential transformer. Adjust a needle gap to arc at the desired test voltage and increase the voltage gradually until the gap arcs over. Decrease the voltage till the arcing ceases and hold the voltage as near as possible to the arcing point for a minute. The voltage should then be decreased gradually. The proper test voltages and spark-gap adjustments are given in the Standardization Rules of the A.I.E.E. (q.v.).

Calculation of Efficiency and Regulation from Test.—From the results of the preceding tests the efficiency and regulation of the transformer for various loads may be calculated by the methods given above, p. 1625 in the paragraph on *Efficiency and Regulation*, using the test data instead of the calculated quantities.

TESTING OF THREE-PHASE TRANSFORMERS.—In testing three-phase transformers the same methods are followed as with single-phase units. The only difference is in testing for polarity; owing to the mixing of the magnetic circuits special care must be exercised. The direct current must be sent in one direction through one primary phase and in the opposite direction through the other two, so that they will not neutralize one another. With a voltmeter similarly connected on the primary and secondary of each phase in turn, break the direct current; if the connections are right the voltmeter on the secondary will deflect in the same direction as the steady deflection on the primary.

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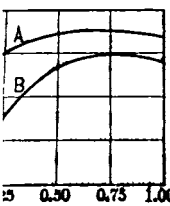
Run. — For the parallel run of two three-phase transformers, con-
ow-potential sides in multiple to a source of three-phase potential.
gether the primary terminals No. 1 of both transformers and bring
terminals No. 2 close together so they may be connected by a small
If no spark is noticeable when the fuse wire spans the connection,
. 2 terminals may be permanently connected. The same procedure
with the No. 3 terminals.

LES OF PERFORMANCE. — Usual values of the performance
:s of transformers are given below.

urrent ranges from 2 to 6 per cent of full-load current in lighting
of the core type and from 5 to 10 per cent in power transformers.
inges from 0.5 per cent to 1.25 per cent of the rated output.
anges from 0.75 per cent in large sizes to 2 per cent in small sizes
utput.

ance drop ranges from 1.25 to 5 per cent of the voltage, being less
type than for the core type. The value depends largely on the
: transformer, methods of construction and opinion of the designer.

nd Regulation. — The variation of the efficiency with the load of
cycle transformers for lighting purposes is shown in Fig. 24. The



ıcy of 60-Cycle Transform-
Kv-a.; B = 10 Kv-a.

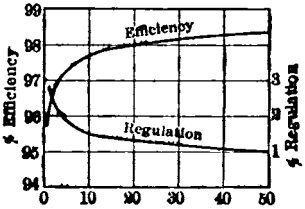


Fig. 25. Efficiency of a Line of 60-Cycle Transformers

egulation at full load of a line of these transformers is shown
hese transformers are small and of the core type. Larger trans-
have even better characteristics.
ve under *Examples of Design*.

TION FOR TRANSFORMERS.* — The following mem-
nded to assist in writing specifications. See also article on

aracteristics and Conditions of Service. — Service for which
o be used, e. g., operating synchronous converters, induction
tc. High- and low-tension voltages at normal load. Taps for
nt voltages. Rating in kilovolt-amperes and in kilowatts at
tor. Frequency.

scription: Details of Construction. — Whether oil-, air- or
tyle and location of terminals. Where line surges are likely
ual to specify, for large transformers, that the end turns, say
: total turns at each end, shall have extra heavy insulation.

Done by Other Contractors. — Who is to supply and install
l supports; high- and low-tension wiring, wiring and supports
-connections, if to be used three-phase.

* By W. A. Del Mar.

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Performance and Tests. — (*See Standardi*
Temperature rises upon which ratings are to b
capacity. Efficiency at 25, 50, 75, 100, and
transformation ratio. High-potential tests of
garding effect of moisture and heat on insulatio
transformers shall contain no material which w
moisture or by an occasional temperature of 95°
ture is not maintained at any one time for a per
transformers shall be capable of operating conti
insulation being damaged thereby. Regulation
Regulation with load of rated kilovolt-amperes
100 per cent and 90 per cent. State formula
calculated. Reactance between primary bus a
transformers are to operate compound-wound
required reactance is usually specified by the ma
converter.) Amount of air or water for coolin
stated pressure. After the transformer has be
efficiency at full load shall be not lower than th
more than a stated percentage and after two y
lower than the guaranteed amount by not more

INSTALLATION OF TRANSFORMERS
special foundations but merely a level floor of
weight. Provision should be made for an electr
of the transformer to the ground.

Oil- and Water-cooled Transformers. —T
operation of transformers in general, and high
ticular, is moisture, in that 0.1 per cent of moi
use. This may result either from rain or drippi
former or onto some of the parts, or from the c
the atmosphere on the various parts. For this r
must be very carefully inspected, cleaned and
put into service. If the operating potential is 1
will tell whether the transformer should be dried
15,000 the drying operation should be carried ou

Methods of Drying. — The best metho
of dry air at 90° C. through and around the t
tinue for 24 hours in all transformers, for 72 ho
ers of reasonable capacity and longer in speci
drying is to short-circuit one winding of the tr
other member a voltage of from 1 to 2 per cen
winding so that a current of from ⅛ to ¼ of the
winding. This current should be adjusted so th
on the low-tension coils shows a temperature of

Preparation of Oil. — No potential sh
cooled transformer unless it is supplied with a
forms the essential insulating medium as well
should be tested before using. Oil is considered
withstand 40,000 volts between disks ½ inch in
Transformers for 40,000 volts or less will operate
tric strength has dropped to 25,000 volts, but
reached the oil should be dried, purified and
voltage greater than 40,000 should not be used wi
35,000 volts in the above described test appar

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urifying the oil is on the market (*see G. E. Bulletin No. 4134*). See
n *Oil, Transformer*.
ormer tanks should be filled by pouring the oil through a fine-cloth
allowing the oil to settle 12 hours before using. Rubber tubing
used for carrying the oil as the sulphur in the rubber will eventually
. The cover of the transformer should prevent any water dripping
former but there should be a free exit allowed for gases which may
ie transformer stands in a moist atmosphere a special "breather"
lcium chloride should be employed. In all transformers the level
ild be well above the top of the transformer proper and this should
r 3 days after the original filling to see whether the transformer
e absorbed sufficient of the oil to lower the level a dangerous

ll sizes of oil-cooled transformers are designed to be suspended
as on poles or the sides of buildings or to be installed in manholes
These transformers are especially protected against the weather.
tion **Against Overheating.** — It is most important to be
proper circulation of the cooling medium as the temperature of
r will rise quickly to an excessive value in case of a failure of the
n. In this case the load must be reduced and kept at such a
temperature of the oil at the top does not exceed 80° C. If at
il reaches an excessive temperature there will be a tendency for
rm on the transformer and coils, which will interfere with the
An inspection should be made occasionally for this purpose
t removed. The oil should be sampled and tested each week
nth and every six months thereafter. In taking samples of the
hould be exercised that the vessel in which the sample is con-
ly dried. The temperature of the oil in a self-cooled transformer
ceed 80° C. and in a water-cooled transformer 65° C. Oil-cooled
ist be in a well-ventilated compartment in which the air should
an 5° above the outside atmosphere. An inspection should be
to time to see that there is no condensation on the inside walls

on for Multiple Operation. — Transformers should never
multiple on both the primary and secondary sides unless it is
polarity is correct and that the ratio and regulation of the two
the same.
nsformers; Ducts and Blower Set. — Air-blast transformers
over an air duct of sufficient size to permit the required current
a velocity of less than 500 feet per minute. The duct should
stible material and should have smooth sides in order to offer
nce to the current of air. Air is supplied to this duct by means
blowers of capacity to supply the proper quantity of air for a
mers at pressures from ½ to 1½ ounces (*see Blowers and Com-*
Roughly the rating of the blower motor in horse-power is

$$\frac{\text{(cubic feet of air per minute)} \times \text{(pressure in ounces)}}{1200}$$

transformer at the bottom, flows vertically through the coils
the top, and also flows transversely through the iron, passing
Separate dampers at each outlet are provided in order to
currents independently. The dampers are regulated so that
as a temperature 20° above the incoming air.

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Since the transformers are so dependent on the air blast for their operat and safety, it is customary to provide a reserve blower set.

Location. — Care must be exercised to protect the transformers fr moisture and dirt and particularly, since they are open at the top, to place th where water and dirt cannot drop in the open top. All terminals of the blast type of transformer are usually brought out below so that the primary secondary cables may be laid in the air duct and all connections and insp tion may be made from below. It is therefore desirable that the air d be sufficiently large to enable a man to move about therein.

Drying and Cleaning. — In putting the transformer in operatio moisture must be removed before applying potential. This may be a.. plished by running the blower set and forcing air through the transform which will be sufficient if the air is dry. Another method is to short-cir one winding of the transformer and apply a low voltage of from 1 to 2 per of the rated voltage to the other winding, so that 75 per cent of full-load cur flows through the windings. This is maintained for from 24 to 36 hours transformers of this type should be cleaned once a month by means of co pressed air at 20 pounds pressure.

Measurement of Temperature. — In determining the temper of the windings only that calculated from a resistance measurement is depe able, as the coils are so thickly wrapped in insulation that a thermometer not show the true temperature.

OPERATION OF TRANSFORMERS. — Single-phase transform may be used singly or in parallel on single-phase circuits, and in various co binations on polyphase circuits as described above. The polarity should determined before making the connections.

Parallel Operation on Single-phase Circuits. — Single-phase transfo ers are very generally operated with the primaries in parallel on the supply cuit and their secondaries in parallel on the load circuit. In order to successf operate in this manner two or more transformers, the transformers must ha (1) the same ratio of transformation; (2) the same regulation; and (3 same value of X/R, where R and X are the total resistance and reactan respectively of any one of the transformers. Transformers divide the l inversely proportional to their reactances, provided the ratio of reactance resistance is the same in both cases. If transformers are purchased to op in parallel with others, proper provision must be made in the design of t transformers, and this fact should be stated in the specifications.

In general, a 50-kilowatt transformer will have about twice the resista and twice the reactance of a 100-kilowatt transformer of the same commerc line, and therefore these transformers will divide the load in proportion to th capacity. But this is not likely to be true of transformers of different bra made at widely different times.

If transformers not satisfying the above conditions are to be run in paral an impedance coil having a proper resistance and reactance may be connec in the circuit of one of them, thus establishing the necessary conditions for proper distribution of load, provided the ratios of transformation are the sa

Transformers on Polyphase Circuits. — See section above on *Transform Connections*.

WEIGHTS AND COSTS (Pre-war prices). — The curves of Figs. 26 to inclusive give approximate values of the weights and costs of several represent tive lines of single-phase transformers of the most usual common capacit voltages and frequencies. These values are sufficiently accurate to be used

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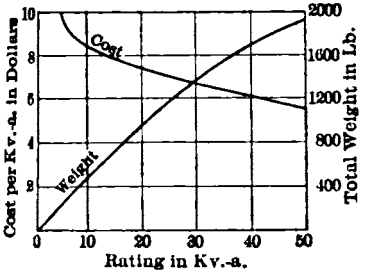


Fig. 26. Oil-cooled, 60-cycle, 2200-volt Lighting Transformers

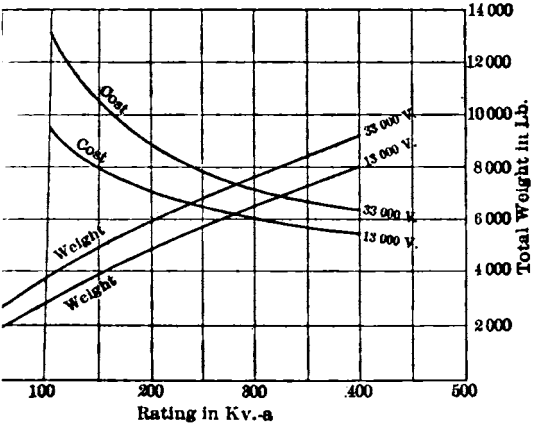


Fig. 27. Oil-cooled, 60-cycle, Single-phase Transformers

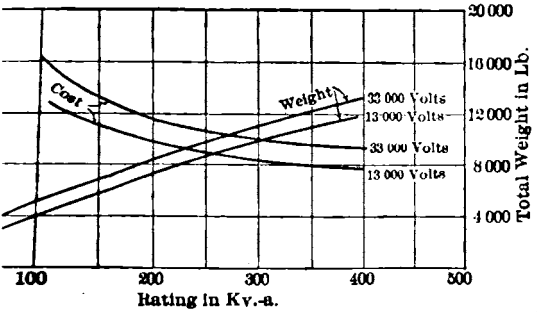


Fig. 28. Oil-cooled, 25-cycle, Single-phase Transformers

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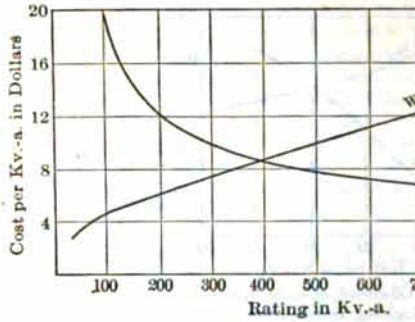


Fig. 29. Air-blast, 25-cycle, 33000-volt, Sin

preliminary estimates, plans, theses, etc. The act
the price of copper, commercial conditions and sp
are from 40 to 50 per cent above those given by th

The weight given is that of the transformer co
if any, but does not include the boxing for shippi

The cost is given in the form of dollars per kv
tion of the lighting transformers of Fig. 26 this
could be obtained in continuous operation with t
ture of 50° C. The transformers of Fig. 26 are
rating is based on the characteristics of a lighting
antee of a maximum rise in temperature of 50°
The prices include the cost of the oil.

The cost per kv-a. and weight per kv-a. of
roughly 90 per cent of the cost and weight per
formers having a combined capacity equal to that

The voltage of the secondary may vary in all
appreciably affecting the cost or weight given.

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Gray A., *Electrical Machine Design;* Berg, E. J.,
C. P., *Alternating-current Phenomena;* Lawrenc
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comparison of Transformers, Elec. W., May 31,
formers in Parallel, Elec. W., Nov. 7, 1914, Ja
Transformer Connections, G. E. Rev., Vol. 19,
Developments in Power Transformers, G. E. Rev.,

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ORMERS, INSTRUMENT. — (*See also Transformers.*) In-
ansformers are either potential transformers or current transform-
ial or voltage transformers are transformers of comparatively small
ıged for shunt connection to the primary lines, designed to produce a
oltage which represents the primary voltage with sufficient accuracy
on to instruments. Current transformers are transformers of com-
nall output arranged for series connection in the primary lines,
produce a secondary current which represents the primary current
nt accuracy for application to instruments. The insulation of
: and potential transformers is designed with reference to the
e circuit on which the transformer is to be used. The most com-
for the secondary of the potential transformer is 115 volts. The
ı current for secondary full load on the current transformer is 5
ıe secondary voltage of the current transformer is usually very
erating conditions, being only sufficient to force the secondary
gh a few instruments of low impedance.

TIONS. — Instrument transformers are used for three principal
to supply current and voltage to measuring apparatus; (2) to
ting devices; (3) to operate circuit protective devices. In each
: two principal advantages to be attained by the use of trans-
:o protect the devices in the secondary circuit against the incon-
ınger of a direct application of the primary voltage or current;
the use of measuring, regulating and protective devices designed
rd current and voltage for the entire range of currents and volt-
ler various operating conditions, thus simplifying design and
ncreasing reliability and accuracy and lowering cost.

nd Reliability Required. — Of the three applications given
olving measuring instruments, requires the highest accuracy in
r; in the operation of regulating devices the certainty of con-
ion is more important; in the operation of circuit protective
moderate degree of accuracy is satisfactory, but certainty of
the highest importance. It is, therefore frequently desirable
transformers for the several purposes, even where convenience
would suggest the use of a single transformer.

)F CURRENT TRANSFORMER. — The current transformer
imary winding in which the line current flows, a magnetic circuit,
y winding for connection to a load of instruments and other
ed in series. The current flowing in the primary is usually
ıe characteristics of the transformer or by the amount of second-
ı the secondary winding short-circuited, the secondary ampere-
equal to the primary ampere-turns, the slight difference being
tively small exiciting current (*see Electricity and Magnetism*,
This exciting current is always of low power factor, while the
the secondary current depends on the resistance and induc-
ondary circuit. While the reversed secondary ampere-turns
ıe primary ampere-turns less the exciting ampere-turns, the
ıe exciting ampere-turns is not usually arithmetical but vecto-
ulting secondary ampere-turns are less than and not in exact
to the primary ampere-turns. This is expressed by stating
mer current ratio varies from the ratio of turns, and that there
between the primary and reversed secondary currents. Since
nd on the relative amount of the exciting current and its phase
pect to the secondary current, they will vary with the imped-

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ance of the secondary load and the current flowing
ary load impedance increases, the voltage across
consequently the flux density in the
magnetic circuit, grows larger.
When the impedance becomes so
great that the transformer magnetic
circuit approaches saturation, the
exciting current becomes so large
that the secondary current is no
longer proportional to the primary
current and also differs from it ap-
preciably both in wave form and
phase position.



Ratio and Phase Angle. — For accurate cu
of a current transformer the exact ratio of the pri
must be known. For power measurements the
currents must also be accurately known. Refer t

u = ratio of the number of secondary to the nu
I_p = primary current,
I_s = secondary current,
k = ratio of exciting current (referred to second
α = phase angle between the exciting current a
θ = phase angle between the secondary current
(positive for lagging current).
β = the "phase angle" of the transformer, i.e.,
current and the secondary current revers
secondary impedance load is higher tha
the secondary current (reversed) leads
positive; if the power factor of the seco
than that of the exciting current, the sec
behind the primary current and β is neg

Then the ratio of transformation is

$$\frac{I_p}{I_s} = u\sqrt{(\cos\theta + k\cos\alpha)^2 + (\sin$$

and the phase angle is

$$\beta = \tan^{-1}\frac{k\sin(\alpha-\theta}{1+k\cos(\alpha-}$$

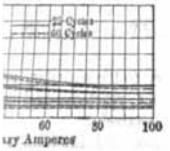
The value of the ratio k for a given primary cur
ance of the load connected to the secondary; t
greater the value of k and therefore increasing th
connected load tends to increase the difference b
the true ratio of the primary and secondary curre
of the secondary also tends to increase the phas
The true ratio $\frac{I_p}{I_s}$ and the phase angle β also dep
the load.

In order to use these formulas for numerical r
the amount and power factor of the exciting cur
ditions of load. Since this is difficult to predete
curves similar to Figs. 2 to 5 below, obtained by

THEORY OF POTENTIAL TRANSFORM
former consists of a primary winding, a magnetic ci

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vinding is placed across the line, and the secondary winding is con-ruments or other devices connected in multiple. The voltage mary is usually unaffected by the characteristics of the trans-the secondary load. With the secondary open the secondary e is approximately equal to the primary impressed voltage divided the number of turns in the primary to the number of turns in the difference being due to the impedance drop produced in the exciting current. The impedance drop in the primary due



Ratio

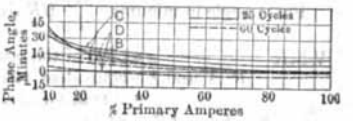
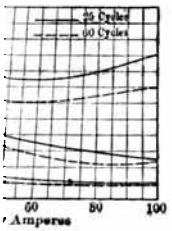


Fig. 3. Phase Angle

Current Transformer No. 1



Ratio

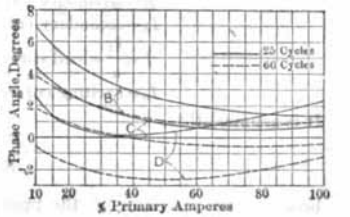


Fig. 5. Phase Angle

Current Transformer No. 2

usually not in phase with the primary voltage; hence its r relation from the primary voltage results both in a vari-atio from the ratio of turns and in a difference of phase and reversed secondary voltages. This no-load ratio and ed under load itional imped-ary and sec-to the load impedance of ill be the cur-windings of herefore the lrops in these eater will be the actual voltages and e impedance

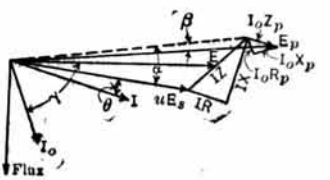


Fig. 6

rent may be in almost any phase, whereas the drop due a constant relation to the induced voltage, the phase us power factors may be either less than or greater than

gle. — For accurate voltage measurements by means er the exact ratio of the primary to the secondary

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terminal voltages must be known. For power m
between the two voltages must also be accurately
The relations of the quantities involved are sh
Fig. 6.

$$\text{Ratio} = \frac{E_p}{E_s} = u\left[1 + \frac{IR\cos\theta + IX\sin\theta}{uE_s} + \frac{(}{}\right.$$

$$\left. + \frac{I}{}\right.$$

$$\text{Phase angle in minutes} = \frac{3438}{E_p}[IR\sin\theta - IX\cos$$

Where u = ratio of the primary to the
R, X and Z = equivalent resistance, reac
transformer, respectively
R_p, X_p and Z_p = resistance, reactance and
winding;
E_p = primary impressed voltage;
E_s = secondary terminal voltage
E = secondary induced voltage;
I_s = secondary current;
$I = \frac{I_s}{u}$ = load current in the pri
I_0 = exciting current.

It is assumed that,

$$\frac{R_p}{R} = \frac{X_p}{X}$$

because the reactance of the primary and sec
directly determined. The third term in the expre
brackets, is very small and can be omitted with
variations in the true ratio $\frac{E_p}{E_s}$ with the power fac
of the load on the secondary, see Figs. 7 and 9.

The phase angle ϕ of a potential transformer,
primary terminal voltage and the secondary ter
range from a positive angle (secondary voltage l
age) to a considerable negative angle (secondary
age), depending on the exciting current, power
secondary load and the impedance of the transf
no-load condition this angle is nearly always negati
where the exciting current is large and of very low
large. The general tendency of non-inductive sec
vary in the positive direction (secondary voltage to
current) loads to cause it to vary in the negative
to lead). It is frequently possible to bring ϕ pr
voltage and load by adding a non-inductive loa
Figs. 8 and 10 for actual variations in the phase an
factor and volt-amperes of the load on the seconda

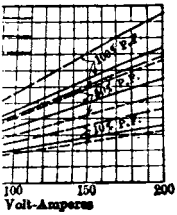
DESIGN. — The general principles of design o
the same as for distribution or power transforme
instrument transformers, however, change the deta
degree.

Design of Current Transformers.—A very im

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he operation of protective devices. When so used the failure nsformer may cause destruction of expensive apparatus, and e designed to stand a higher insulation test than other types

Again, the exciting current of the current transformer has the phase angle and errors of ratio. The flux density in the s therefore kept very low for the ordinary metering conditions, errors within satisfactory limits. The resistance and leakage primary winding do not affect the ratio of the transformer nor between primary and secondary currents; their only effect is dance in the primary line. Resistance and leakage reactance



Ratio

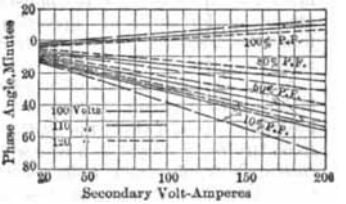
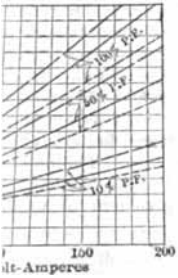


Fig. 8. Phase Angle

Potential Transformer No. 1



Ratio

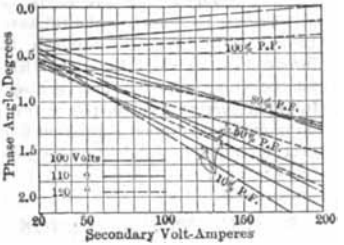


Fig. 10. Phase Angle

Potential Transformer No. 2

akage between primary and secondary, constitute definite ndary load, and affect the phase angle and ratio of the current rating of a current transformer is always greater ntinuous current to be carried by the lines of which it is a overload capacity is required.

- current transformers, therefore, should include:

ety in insulation,

ix under the conditions of metering service (this is best oderate cross-section of magnetic circuit with a relatively turns),

l leakage reactance in the secondary winding,

actance of the primary winding low enough so that the ot cause an objectionable drop in voltage in the primary ransformer is to be used in low-voltage circuits.

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Special Designs of Current Transformer poses special designs are useful. In stations wher bus-bars while small power circuits, such as statio the same bus-bars, current transformers must be operate on small current, while under enormous e formers must at least remain in service long enou devices. Where the currents are not too low, trans bar as primary may be used. These resist me circuit, but the number of ampere-turns under th limited to the number of amperes flowing in the transformers have an accuracy suitable for meteri rated current of the line is comparatively large. are too low for satisfactory operation with a single formers of large size, great primary current capaci sometimes used.

A somewhat similar case arises where the cost of in high-tension circuits is prohibitive. A transfo bushing of an oil switch, the lead inside the bushi secondary being wound on a core which encircles t current is usually small, while the length of the tively large, the accuracy of these transformers is narily confined to tripping devices or specially cali

Design of Potential Transformers. — The desi is very similar to that of a small distribution or po accuracy of ratio and small phase angle between pri the flux density in the core should be kept compar and leakage reactance of the primary and secondar these transformers are ordinarily connected to t insulation is sufficient if it equals that of good distri for the same voltage. The exciting current is us full-load current than in power transformers, bec no moment, and good regulation is necessary. Th ever, is roughly dependent on the product of the ex resistance; hence too large an exciting current undesirable.

RATING AND PRECISION. — The volt-a transformers as given by many manufacturers is the most distant relation to the characteristics is no general correspondence between accuracies various manufacturers for the same load. Wher with oil immersion for high-voltage circuits, thei poor than in the small types without oil, because in cost of manufacture between good and poor tr tively small.

Standard Voltage Ratings. — The following ar for which the manufacturers usually list separate l 2300, 4600, 6900, 11,500, 23,00, 33,000, 44,000, 66,

The following are the voltages for which poten listed: 230, 460, 575, 2300, 4600, 6900, 11,500, 1 66,000.

A transformer listed for one of these nominal vo operate satisfactorily on lines ten per cent above the

Standard Current Ratios. — The current tra by manufacturers in the following current ratios, f

50 : 5	200 : 5	750 : 5	2500 : 5	7,500 : 5
75 : 5	300 : 5	1000 : 5	3000 : 5	10,000 : 5
100 : 5	400 : 5	1500 : 5	4000 : 5	
150 : 5	500 : 5	2000 : 5	5000 : 5	

y Volt-Ampere Rating. — Current transformers intended for use e measuring instrument usually have a secondary rating of 10 volt- d for use with more than one measuring instrument a rating of eres, at rated secondary current

ransformers usually have a rating of 200 volt-amperes at rated oltage.

ation. — By properly proportioning the number of turns in the wind- rent transformer, it is possible to raise the secondary current to e ratio error, with a given condition of load. It is usual to com- rrent transformer for one-half its rated secondary capacity, with wer factor of 80 per cent and frequency of 60 cycles.

ratio of turns in a voltage transformer differ from the marked amount sufficient to make up the voltage drop in the transformer load. Voltage transformers are usually compensated for one-fifth pere rating, with a secondary power factor of 80 per cent, and at cy.

of phase displacement, however, cannot be compensated for. as it nly on the constants of the transformer itself, but on the power load on the voltage transformer, and on the power factor of the the current transformer.

of Current Transformer. — The variation of ratio and phase e load on the secondary of two typical 2300-volt, 20 : 1 ratio, cur- ers is shown in Figs. 2 to 5. Figs. 2 and 3 show curves of ratio gle obtained from tests on a current transformer (No. 1) of low high ampere turns, and comparatively low secondary resistance eactance. Figs. 4 and 5 show the results of similar tests on a ormer (No. 2) where these values are not so strictly limited. It

ed that the scales of $\frac{\text{true ratio}}{\text{marked ratio}}$ and of phase angle in Figs. 4 times those used in Figs. 2 and 3.

f curves was made with a different load on the secondary, loads series of combinations of instruments, watt-hour meters, and evices representing conditions in ordinary practice. Table I amperes and power factor of the loads, designated by the letters

TABLE I

LOADS REFERRED TO IN FIGS. 1 TO 4

-amperes, t 60 cycles 5 amperes	Power factor at 60 cycles and 5 amperes, per cent	Equivalent resistance, ohms	Inductance, milli-henries
4.8	99.8	0.192	0.032
10.9	90	0.392	0.504
45.1	54	0.972	4.03
32 4	38	2.012	13.0

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A to *D*, at 60 cycles and 5 amperes and also t
and equivalent resistance components.

Precision of Potential Transformers. — The
angle with the power factor of the load on the secor
volt amperes of two typical 2300-volt, 23-cycle, 2
potential transformers is shown in Figs. 7 to 10. Fi
ratio and phase angle obtained in test on a potential
the flux density is low, and the resistances and lea
ings are within moderate limits. Figs. 9 and 10 sh
on a transformer (No. 2) of the same rating in
larger limits, resulting in inferior regulation and la

GENERAL TESTS DURING MANUFACTU
manufacture the insulation of every current or pot
tested at a voltage greater than that at which it i
age selected being determined by the A.I.E.E. S
manufacturers find it desirable to apply considerat
these to insure additional safety. A sufficient nu
given heating tests to assure safety of operation fo
on accuracy should be made on all transformers
counting turns, short-circuits, etc.

TESTING OF CURRENT TRANSFORM
PHASE ANGLE. — Where large numbers of cu
tested to a high degree of accuracy for ratio and
which use primary and secondary shunts, balancin
zero reading instrument, are most rapid and satisfa
of such an outfit is justified only where a large n
be carefully tested. The phase angle may also
two wattmeters or electrodynamometers. Where
require an occasional check to determine that the
acteristics, a simple method which covers most ca
with that of a standardized portable transforme
scribed below.

The uniformity among transformers of a cert
usually very good; in the case of a large lot of tra
be made only on a few representative ones.

Demagnetization of Core Before Testing. —
formers should be demagnetized before the test for
With small low-voltage current transformers dem
out by putting at least one-half-load primary curr
with 10 ohms or more connected to the seconda
ments to be used. With large high-voltage curre
sive cores the resistance should be several time
demagnetization. This resistance should then be
steps of one ohm or less.

When however current transformers are subject
results for the correction of observations already ta
in such a way as to avoid changing the magnetic
the test results are secured. The secondary shou
that used in the working condition, and especia
current is not allowed to flow in the primary or th
winding is open circuited. The current should b
current point first, and raised to the higher points
have been made.

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quency of Test Current. — In all current-transformer work where est are to be used for correction, the frequency used in test should e as that of the circuit in which the transformer is to be employed. ntention is only to check the condition of the transformer, any com- quency may be used.

Methods of Testing Current Transformers. — The following is a of the details of one of these methods which has been found satis- se.

ratus. — Referring to Fig. 11 a three-phase supply is used to excite fting transformer with a single-phase secondary. The supply of he transformer under test is obtained from one phase of the same ugh a control resistance R_1 and a step-up current transformer. ios the step-up transformer is omitted. Its input side is wound to he voltage of the supply (125 volts). The high-current winding eavy loose cable, of which one or more turns may be wound through re opening. By suitably selecting the number of turns, currents 4000 amperes are obtained. The primary shunt has a resistance ll rated current gives a drop of 0.5 volt. It is arranged to carry

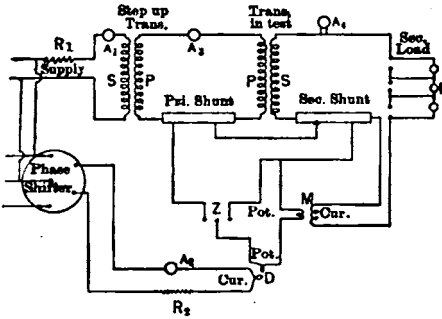


Fig. 11. Connections for Shunt Method

overload current for a short time for testing purposes. The sec- is adjustable, and is marked in percentage of a normal resistance. several interchangeable scales the normal resistance correspond- cent may be made 0.06, 0.075, 0.08, 0.12, or 0.125 ohm. These of a primary 100-ampere shunt of 0.005 ohm resistance for trans- :: 1, 15: 1, 16: 1, 20: 1, 24: 1 and 25: 1 rated ratios, while still irect reading on the secondary scale of the $\frac{\text{true ratio}}{\text{marked ratio}}$ of the

A set of primary shunts rated 5, 10, 20, 50, 100, 200, 500, 1000,) amperes will thus cover all probable ratios from 1: 1 to 1250: 1. table calibrated mutual inductance whose current coil is in series ndary of the transformer under test, and whose potential coil is he potential element o the sensitive electrodynamometer D, whose nt in turn is supplied from the secondary of the phase-shifting ientioned above. Z is a double-throw single-pole switch. L is ondary loads suitable to represent the instrument combinations in practice.

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Procedure. — The proper load is connecte former, and the primary current is adjusted to th resistance R_1. This current may be read by ammeter at A_4 which is short-circuited after re to the right. The mutual inductance then ac supplying to the dynamometer potential elem with the secondary current of the transformer field current of the dynamometer is then adj dynamometer reads zero for all positions of th the position of maximum sensibility to changes in shunt. The switch Z is then thrown to the left, secondary shunt is adjusted by moving the drop reads zero. The phase of the dynamometer field go electrical degrees by moving the handle of th definite distance. This is the position of maxi variation. The mutual inductance is then adj reads zero. The phase of the field current is th position, and a slight readjustment of the secon necessary.

Calculations. — From the reading of th angle is determined by the formula

$$\beta = \tan^{-1} \frac{2\pi fM}{R_s},$$

where f is the frequency of the circuit in cycle inductance in henries, and R_s the resistance of Then the true ratio is expressed by the formula

$$\text{Ratio} = \frac{R_s}{R_p} \times \frac{1}{\cos}$$

where R_p is the resistance of the primary shunt.

The correction factor $\frac{1}{\cos \beta}$ for $\beta = 1^\circ$ is 1.000

At these values it is negligible in comparison measurement work involving transformers an angle is so great that this correction becomes in inferior that it should not be used for any purpo ment.

Speed of Operation. — By this means a 30 points of ratio and the same number of p helper to perform necessary calculations and a su ing transformers in the circuit, it is quite practica of transformers including from 6 to 12 points each of determinations of phase angle in an eight-hou can be made practically as fast as the transfor current and secondary load adjusted.

Standardized Transformer Method for D Transformer. — A portable transformer with f series-multiple connection, giving ratios of 5 : 1 practically everything up to 100 amperes. A without primary, so arranged that one turn th ratio of 200: 1, and more turns a corresponding 100 to 1000 amperes. In testing, the primary

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t and the standardized portable transformer are connected in ither ammeters, wattmeters or watthour meters may be used ng instruments, the last being susceptible of giving the higher

of Ammeters with Standardized Transformer. — The of the standardized transformer is connected to a standard- ere ammeter, and that of the transformer under test to a similar nd a suitable secondary load. With a sufficient current flowing atisfactory readings on the ammeters, readings are made; the are interchanged, and readings are repeated, to eliminate dif- ween the instruments. From the mean of the results and the standardized transformer, the ratio of the transformer under test

of Wattmeters with Standardized Transformer. — The two secondaries are connected to the current coils of the wattmeters tential elements are placed in multiple and supplied with a definite n a phase-shifting transformer. The phase shifter is adjusted at to cause the wattmeter connected to the standardized transformer naximum. The instruments then are read as ammeters, using a made with the same voltage applied to the potential element. By larger deflection is obtained for low-current values, and consequently racy. If only transformers of moderate-current rating are tested, current may be kept nearly in phase with the supply voltage by the resistance, the phase-shifting transformer may be omitted and the otential circuits excited from the supply voltage.

nod requires little apparatus or care beyond that necessary for ruments and transformers in good condition. It does not test but gives a check on ratio, whose error may readily be kept within . This includes the error of comparison, using ordinary care, and the standard transformer. It is reasonably convenient and rapid, dapted for use in the laboratories maintained by most companies ht and power.

amometer Method of Determining Phase Angle of Current rs. — Phase angle may be determined (where primary currents are) by the use of similar types of dynamometer wattmeters whose ents are connected in the primary and secondary circuits, and ial elements are supplied in multiple by a phase-shifting trans- phase of the voltage is shifted until the primary wattmeter in- showing a quadrature relation of its current and voltage. If W eading of the secondary wattmeter, E the voltage applied to its ent, and I the current in its current coil

$$\beta = \sin^{-1}\frac{W}{EI}.$$

y of this method is very low with ordinary portable wattmeters, sfactory with sensitive reflecting dynamometers. It is the best for the accurate determination of phase angle.

-hour Meter Method of Determining Ratio and Phase rent Transformers. — This method is used by many operating checking their current transformers. It consists of comparing r under test with another of known characteristics. The advan- ethod are:

no special apparatus required.
atus is simple and rugged.

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3. No special skill required to operate.
4. Transformers may be tested where they are installed.
5. Ordinary variations of voltage, frequency and load during the test do n affect the results.

Apparatus.—The primaries of the standard transformer (S) and t transformer (T) being tested, are connected in series with a variable resistan as shown in Fig. 12. The secondaries are connected through the desired lu

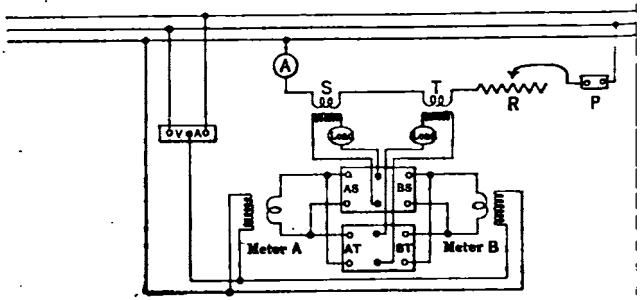


Fig. 12

to the current coils of the two watt-hour meters which are calibrated so th they can be read to $\frac{1}{100}$ of a revolution. Ordinary portable standard watt-hou meters are generally used. In making the ratio test the voltage coils of the wat hour meters are excited from the same phase which supplies the primaries the current transformers, and in making the phase angle test, from one of th other two phases.

Procedure.—The double pole double throw switches are thrown to A and BT and loads of the desired value are connected in the secondary circui of the two transformers. Switch P is then closed and the primary curre adjusted to the desired value. The switch V is now closed and the meter allowe to run until a reading is obtained. Then the switches V and P are opened, an the other switches thrown to AT and BS. Another reading is taken wit switches V and P closed. For convenience in calculation, the meters shoul be stopped when the one connected to T shows an even reading, say 10 com divisions. These readings give the data for calculating the ratio. For th phase angle measurement the same procedure is followed, except that th voltage switch is thrown to A instead of V, and the meters should be stopp when the one connected to S shows an even reading.

Calculations.—

Let R_S, R_T = ratio of the standard transformer and the transformer under test respectively;

α_S, α_T = the respective phase angles (positive for reversed secondary leading primary);

a_S, a_T = reading on meter A when connected to transformer S and T respectively;

b_S, b_T = ditto for meter B;

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os θ = effective power factor on the meter,
= 0.866 for the connection shown, with the voltage switch thrown to A.

$$R_T = R_s \sqrt{\frac{a_s b_s}{a_T b_T}},$$

$$\frac{R_T - R_s}{R_s} = \frac{1}{2}\left[\frac{a_s - a_T}{a_T} + \frac{b_s - b_T}{b_T}\right] \text{ (approximately),}$$

a's and b's are readings taken with the voltage switch thrown

$$\tan a_T - \tan a_s = \frac{1}{2 \tan \theta}\left[1 - \frac{a_T b_T R_T^2}{a_s b_s R_s^2}\right],$$

$$\text{inutes)} = a_s \pm \frac{3438}{\tan \theta}\left[\frac{a_s - a_T}{2a_s} + \frac{b_s - b_T}{2b_s} - \frac{R_T - R_s}{R_s}\right] \text{ (approximately),}$$

a's and b's are readings taken with the voltage switch thrown

st expression the + sign before the bracket should be used when with the voltage switch thrown to A, are working on leading l the − sign when the current is lagging. Or the sign may be deter- imently from the fact that adding non-inductive resistance to the a current transformer tends to advance the phase of the secondary

d of Operation. — An observer who is accustomed to this method e point of ratio and one of phase angle in about ten minutes. If being made where the transformer is installed, additional time is ut the apparatus into the circuit and out again.

thods of Testing Current Transformers. — Many modifications methods and other entirely different methods are in more or less se in various laboratories.

3 POTENTIAL TRANSFORMERS FOR RATIO AND GLE. — Where a large number of potential transformers are to potentiometer method of testing ratio is very satisfactory. In this ow-tension voltage is balanced against a part of the drop through ance in which current is maintained by the high-tension voltage. combined with the two-dynamometer method of testing phase n primary and secondary voltages. Where the number of trans- tested is not large, and where only a few ratios are to be tested compared with standardized transformers.

eter Method of Testing Potential Transformers. — The fol- escription of the apparatus and method of procedure which has tory results.

atus. — The general connections of such an outfit are shown in supply is 3-phase for the excitation of the phase-shifting trans- ne phase is connected through a voltage regulator Q to the low- f the step-up transformer T_1, which has a sufficient number of

connections to provide the range of voltages required for testing. This supply excites the high-tension side of the transformer T_2 which is under test. r_2 and r_1 are placed across the high-tension circuit in multiple with the high-ten-

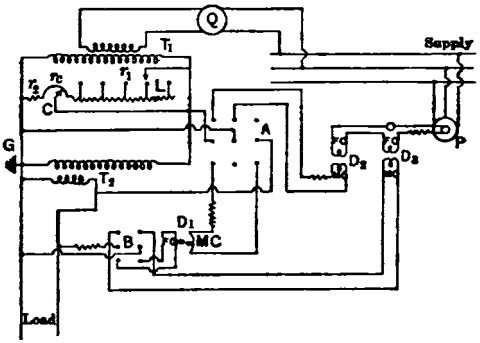


Fig. 13. Connections for Potentiometer Method

sion side of the transformer under test. They consist of non-inductive resistances, containing a non-adjustable portion constituting the greater part of r_2, a middle portion r_c subdivided into equal steps on which a contactor C travels, and a third part constituting the greater part of r_1 on which taps are brought out at points suited to the various voltages to be used in test. One side of the secondary winding is connected to the end of r_2 and the ground G; the other is connected (for ratio test) through switch A, which is in the downward position, through a resistance and the moving element of the dynamometer D_1 to the contactor C. By suitably proportioning the resistances r_1, r_2 and the steps of r_c, the outfit is made direct reading in terms of $\frac{\text{true ratio}}{\text{marked ratio}}$ of the transformer.

Precaution. — Balance can only be secured by a proper connection with regard to polarity of the secondary of the transformer under test to the primary. If the reversed connection is used, double the secondary voltage is applied to the circuit through contactor and dynamometer. A sufficient resistance to protect the dynamometer should therefore be inserted when trying out each transformer to be tested. As soon as an approximate balance is obtained, this resistance may be reduced to secure sensitiveness.

Determination of Ratio. — The fixed coil of the dynamometer D_1 is excited from the low-tension terminals of the transformer under test through the switch B in the downward position. Other secondary load may also be applied to the secondary terminals. With this load and the voltage and frequency suitably adjusted, and with the high-tension lead L connected to the proper tap on r_1, the contactor C is moved until the dynamometer D_1 indicates nearly zero. If the resistance at which the dynamometer indicates zero lies between two steps of the contactor, the nearest may be taken or the readings of dynamometer on both steps may be noted and the result obtained by interpolation. If r_1 and r_2 are respectively the resistances from the contactor C to the high-tension and to the grounded lines, then

$$\text{True ratio} = \frac{r_1 + r_2}{r_2},$$

subject to a small error due to phase angle between primary and secondary voltages, which is negligible for a phase angle of a degrees or less, provided

ce of the circuit from the contactor C through the dynamometer is ely equal to r_3.

ermination of Phase Angle. — To obtain the phase angle the and B are thrown upward. The drop of primary voltage across r_3 is l to the potential element of dynamometer D_3, while the secondary pplied to the potential element of dynamometer D_3, both through nductive resistances. The current elements of the dynamometers n series and excited from the phase-shifting transformer P. When f the excitation is shifted so that dynamometer D_3 indicates zero, ngle between primary and secondary voltages is

$$\gamma = \sin^{-1} \frac{W}{VA},$$

the watts indicated by the dynamometer D_3, V is the voltage and it applied to its potential and current elements respectively.

d of Operation. — Ratio points may be taken at the rate of one while operating, and phase-angle points at a somewhat slower -point checks can be made practically as rapidly as the trans- be connected and the voltage, load and frequency adjusted. One equired for ratio test, two for phase-angle test.

zed Transformer Method for Determining Ratio of Potential r. — The transformer to be tested should be placed in multiple dard transformer of the same rated ratio on the high-tension side, ized portable voltmeters should be connected to the two second- should be read, interchanged and read a second time to elimi- calibration of the voltmeters. It is not difficult to maintain an bout 0.2 per cent on ratio test by this method with carefully stand- ratus near the rated voltages of the transformer. More accurate ts of ratio and determinations of phase angle if desired should thoroughly equipped laboratory, and the check results used simply unchanged condition of the transformer.

and Resistance Method of Determining Ratio. — Where ers of the same rated ratio and a voltmeter with suitable multi- ailable, good checking according to the method . 11. T_1 is a step-up furnish the voltage for T_2 and T_3 are potential of similar ratio, T_3 being er under test. V_2 is a eter. V_1 is a good port- or a laboratory stand- t. M is a multiplier of e R_m that closing the ses the voltmeter and read nearly the same ary supply as the volt- ads from the secondary

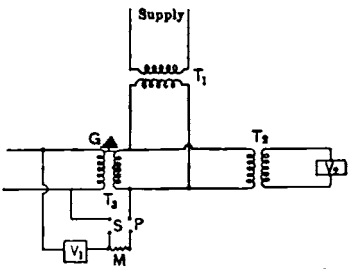


Fig. 14. Connections for Voltmeter and Resistance Method

S closed. In operation the switch P is closed, and readings made Then the switch P is opened and S is closed. V_2 is held at the and V_1 is read. If the resistance of V_1 is R_v, its first reading E_1 reading E_2,

$$\text{True ratio} = \frac{E_1 (R_m + R_v)}{E_2 R_v}.$$

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If the two readings are close together in the scale of V_1, no specially standardized instrument is necessary. The reading of V_2 does not enter into the result, as it is only used to hold the primary voltage at the same point for the two readings. The accuracy of the method depends on the accuracy of reading of the instruments used, although the absolute values of the readings do not affect it. With care the error should not exceed 0.2 per cent.

Mutual Inductance Method of Determining Phase Angle of Potential Transformer. — The phase angle may be determined by the addition to the ratio-testing outfit described above of a mutual inductance whose primary is placed in series with r_1 or r_2 and whose secondary is in series with the circuit from the contactor C through the dynamometer D_1 in a way similar to that described under current transformers. The primaries of two similar transformers may be placed in multiple, and the difference in their secondary voltages read on a low reading instrument. Where the phase angle is the same in both the transformers, this is an excellent method of comparison if the current drawn in the voltmeter is kept small by the use of a high-resistance instrument.

Two Watt-hour Meter Method of Determining Ratio and Phase Angle of Potential Transformers. — This is similar to the method used for current transformers (see page 1745) and consists in comparing the transformer to be tested with one whose characteristics are known. It has advantages similar to the method for current transformers and in addition all instruments are on the low-voltage circuit.

Apparatus. — In Fig. 15 the standard transformer is shown at S and the one under test at T. The connections to the two watt-hour meters and the

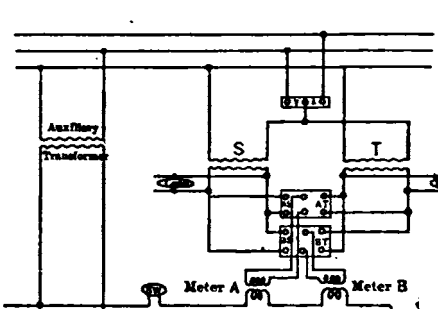


Fig. 15

loads are also shown. The watt-hour meters can be read to 1/100 of a revolution, portable standard watt-hour meters being most frequently used. The auxiliary transformer supplies current for the current coils of the watt-hour meters, and may be one of the main power transformers. The switch SW is a convenient means of starting and stopping both meters simultaneously. If ratio only is desired, the whole power supply may be taken from a 115-volt circuit, the auxiliary transformer being used to step up the voltage for the primaries of the instrument transformers.

Procedure. — The primary switch is thrown to V and the loads on the secondaries are adjusted to the desired values. The current in the current

meters is adjusted to about 5 amperes by means of the resistance R. -throw switches are now thrown to AS and BT and a reading is taken. ouble-throw switches are thrown to BS and AT and another reading For convenience in calculation it is well to stop these readings when onnected to T shows an even number of divisions, say 10,000. These re the data for calculating the ratio. For the phase-angle measure- ame procedure is followed except that the primary switch is thrown l of to V, and the meters should be stopped when the one connected an even reading.

ulation. — The equations are the same as given for current trans- page 1747, namely,

$$R_T = R_S \sqrt{\frac{a_S b_S}{a_T b_T}},$$

$$\frac{R_T - R_S}{R_S} = \frac{1}{2}\left[\frac{a_S - a_T}{a_T} + \frac{b_S - b_T}{b_T}\right] \text{ (approximately),}$$

s and b's are readings taken with the primary switch thrown to V,

$$\tan \alpha_T - \tan \alpha_S = \frac{1}{2 \tan \theta}\left[1 - \frac{a_T b_T R_T^2}{a_S b_S R_S^2}\right]$$

nutes) $= \alpha_S \pm \frac{3438}{\tan \theta}\left[\frac{a_S - a_T}{2a_S} + \frac{b_S - b_T}{2b_S} - \frac{R_T - R_S}{R_S}\right]$ (approximately),

s and b's are readings taken with the primary switch thrown to A. ave the same meaning as given on page 1746. In the last expression, efore the bracket should be used when the meters, with the primary n to A, are working on lagging current, and the $-$ sign when the ading. Or the sign may be determined experimentally from the ing a non-inductive load to a voltage transformer always tends to lary voltage.

of Operation. — The speed of operation is about the same as current transformers by the same method as shown on page 1747.

ATIONS. — Heating limits, insulation test, etc., should be in th the Standards of the A.I.E.E. (*q.v.*).

phase angle under definite conditions of secondary connected the highest class of commercial product, be defined substantially with Figs. 2, 3, 7 and 8. Even better accuracy than that shown s can sometimes be secured with considerable increase in cost and aterial. For less exacting service transformers of lower cost racy can be procured. The conditions to be fulfilled vary so inite general specifications cannot well be given.

work, especially with current transformers and in cases where on the result, abridged tests covering the performance under itions may be required in connection with each individual trans- s very careful tests are made, however, the information from a ing the average of many determinations is apt to be more reliable s of one determination.

TION. — Instrument transformers previous to installation n a cool, dry place. All handling should be done in such a manner nage to the insulation, particular care being used on those types lation is exposed. Oil-type transformers are usually shipped

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without oil, and temporary wooden blocking is c
blocking should be removed before installation.
stored for a considerable time, or if they have b
should be thoroughly dried out before installing
of the oil type should be filled with a good qualit

Grounding of Transformers. — Both curre
should be installed in a clean, dry place, prefera
board in the case of low-voltage transformers,
that are grounded, will clear all conducting or s
least twice and preferably by three times the sp
line voltage. The casings and frames should
wiring should be grounded at such a point as
operation of instruments connected to the transfo
Connections.

Resistance of Leads. — Secondary leads sho
special attention should be given to making all c
connected to the secondary of current transform
ing 0.2 ohm (200 feet of No. 10 wire) is usually
circuit of a current transformer operating watt-hou
siderably greater length of leads may be used wh
devices only are used because of the lower acc
transformers, the error due to drop in leads is p
current passing through them, which is determi
of devices operated. For ordinary circumstances
0.5 per cent; where special accuracy is desired,
negligible, or the accuracy test of the transformer
ance equivalent to the actual leads placed in series
should always be close together, enclosing as little a

Fuses. — Potential transformers should be fus
fuse should be designed to protect the line from
the transformer, rather than to protect the transfo
loads. The fuse should be of such resistance a
errors in the ratio of transformation. A combina
rent capacity fuse and resistor is sometimes used.
rent to 20 or 40 amperes, while the fuse is desig
such a current.

OPERATION. — After the current transforme
need no other care than being kept clean. The s
former must never be left open-circuited. If it be
secondary winding to insert or remove instrument
rent transformer should first be carefully short-c
has been open even momentarily while current flow
former should be demagnetized; see above und
formers should always be considered as part of the
be handled except to change connections. Even th
should be touched. When it becomes necessary t
tions the ground connection should be inspected to
dition and is so made that it will not be disconnecte
leads. Grounded protective cases should be use
vent attendants from coming in accidental contact

Potential transformers should receive the same
transformers. No power should be drawn from th
a suitable load of instruments and the usual switc
precautions should be used in handling as with pow

IS. — In general, replacement or repair by the maker is to be pre- pairs made by the user where anything more than broken leads or rnal injuries are to be remedied. If repairs to magnetic circuit or e attempted, care should be exercised to duplicate as exactly as original construction especially in regard to number of turns and f windings and exact assembly of punchings. After repairs are he transformer should be carefully tested both for accuracy and for rength.

TS, DIMENSIONS AND COSTS. — Current transformers in for circuits from 115 to 110,000 volts range from 4 pounds to 1500 ht with oil, and from a maximum dimension of 6 inches to a height th a diameter of 30 inches, depending on the quality of the trans- he voltage of the circuit on which it is to operate. Potential trans- nearly the same range of sizes.

f instrument transformers depends on the circuit voltage for which igned, and is also affected in the case of current transformers by he transformer. There is a considerable range between the prices arious manufacturers for transformers of the same rating; the are, however, associated with less accuracy or with less insulation oth.

ximate cost of an instrument transformer of high grade represent- s as per Figs. 2 and 3 for current transformers and Figs. 7 and 8 transformers is as follows:

F VOLTAGE AND CURRENT TRANSFORMERS (1922)

Voltage of circuit	Insulation test voltage	Price in dollars	
		Operated dry	Operated with oil
230	5,000	20 to 25	.....
460	5,000	23 to 27	.....
575	10,000	25 to 30	.....
2,300	10,000	26 to 32	39 to 44
4,600	10,000	40 to 48	61 to 70
6,900	15,000	52 to 61	70 to 78
11,500	25,000	.....	97 to 117
13,800	30,000	.....	100 to 122
23,000	50,000	.....	325
34,500	70,000	.....	435
44,000	95,000	.....	610
66,000	140,000	.....	870 to 1050
2,500	10,000	.....	17 to 26
6,900	20,000	.....	32 to 45
13,800	35,000	.....	44 to 56
23,000	56,000	.....	87
34,500	81,000	.....	195
44,000	108,000	.....	283
66,000	160,000	.....	400

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Vol. 27, p. 1005; Sharp, C. H. and Crawford,
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TRANSIENT ELECTRIC PHENOMENA AND OSCILLATIONS.

- (*See also Alternating Currents; Capacity and Charging Current; Electricity nd Magnetism, Principles of; Inductance and Inductive Reactance; Transmis-on Lines.*)

Establishment of a Direct Current in a Coil. — Let E be a constant rect electromotive force, r the resistance of the coil, L the inductance of the il (assumed constant); then t seconds after closing the circuit (placing the coil id e.m.f. in series) the current in the coil is

$$i = \frac{E}{r}\left(1 - \epsilon^{-ut}\right), \tag{1}$$

here ϵ is the base of the natural logarithms and $u = \frac{r}{L}$. See *Exponential unctions* for values of ϵ^{-x}.

Time Constant of a Coil. — The time required for the exponent $ut = \frac{rt}{L}$ reach the value unity, and therefore for the current to reach 63.2 per cent of s final value, is called the time constant of the coil, and is equal to $\frac{L}{r}$. The rger the time constant the longer the time required for the current to reach its eady value $\frac{E}{r}$.

Decay of Current in a Coil when Coil is Short-circuited. — Using e same notation as above, the current in the coil t seconds after short-circuit-g it is

$$i = I_0 \epsilon^{-ut}$$

here I_0 is the current in it at the instant the short-circuit is made.

Charging a Condenser Through a Resistance from a Source of Constant E.M.F. — Let E be a constant e.m.f., C the capacity of the condenser, the resistance in series with it, and let the condenser be originally uncharged. Then if the conductance of the condenser and the inductance of ie circuit are both negligible, the voltage across the condenser, the current the circuit and the charge on the condenser t seconds after the circuit is osed (thereby connecting the condenser, resistance and e.m.f. in series), are spectively

$$\left.\begin{aligned} v &= E(1 - \epsilon^{-ut}), \\ i &= \frac{E}{r}\epsilon^{-ut}, \\ q &= CE(1 - \epsilon^{-ut}), \end{aligned}\right\} \tag{2}$$

here $u = \frac{1}{rC}$. For values of ϵ^{-x} see *Exponential Functions*.

Time Constant of a Condenser and Resistance in Series. — The me required for the exponent $ut = \frac{t}{rC}$ to reach the value unity, and therefore e the voltage and charge on the condenser to reach 63.2 per cent of their final alues, is called the time constant of this circuit, and is equal to rC. The larger ie time constant the longer the time required for the voltage across the conenser to reach the value of the e.m.f. impressed on the circuit.

Discharge of a Condenser Through a Resistance. — Using the same notation as above, and assuming negligible conductance in the condenser and negligible inductance in the circuit, the voltage across the condenser, the current

in the circuit and the charge on the condenser i
it through a resistance r, the condenser being ch
instant of short-circuit (but no current flowing),

$$\left.\begin{aligned} v &= V_0 \epsilon^{-ut}, \\ i &= -\frac{V_0}{r}\epsilon^{-ut}, \\ q &= CV_0 \epsilon^{-ut}, \end{aligned}\right\}$$

where $u = \frac{1}{rC}$.

GENERAL EQUATIONS FOR LUMPE CAPACITY. — Let the various quantities be as d ferential equations for this circuit are

$$\left.\begin{aligned} i &= gv + C\frac{dv}{dt}, \\ v &= e - ri - L\frac{di}{dt}, \end{aligned}\right\} \qquad (4)$$

where i is the instantaneous current in the impe dance coil (equal to the total displacement an conduction current through the condenser), v is th potential drop through the condenser in the directi impressed voltage, constant or varying. g repre condenser, i.e., the power dissipated in the conde

At any given instant, say at $t = 0$, let the imp any previous value to a new value $E \sin \theta$, and this instant vary sinusoidally, i.e., at any insta $(\omega t + \theta)$, where $\omega = 2\pi f$ and f is the frequency of t (The solution for a constant impressed e.m.f. E $f = 0$ and $\theta = \pi/2$ in the equations below.) Let values of the current i and of the potential dro time $t = 0$. I_0 and V_0 may or may not be zero, of the circuit previous to the change in the impre

Steady State Relations. — The complete so that the current and voltage at any instant afte circuit are each composed of two terms, (1) a t and (2) a term, added to the first, which represe nating) state of the current and voltage respe solution of (4) is readily effected by the ordi current calculation (*see Alternating Currents*), and

$$i_2 = \frac{E}{Z}\sin(\omega t + \theta - \phi),$$

$$v_2 = \frac{E}{yZ}\sin(\omega t + \theta - \phi - \eta$$

where

$$Z = \sqrt{R^2 + X^2} \qquad \text{and} \qquad \phi$$

$$R = r + \frac{g}{g^2 + b^2}, \qquad X$$

$$b = \omega C, \qquad x$$

$$y = \sqrt{g^2 + b^2}, \qquad \eta$$

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scillations. — The transient terms in the complete solution of equa- re as follows:

$$\left.\begin{aligned} i_1 &= \epsilon^{-\alpha t}\left[D\cos\omega_0 t - \left(\frac{D'}{\omega_0 L} + \frac{qD}{\omega_0}\right)\sin\omega_0 t\right], \\ e_1 &= \epsilon^{-\alpha t}\left[D'\cos\omega_0 t + \left(\frac{D}{\omega_0 C} + \frac{qD'}{\omega_0}\right)\sin\omega_0 t\right], \end{aligned}\right\} \quad (7)$$

$$\left.\begin{aligned} \alpha &= \frac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right) \quad \text{and} \quad q = \frac{1}{2}\left(\frac{r}{L} - \frac{g}{C}\right), \\ \omega_0 &= \sqrt{\frac{1}{LC} - q^2}\,. \end{aligned}\right\} \quad (8)$$

e constants, α, q and ω_0 are constants of the circuit, and are inde- the manner in which the transient oscillation is set up. The fre- his "natural" oscillation is

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - q^2}.$$

small compared with $\frac{1}{LC}$ the natural frequency is $f_0 = \frac{1}{2\pi\sqrt{LC}}$.

resistance of the coil and leakance of the condenser, these natural die out with time proportionally with $\epsilon^{-\alpha t}$, or the amplitudes of ansient current and the transient voltage decrease by the fraction cond.

tants D and D', which determine the amplitudes of the transient tions 7) are given by the following relations:

$$\left.\begin{aligned} D &= I_0 - \frac{E}{Z}\sin(\theta - \phi), \\ D' &= V_0 - \frac{E}{yZ}\sin(\theta - \phi - \eta), \end{aligned}\right\} \quad (9)$$

he current in the coil and V_0 the voltage across the condenser at $(t = o)$ at which any change is made in the circuit conditions, i.e., d or closed, or e.m.f. short circuited.

when Damping is Great. — When q^2 is greater than $1 \div (LC)$, maginary and the oscillation therefore has an imaginary frequency, that the transient terms die out without oscillating. Equations 9) still hold in this case and will give the *real* solution *provided* that in "cos" is changed to "cosh" (hyperbolic cosine), and "sin" is changed rperbolic sine) and for ω_0 is taken the value $\sqrt{q^2 - \frac{1}{LC}}$. See *Hy- tions* for tables of "sinh" and "cosh." The expressions for α, q, nain unaltered.

amping. — Where $\omega_0 = o$, that is, when $q^2 = 1 \div (LC)$, equations ansient current and voltage become

$$\left.\begin{aligned} i_1 &= \left[D\left(1 - q\ell\right) - \frac{D'\ell}{L}\right]\epsilon^{-\alpha t} \\ e_1 &= \left[\frac{D\ell}{C} + D'\left(1 + q\ell\right)\right]\epsilon^{-\alpha t} \end{aligned}\right\} \quad (10)$$

D' are given by equations (9).

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Complete Solution. — The complete expressions for the current and voltage at any instant are in all cases

$$\left.\begin{aligned} i &= i_1 + i_2, \\ v &= v_1 + v_2, \end{aligned}\right\} \qquad (11)$$

where i_2 and v_2 are given by equations (5) and i_1 and v_1 are given by equations (7), the latter changed as noted above when q^2 is greater than $1 + (LC)$ or reducing to equation (10) when $q^2 = 1 + (LC)$.

Discharge of a Condenser through an Impedance Coil. — The above equations may be used to obtain the solution of the special case of a condenser charged to a voltage V_0 and short-circuited at time $t = 0$ through a coil having both resistance and inductance. Assume that at time $t = 0$ the current through the condenser is zero. The "steady state" terms in this case are zero, and only the transient terms appear, viz.,

$$\left.\begin{aligned} i &= -\frac{V_0}{\omega_0 L} \epsilon^{-ut} \sin \omega_0 t, \\ v &= V_0 \epsilon^{-ut} \left(\cos \omega_0 t + \frac{q}{\omega_0} \sin \omega_0 t \right), \end{aligned}\right\} \qquad (12)$$

where the values of u, q and ω_0 are as given above, equations (8). When $1 + (LC)$ is greater than q^2, equations (12) apply directly; the current-time curve in this case is shown in Fig. 2. When $1 + (LC)$ is less than q^2 the circular functions become hyperbolic functions and $\omega_0 = \sqrt{q^2 - \frac{1}{LC}}$ and the current-time curve is as shown in Fig. 3. When $q^2 = 1 + (LC)$, equations (12) reduce to

$$i = -\frac{V_0}{L} t\epsilon^{-ut} \qquad \text{and} \qquad v = V_0 \epsilon^{-ut}(1 + qt). \qquad (13)$$



Fig. 2. $q < \frac{1}{\sqrt{LC}}$

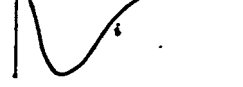


Fig. 3. $q > \frac{1}{\sqrt{LC}}$

OSCILLATIONS IN TRANSMISSION LINES. — Oscillations similar in nature to those discussed above occur in a transmission line when any change takes place in the load connections and particularly when high voltages are suddenly induced in the line by lightning discharges or when heavy currents are suddenly interrupted. The mathematical analysis of such cases is extremely involved, since account must be taken of the distributed nature of the inductance and capacity, and also of the fact that the possible periods of oscillations depend not only upon the line constants but also upon the constants of the apparatus at the two ends of the line. See article on *Transmission Lines*.

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MISSION LINES. — (*See also Capacity and Charging Current; nd Conduit Lines, Underground; Copper; Corona, Electric; Cross Arms; n Lines; Distribution and Transmission Systems; Inductance and In- ctance; Insulators for Overhead Lines; Insulator Pins; Trolley Systems, Wind Pressure; Wires and Cables, Bare; Wires and Cables, Insulated; Buildings.*) Circuits designed for transmitting relatively large amounts om one fixed point to another are called transmission lines, while those ing small amounts at numerous points are called distribution circuits. type of construction is used for both kinds of lines when designed for at the same voltage. The formulas used in the electrical design of bution and transmission lines and in the mechanical design of wire ncluded in this article; see also the articles on *Trolley Systems, Over-* rmulas for railway distribution, and *Wiring of Buildings* for formulas wiring. The construction details given in this article refer primarily ase lines designed to operate at or above 13,200 volts; for the con- f low-voltage lines see *Distribution Lines*. For a discussion of the tures of the various types of distribution and transmission systems cle on *Distribution and Transmission Systems*.

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IONS AND FUNDAMENTAL RELATIONS. — The follow- ns and relations apply to all types of transmission and distribution

r End and Load End. — By the generator end of the line is meant h is connected to the source of power (either directly or through), and by the load end is meant the end which is connected to the ation which is supplied with power over the line.

Power Loss (Q). — By per cent power loss as used in this article percentage ratio

$$Q = 100 \cdot \frac{\text{total power lost in the line}}{\text{total power delivered at load end}}. \quad (1)$$

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Hence if P is the power delivered, then the total power supplied to the line and load is

$$P_s = P\left(\frac{100+Q}{100}\right). \qquad (5)$$

Per cent Voltage Loss (D). — By per cent voltage loss as used in this article is meant the percentage ratio*

$$D = 100 \cdot \frac{\text{(voltage at generator end)} - \text{(voltage at load end)}}{\text{voltage at load end}}. \qquad (6)$$

Hence calling E the voltage at the load end, the voltage at the generator end is

$$E_s = E\left(\frac{100+D}{100}\right). \qquad (7)$$

The per cent voltage loss allowed under various conditions is discussed in detail in the article on *Distribution and Transmission Systems;* the allowable voltage loss is usually between 2 and 20 per cent, the most common figure being 10 per cent.

In the case of a direct-current line with a single load at its far end, the per cent power loss and the per cent voltage loss are always equal, but in the case of an alternating-current line the per cent voltage loss may be either greater or less than the per cent power loss, depending upon the constants of the line and the power factor of the load, or may even be negative, i.e., there may be an actual rise of voltage at the load end above the voltage at the generator end; see below.

Efficiency of Transmission. — By the efficiency of transmission is meant the percentage ratio

$$100 \cdot \frac{\text{power output of line at load end}}{\text{total power input to line at generator end}}. \qquad (8)$$

The per cent efficiency is related to the per cent power loss Q as follows:

$$\text{Per cent efficiency} = \frac{10{,}000}{100+Q}. \qquad (9)$$

ELECTRICAL DESIGN OF DIRECT-CURRENT LINES. — Two types of problems arise: (1) given a definite line with known constants, what is the power loss and voltage loss for a given load, and (2) to transmit a given amount of power a given distance with a given allowable loss, what will be the size and weight of the conductor required? In the following paragraphs are given the necessary formulas for the several cases.

Two-wire Line; Concentrated Load at Far End. — Let

E = volts between wires at the load end of the line,

$P = \frac{EI}{1000}$ = kilowatts taken by load,

$I = \frac{1000\,P}{E}$ = amperes taken by load,

l = length of each line wire in feet,

r = ohms per 1000 feet of conductor; see tables in article on *Wires and Cables, Bare,*

$R = \frac{rl}{500}$ = total resistance of line (both conductors), in ohms.

* In the case of an alternating-current line the difference in the numerator of this ratio is the algebraic difference between r.m.s. values of the two voltages, not the vector difference.

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ving relations then hold:

ilowatts lost $= p = \frac{RI^2}{1000} = \frac{rlI^2}{500{,}000} = \frac{2\,rlP^2}{E^2}$, (7)

olts lost $= v = RI = \frac{rlI}{500} = \frac{2\,rlP}{E}$, (8)

t power loss $= Q = \frac{100\,p}{P} = \frac{rlI^2}{5000\,P} = \frac{200\,rlP}{E^2}$, (9)

voltage loss $= D = \frac{100\,v}{E} = \frac{rlI}{5\,E} = \frac{200\,rlP}{E^2}$, (10)

ce of each conductor per 1000 feet $= r = \frac{500\,v}{lI} = \frac{QE^2}{200\,lP} = \frac{DE^2}{200\,lP}$. (11)

lation of Size and Weight of Conductor for Concentrated m the value of r calculated from any one of the relations given in , the size of wire may be found from the tables in the article on *bles, Bare;* the next larger size of wire (next smaller gauge number) y be chosen when the calculated resistance lies between that of two zes. The wire selected must also have sufficient current-carrying *Wires and Cables, Bare; Wires and Cables, Insulated;* and *Wiring* For outside lines, however, the current-carrying capacity will in ple unless the allowable voltage loss is excessive. For an outside wire smaller than No. 6 A.W.G. (or B. & S.) gauge is seldom used, ount of its lack of mechanical strength.

ght per 1000 feet of the wire finally selected, then

Total weight of conductor in pounds $= W = \frac{wl}{500}$. (12)

Calculation of Total Weight of Conductor (W); Two-wire reliminary estimates it is sometimes convenient to calculate the conductor directly, without reference to a wire table. The total uctor for a two-wire line with concentrated load at its end is given

$$W = \frac{KP}{Q}\left(\frac{l}{E}\right)^2 \text{ pounds}, \quad (13)$$

power taken by the load, l the length of the line (length of each ltage at the load, Q the per cent power loss (= per cent voltage d-c. line) and K a constant depending upon the material of the he units in which P, l and E are expressed, viz.,

VALUES OF K IN FORMULA 13

Material	E in volts, l in feet, P in kilowatts	E in kilovolts, l in miles, P in kilowatts
cent conductivity).....	13.5	380
per cent conductivity)...	6.5	185
specific gravity δ having of c per cent at 20° C...)	$\frac{141\,\delta}{c}$	$\frac{3940\,\delta}{c}$

lues of K given for copper and aluminum are about 5 per cent greater ical values to allow for stranding, higher working temperature, etc.; uctivity corresponds to 1.724 microhms per centimeter cube at 20° C.

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Example: Two-wire D-C. Line, Conc 100 kw. is to be transmitted over a two-wire lin volts, the motor being 1000 feet from the pow 10 per cent power loss or voltage drop in the line of copper required is, from equation (13),

$$W = \frac{13.5 \times 100}{10}\left(\frac{1000}{230}\right)^2 = 25$$

From equation (11) the resistance per 1000 feet i

$$r = \frac{10 \times (230)^2}{200 \times 1000 \times 100} = 0.0264 \text{ oh}$$

The nearest even circular mil size is 400,000 circ a resistance of 0.0270 ohm per 1000 feet at 77° F and a weight of 1240 pounds per 1000 feet. From of conductor is then

$$W = \frac{1240 \times 1000}{500} = 2480$$

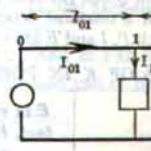
This wire, if bare, weather-proofed, or insulated wi will safely carry the required current of 100,000/23 insulated and mounted indoors, a larger wire shoul cular mils, according to the National Electric Co

Calculation of Two-wire Direct-current L Generator End.—When the volts E_0 at the gen the volts E at the load end, the calculations for of R ohms with a concentrated load of P kilowatt in the same manner as above by first finding t formula

$$E = \frac{E_0}{2}\left[1 + \sqrt{1 - \frac{4000}{E_0^2}}\right.$$

For an efficiency of transmission of less than 50 radical should be − instead of +, but an effici practically never occurs in power transmission. for an efficiency of 50 per cent $P = E_0^2 \div (4000 R$ which can be delivered at the far end of the line at the generator end.

When E has been calculated by this formula (14), the formulas (7) to (13) above may be applied directly.



Two-wire Line; Distributed Load. — When a line supplies a number of loads at different distances from the generator end, the voltage loss to the far end of the line is the same as would be produced by a load, concentrated at the "center of gravity" of the line and taking a current equal to the t The center of gravity of the line is defined as follows: taken from the line by the various loads, Fig. 1, and le resistances (both wires) from the generator end to the

$$I = I_1 + I_2 + I_3 + \ldots$$

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en the center of gravity is that point between which and the generator end of the line total line resistance is

$$R_g = \frac{R_1 I_1 + R_2 I_2 + R_3 I_3 + \dots}{I}. \tag{16}$$

ien the line conductor has the same cross-section throughout its length, then the ter of gravity is at the distance,

$$l_g = \frac{l_1 I_1 + l_2 I_2 + l_3 I_3 + \dots}{I} \tag{16a}$$

m the generator end, where l_1, l_2, l_3, etc., are the distances of the respective loads from generator end.

The total voltage loss to the far end of the line is then

$$v = R_g I = \frac{r l_g I}{500}, \tag{17}$$

ere the distance l_g is in feet and r is the resistance of the conductor per 1000 feet, the ond relation in (17) holding only when the conductor has the same cross-section through- its length.

The total kilowatts lost in the line are

$$p = \frac{1}{1000}\left(R_{01} I_{01}^2 + R_{12} I_{12}^2 + R_{23} I_{23}^2 + \dots\right), \tag{18}$$

ere, referring to Fig. 1, R_{01} = total resistance (both wires) from 0 to 1, R_{12} = total stance (both wires) from 1 to 2, etc., and $I_{01} = I_1 + I_2 + I_3 + \dots$ = the current in the from 0 to 1, $I_{12} = I_2 + I_3 + \dots$ = the current in the line from 1 to 2, etc. When cross-section of the line conductor is the same throughout its length equation (18) y be also written

$$p = \frac{r}{500{,}000}\left(l_{01} I_{01}^2 + l_{12} I_{12}^2 + l_{23} I_{23}^2 + \dots\right), \tag{18a}$$

ere the distances l_{01}, l_{12}, l_{23}, etc., are as shown in Fig. 1, and are measured in feet, and the resistance of the line conductor per 1000 feet.

Calculation of Size and Weight of Conductor for Distributed Load. — For onductor of the same cross-section throughout, the required resistance per 1000 feet a given voltage loss of v volts to the end of the line may be calculated from the formula

$$r = \frac{500\, v}{l_g I}, \tag{19}$$

ere l_g, expressed in feet, and I are given by formulas (16a) and (15). The size and ght of conductor can then be found by reference to the wire tables in the article on *ires and Cables, Bare.*

When the loads are far apart and the smaller loads are farthest from the generator, s sometimes advisable to use different sizes of conductors for the various portions of line. For a given voltage loss v to the end of the line, the minimum weight of conduc- is obtained when the volts lost per unit length of conductor in each section of the line roportional to the square root of the current in this portion of the line. For minimum al weight of conductor then, referring to Fig. 1, the resistance per 1000 feet *of wire* the section between 1 and 2, may, must be

$$r_{12} = \frac{1}{\sqrt{I_{12}}} \cdot \frac{500\, v}{l_{01}\sqrt{I_{01}} + l_{12}\sqrt{I_{12}} + l_{23}\sqrt{I_{23}} + \dots}, \tag{20}$$

ere the lengths are in feet; and similarly for the other sections. The weight of wire each section may then be found by reference to the wire tables in the article on *Wires l Cables, Bare*, and the total weight W can then be computed. Vice versa, for a line portioned in this manner the voltage loss to the end of the line for a given total weight copper will be a minimum.

A line proportioned in this manner, however, does not give minimum power loss for total weight of conductor used. For a given total weight of conductor the total wer loss will be a minimum when the power loss per unit length of conductor in each tion of the line is directly proportional to the current in this section, i.e., when the

voltage loss per unit length in each section is the same, unit length of each section must be proportional to the li letting W be the total weight of the conductor in pou minimum when the section from 1 to 2, say, has a we

$$w_{12} = I_{12} \frac{500\,W}{l_{01}I_{01} + l_{12}I_{12} + l_{23}I_{23}}$$

where the lengths are in feet; and similarly for the ot each section may be obtained from the wire tables in *Bare*. When the sizes as found by the two formulas the choice will depend upon which is the more important voltage loss.

Three-wire Direct-current Line. — When balanced, i.e., when the loads between each of th tral are the same and are connected to the neutr no current flows in the neutral wire. The formu line then apply directly to the case of a balanc ever that the E (= volts between wires) in the the volts between the *outer* wires, and that the above formulas is the weight of the two outer usually made equal in size to each outer wire, but as expected it is sometimes made smaller. When size to the outer wire the total weight of the three more than that given by formula (13), when E to the volts between the outer wires.

The exact calculation of the voltage loss and po two sides of the system are different and are c somewhat complicated, but can always be effecte hoff's Laws for an electrical network; see *Electric of*.

SIZE AND WEIGHT OF CONDUCTOR CURRENT LINES. — As a rough guide in fixi the following facts should be noted; complete for tions required are given later.

1. A power loss of approximately 10 per cent of allowed.

2. A line voltage of approximately 1000 volt practice for long-distance lines not over 150 miles l line a line voltage of 10,000 volts would be emplo voltage of 100,000 volts would be used. The ma (1914) employed is 150,000 volts and the maximu 240 miles.

3. On the basis of 1000 volts per mile of line, u a 10 per cent power loss, and copper at 15 cent copper required for a three-phase line is $4.00 per single-phase or two-phase four-wire line $5.33 per k

Calculation of Total Weight of Conductor and total weight of the conductor required for any delivered, power factor, line voltage and power loss

* These formulas are based on the assumption that in comparison with the load current, which condition is longest high-voltage lines; formulas for power loss tak count are given later.

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et

E = voltage between wires at the load end of the line,
P = total power taken by all phases of the load,
$\cos \phi$ = power factor of load, as a decimal,
l = length of line (= length of each line wire),
Q = allowable total power loss in per cent of delivered power.

hen the total weight of all conductors is given by the formula

$$W = \frac{KP}{Q}\left(\frac{l}{E \cos \phi}\right)^2 \quad \text{pounds,} \qquad (22)$$

here K is a constant depending upon the number of phases and wires, the mate-ial of the conductor and the units in which the various quantities are expressed, iz.,

VALUES OF K IN FORMULA 22

Material and units	Single-phase or balanced 4-wire 2-phase*	Balanced 3-wire 3-phase
Copper (98 per cent conductivity):		
E in volts, l in feet, P in kilowatts ...	13.5	10
E in kilovolts, l in miles, P in kilowatts	380	280
Aluminum (61 per cent conductivity):		
E in volts, l in feet, P in kilovolts....	6.5	4.9
E in kilovolts, l in miles, P in kilowatts	185	140
Any material of specific gravity δ having a conductivity of c per cent at 20° C.:		
E in volts, l in feet, P in kilowatts....	$\frac{141\,\delta}{c}$	$\frac{106\,\delta}{c}$
E in kilovolts, l in miles, P in kilowatts	$\frac{3940\,\delta}{c}$	$\frac{2950\,\delta}{c}$

NOTE. — The values of K given for copper and aluminum are taken about 5 per cent reater than their theoretical values to allow for stranding, higher working temperatures, c. 100 per cent conductivity corresponds to 1.724 microhms per centimeter cube at 0° C.

* For a 3-wire 2-phase system with the middle conductor having a cross-section equal $\sqrt{2}$ times the cross-section of either outer wire multiply these constants by 0.85, tak-g for E the voltage (volts or kilovolts) between the middle wire and either outer wire.

Calculation of Commercial Size of Conductor and Corresponding Total Weight. — Formula (22) takes no account of the available commercial sizes f wire. These sizes differ successively by approximately 25 per cent in cross-ection. The weight can also be determined by calculating the resistance of ne required conductor per 1000 feet or per mile, and taking from the wire ables in the article on *Wires and Cables, Bare*, the nearest commercial size. Neglecting the charging current, the required resistance per unit length of wire

$$r = \frac{K_1 Q (E \cos \phi)^2}{lP} \quad \text{ohms,} \qquad (23)$$

here K_1 is a constant depending on the number of phases and wires and the nits in which the other quantities are expressed, as given in the table below.

From the wire table the corresponding weight (w) per unit length of conductor having a resistance nearest to that calculated by formula (23) is obtained; the total weight of conductor, including all wires, is then

$$W = K_2 wl \quad \text{pounds,} \tag{24}$$

where K_2 is a constant depending upon the number of phases and wires and the units in which w and l are expressed, as given in the table below.

VALUES OF K_1 AND K_2 IN FORMULAS 23 AND 24

Units	Single-phase	Balanced 4-wire 2-phase*	Balanced 3-wire 3-phase
E in volts, l in feet, P in kilowatts, r in ohms per 1000 feet and w in pounds per 1000 feet.	$K_1 = 0.005$ $K_2 = 0.002$	$K_1 = 0.01$ $K_2 = 0.004$	$K_1 = 0.01$ $K_2 = 0.003$
E in kilovolts, l in miles, P in kilowatts, r in ohms per mile and w in pounds per mile.	$K_1 = 5$ $K_2 = 2$	$K_1 = 10$ $K_2 = 4$	$K_1 = 10$ $K_2 = 3$

* The values of K_1 given in this column when used in formula (23) will give the resistance per 1000 feet or per mile of either outer wire in a 3-wire 2-phase system; the middle wire should, for the same energy loss per pound, have a cross-section 41 per cent greater than either outer, but when commercial sizes (B. & S. gage) are used, either a wire one gage number smaller (25 per cent greater cross-section) or two gage numbers smaller (60 per cent greater cross-section) may be used; in the first case the corresponding value of K_2 is 0.81 times the values given in this column and in the second case 0.90 times the values given in this column.

Current per Wire; Heating of Line Conductors. — The size of wire as determined from formula (23) must be ample to carry the required current without overheating. Heating of the line conductors is seldom a limitation in outside overhead lines, but for inside wiring or underground cables the temperature rise may set a limit to the size of wire which may be used. It is therefore always wise to determine the current which the conductor must carry, and make sure that the wire is sufficiently large not to overheat; see articles on *Wires and Cables, Bare; Wires and Cables, Insulated;* and *Wiring of Buildings*, for tables of current-carrying capacity under various conditions.

The current per line wire in amperes may be calculated from the following formulas, in which E *is the kilovolts* between wires at the load end, P *the kilowatts* (all phases) delivered to the load, and $\cos\phi$ the power factor of the load as a fraction.

$$\left.\begin{aligned} &\text{Single-phase:} && I = \frac{P}{E\cos\phi}. \\ &\text{Two-phase,* 4-wire, balanced:} && I = \frac{P}{2E\cos\phi}. \\ &\text{Three-phase, 3-wire, balanced:} && I = \frac{P}{\sqrt{3}E\cos\phi}. \end{aligned}\right\} \tag{25}$$

Example: Calculation of Weight and Size of Conductor for a Three-phase Line. — A load of 20,000 kilowatts is to be transmitted by means

* E is here the volts between the two wires of the same phase. This formula also gives the current in each outer of a balanced 2-phase 3-wire line, E being the kilovolts between either outer and the middle wire; the current in the middle is $\sqrt{2}$ times the current in each outer.

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rhead three-phase line of copper wire to a substation 50 miles away at 60,000 volts between wires, the frequency being 25 cycles per nd the power factor of the load 80 per cent with the current lagging; ss of 10 per cent of the delivered power to be allowed. From formula equired total weight of copper is

$$W = \frac{285 \times 20{,}000}{10}\left(\frac{50}{60 \times 0.8}\right)^2 = 607{,}000 \text{ pounds.}$$

ula (23) the required resistance per mile of conductor is

$$r = \frac{10 \times 10(60 \times 0.8)^2}{50 \times 20{,}000} = 0.231 \text{ ohm per mile.}$$

t commercial size is 250,000 circular mils (stranded), which has a f 0.328 ohm per mile at 77° F. (*see Wires and Cables, Bare*), and a 080 pounds per mile. From formula (24) the total weight is then

$$W = 3 \times 4080 \times 50 = 612{,}000 \text{ pounds.}$$

t corresponding to the given load is, from formula (25),

$$I = \frac{20{,}000}{\sqrt{3} \times 60 \times 0.8} = 241 \text{ amperes,}$$

ive a negligible temperature rise in the wire. See section on *Current-pacity* in article on *Wires and Cables, Bare.*

on of Size and Weight of Conductors for a Given Per cent ss. — The voltage loss in an alternating-current line depends not e resistance of the line, but also upon the line reactance, and in the lines upon the electrostatic capacity of the line. It is therefore o express directly in a simple formula the size or weight of the wire ie voltage loss. The most practical method of making such calcula- sume first that the per cent power loss is equal to the given per cent and calculate the size by formula (23); then using this size of wire per cent voltage loss by the formulas given below. If this cal- ge loss differs appreciably from the given voltage loss, choose the r smaller size of wire (accordingly as the calculated loss is greater he given loss) and recalculate the voltage loss, and so on, until the wire has been found.

S WHICH AFFECT THE VOLTAGE AND POWER LOSS NES. — Due to the inductance and electrostatic capacity the per oss in an alternating-current line is not so easily calculated as the n a direct-current line and is in general different from the per cent r an amount dependent upon the inductance and capacity of the iency and the power factor of the load.

tion of Line Constants. — The four fundamental line constants nce (r) and inductance (L) of the line conductors per unit length ity (C) and leakage conductance (G) per unit length. For all but ransmission lines the mile is usually the most convenient unit of is unit will be used throughout the remainder of this article unless ted otherwise. Tables of resistance, inductance and capacity and per 1000 feet are given respectively in the articles on *Wires re; Inductance and Inductive Reactance;* and *Capacity and Charging* n the inductance and capacity per mile or per 1000 feet may be any given frequency the reactance x ($= 2\pi fL$) and the capacity

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susceptance* b ($= 2\pi fC$) for the corresponding unit of length. In the last two articles just mentioned are given full tables of reactance and of capacity susceptance per mile for frequencies of 60 and 25 cycles per second; dividing the numerical values given in these tables by 5.28 will give the corresponding quantity per 1000 feet. For any other frequency of f cycles per second, multiply the numerical values given in the tables for 25 cycles by the ratio $f/25$; i.e., for 40 cycles the reactance is 1.6 times the reactance for 25 cycles.

Allowance for Skin Effect in Conductors. — For non-magnetic wire the increase in the conductor resistance due to the so-called skin effect is equal to 2 per cent when the quotient

$$\text{(cycles per sec.)} \div \text{(ohms per mile of conductor)} = 485. \qquad (58)$$

For smaller values of this quotient the increase of resistance due to skin effect diminishes very rapidly; see article on *Skin Effect*. The skin effect is therefore practically negligible at 25 cycles for all copper conductors smaller than 1,000,000 circular mils, and at 60 cycles for all copper conductors smaller than 450,000 circular mils. The corresponding limiting sizes for aluminum are about 30 per cent larger. The skin effect is quite appreciable in copper or aluminum cables with a steel core; it is usual to neglect the conductivity of the steel core entirely in calculating the resistance of such cables.

Apparent Resistance and Reactance in Unsymmetrical Arrangements of Wires. — When the three wires of a three-phase line are so arranged that they form the three edges of an equilateral prism the reactance of each wire is the same as for one wire of a two-wire line. However, when the wires are arranged all in one plane, as is frequently done, the unequal mutual induction sets up a reactive electromotive force in each outer wire which is not in quadrature with the current in this wire; see equation (20) in the article on *Inductance and Inductive Reactance*. As a result, both the apparent resistance and the apparent reactance of each outer wire is different from its true resistance and reactance. Let r = the true resistance per mile of each wire in ohms, x = the reactance per mile of each wire in ohms, as given in the tables in the article on *Inductance and Inductive Reactance;* and f = the frequency in cycles per second, then the apparent resistances and reactances per mile of the three wires, No. 2 being the middle wire, are

$$\left.\begin{array}{lll} r_1 = r + 0.00121f, & r_2 = r, & r_3 = r - 0.00121f, \\ x_1 = x + 0.00070f, & x_2 = x, & x_3 = x + 0.00070f. \end{array}\right\} \qquad (59)$$

The changes in the apparent resistances do not indicate any change in the power dissipated as heat in the wires but a transfer of energy from one wire to the other by the magnetic field surrounding the wires. These relations are deduced from equations (20) in the article on *Inductance and Inductive Reactance*, assuming sine-wave currents equal in effective value and differing in phase by exactly 120°. The assumption that the currents are exactly balanced cannot be strictly true, since the inequality in the apparent resistances and reactances of the three wires tends to unbalance the system, but the values just given may be taken as a fair approximation when the voltage loss in the line is not over 10 per cent, say. When the line wires are transposed these mutual inductive effects are eliminated from the line as a whole, though the apparent impedances of the three wires in any one "exposure" of the transposition will be different; the transpositions, however, keep the currents balanced.

Similar effects take place in a two-phase three-wire line, see p. 1773.

Leakage Conductance. — The leakage current, even at very high voltages, is usually negligible in power transmission lines, but for telephone lines, the leakage is much greater, due to the large number of small insulators used, and has a very appreciable effect on both the attenuation and distortion of the voice currents. McMeen (*see article on Telephone Lines*) gives the following

* The capacity susceptance to neutral as given in the tables (i.e., in microsiemens per mile) is equal to the charging current in amperes per mile per million volts between wire and neutral; the charging current for any other voltage to neutral is in proportion.

alues of the leakage conductance of telephone lines, the conductance
m one wire to neutral,

dry	$g = 0.004$ micromhos per mile.	(28)
age	$g = 0.08$ micromhos per mile.	
wet	$g = 1.0$ micromhos per mile.	

ge conductance from one wire to the other is one-half these values.
A megohms per mile equals $1/A$ micromhos per mile.
he voltage is sufficiently high on a power line to cause the formation of
e article on Corona), an appreciable leakage current passes from one
e other. Even for a sine-wave voltage this leakage current is by no
usoidal, since its instantaneous values are practically zero except
peak of the voltage wave, and consequently the corona loss cannot
ely represented by a constant leakage conductance. Roughly, how-
g p_c the average value of the corona loss from each wire in watts per
sponding to the given line voltage, the leakage conductance to neutral
hos per mile due to the corona may be taken equal to

$$g_c = \frac{p_c}{V^2}, \tag{29}$$

the effective (r.m.s.) kilovolts to neutral.

Voltage at Load End of Line on Open Circuit. — In every current transmission line the voltage at the load end when this end higher than at the generator end, although in short low-frequency e is inappreciable. In overhead lines for which the product

$$(\text{cycles per sec.}) \times (\text{length of line * in miles}) < 10{,}000, \tag{30}$$

rise as a percentage of the delivered voltage is, to a close approxima-
e resistance of the wire is less than that of a No. 0 B. & S. copper

to $\left(\frac{fl}{40000}\right)^2$, where f is the frequency in cycles per second, and l the
line in miles. For example, in a 25-cycle line 160 miles long this
is 1 per cent of the delivered voltage, in a 60-cycle line of the same
-load rise in voltage is 5.8 per cent of the delivered voltage. The
essed by the above formula under the conditions stated is inde-
he value of the delivered voltage and of the size and spacing of
least for all practical cases.
hich is due to the charging current taken by the line, may be looked
nt at all loads, but when the load is appreciable the voltage drop,
ad current, unless leading, more than offsets this voltage rise. A
it may increase the rise in voltage at the load end as the load

nchronous Condensers (or Phase Modifiers) to Maintain ltage at Load End. — By making the line current at the load lead the line voltage by the proper phase angle, it is possible to ntirely for the change in the load voltage which normally takes oad current increases. An overexcited synchronous motor con-lel with the load is sometimes used for this purpose, as described e article on *Motors, Synchronous*. A synchronous motor so used alled a synchronous condenser, since the current taken by it leads pressed on its terminals. A striking example of the use of syn-s for this purpose is in connection with the 150,000-volt, 240-mile

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* Length of each conductor.

line from Big Creek, Cal., to Los Angeles, constructed in 1913. Two separate lines are used, the total generator output is 70,000 kilovolt-amperes, and the voltage at the load end is controlled by two 15,000-kilovolt-ampere overexcited synchronous motors.

METHODS OF CALCULATING VOLTAGE AND POWER LOSS IN A-C. LINES. — The absolutely rigorous calculation of an alternating-current line requires that the distributed nature of the inductance and capacity be considered, i.e., that the line be considered as made up of an infinite number of sections such as shown in Fig. 7. However, simpler approximate methods may be employed for nearly all power lines such as are now used, and give results sufficiently accurate for all practical purposes. The accuracy of these approximate methods depends primarily upon the frequency and length of the line; the less the value of the product of these two quantities the simpler is the method which may be employed. Accurate calculation of even a short a-c. line with distributed load can be effected only by rather complicated network equations; see under *Kirchhoff's Laws* in the article on *Alternating Currents*.

Limitations of Approximate Methods of A-C. Line Calculations. — The approximate methods of calculating a-c. lines, in the order of their simplicity, may be designated as (1) the simple impedance method; (2) the single end-condenser method; (3) the middle condenser or "T" method and (4) the split condenser or "π" method; the "π" method is also called the "U" method. For short low-voltage lines, the simple impedance method, which neglects entirely the charging current, is usually sufficiently accurate. The single end-condenser method takes the charging current into account in a manner usually sufficiently accurate for all but the longest high-voltage lines. The "T" and "π" methods are still more accurate, but for exact calculations the rigorous method given on p. 1681ff should be used. In fact, it is always well to check an approximate solution by this exact method.

Fundamental Assumptions on which Formulas Given Below are Based. — All the formulas given below are based on the assumptions of pure sine-wave currents and voltages and a perfectly balanced * system. By using the voltage to neutral instead of the voltage between wires, the formulas are also put in such shape that they may be applied directly to either a single-phase, a two-phase four-wire line or to a three-phase three-wire line, a two-phase four-wire line being considered as two separate single-phase lines. The fundamental idea in this method of treatment is that each line wire is considered as a separate circuit. The return wire shown in the various diagrams is therefore to be considered as having no impedance. This method of treatment of *balanced* polyphase circuits is strictly accurate (*see Alternating Currents*), but when the system is not balanced the circuit must be treated by the more general methods of network calculations; see section on *Kirchhoff's Laws in Symbolic Notation* in the article on *Alternating Currents*. Also, when the voltage and current waves are not sinusoidal, each harmonic must be treated separately as described in the article on *Alternating Currents*. The calculation of a two-phase three-wire line is treated separately, p. 1773.

SIMPLE IMPEDANCE METHOD. — This method is based upon the assumption that the electrostatic capacity of the line may be neglected entirely, and that the line may be considered simply as an impedance in series with the load, this impedance having a resistance equal to the total resistance of the line conductor and a reactance equal to the total inductive reactance of the line

* The meaning of a "balanced" system is fully explained in the article on *Alternating Currents* (q.v.).

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Fig. 2 is a diagram of the circuit, and Fig. 2a is a complete vector of the current and voltage. When the wires are unsymmetrically arrangements are assumed.

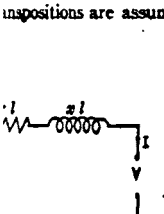


Fig. 2.

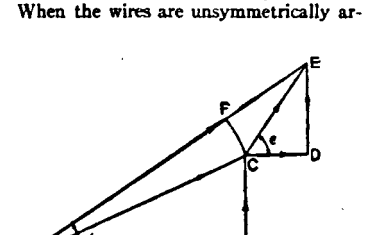


Fig. 2a.

$\overline{AH} = I$, $\overline{BC} = V \sin \phi$, $\overline{CE} = xI$,
$\overline{AC} = V$, $\overline{CD} = rI$, $\overline{AE} = V_0$,
$\overline{AB} = V \cos \phi$, $\overline{DE} = xI$, $\overline{FE} = V_0 - V$

volts to neutral at load end of the line (= volts between wires divided by 2 in case of a single-phase line, and volts between wires divided by $\sqrt{3}$ in the case of a three-phase line),
amperes per wire; see formula (25) above,
length of each line wire in miles,
$\frac{V}{lI}$ = "equivalent" impedance of the load per mile of line,
power factor of the load at end of line,
$\sqrt{1 - \cos^2 \phi}$ = the reactive factor of the load; $\sin \phi$ is to be taken positive for a lagging and negative for a leading current,
volts to neutral at the generator end of the line,
conductor resistance per mile of line in ohms; see tables in article on *Wires and Cables, Bare*,
conductor reactance per mile of line, in ohms; see tables in article on *Inductance and Inductive Reactance*,
$\sqrt{r^2 + x^2}$ = conductor impedance * per mile of line, in ohms,
per cent power loss, as a percentage of delivered power,
per cent voltage loss, as a percentage of delivered voltage.

tor diagram it is evident that the voltage at the generator end is

$$V_0 = \sqrt{(V \cos \phi + rlI)^2 + (V \sin \phi + xlI)^2}, \qquad (31)$$

---

nt way of calculating an expression of the form $\sqrt{a^2 + b^2}$ is to write it
or $b \sqrt{1 + \left(\frac{a}{b}\right)^2}$ accordingly as a is greater or less than b; the expression
al will then always lie between the numbers 1 and 2, and no difficulty
ced with decimal points. When b/a is less than 0.3, then the expression
$- \frac{b^2}{2a}$ with an error of less than 0.1 per cent, and when a/b is less than 0.3,
$= b + \frac{a^2}{2b}$ with an error of less than 0.1 per cent. The error in the ap-
sions, diminishes very rapidly as the ratio of b/a or a/b, as the case may
ing only 0.02 per cent when the ratio is 0.2.

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which may also be written

$$V_0 = V\sqrt{\left(\cos\phi + \frac{r}{Z}\right)^2 + \left(\sin\phi + \frac{x}{Z}\right)^2}, \tag{32}$$

where r and x are per mile of line.

The current at the generator end is the same as at the load end.

The per cent power loss is

$$Q = \frac{100\,rlI}{V\cos\phi} = \frac{100\,r}{Z\cos\phi}, \tag{33}$$

and the per cent voltage loss is

$$D = \frac{100\,(V_0 - V)}{V} = 100\left[\sqrt{\left(\cos\phi + \frac{r}{Z}\right)^2 + \left(\sin\phi + \frac{x}{Z}\right)^2} - 1\right]. \tag{34}$$

The power factor at the generator end is

$$\cos\phi_0 = \left(\frac{100 + Q}{100 + D}\right)\cos\phi. \tag{35}$$

Relation between Impedance Drop and Voltage Loss. — The total impedance drop, which is zI volts, should be carefully distinguished from the voltage loss, which is $v = V_0 - V$ volts. The vector diagram, Fig. 2a, will make the difference clear. For a given impedance drop of, say, A per cent, the voltage at the load end of the line may be anything from A per cent less than the voltage at the generator end to A per cent greater than the voltage at the generator end. The determining factor is the difference between the power-factor angle (ϕ) of the load and the power-factor angle $\left(\epsilon = \tan^{-1}\frac{x}{r}\right)$ of the line; only when $\epsilon - \phi = 0$ are the voltage loss and impedance drop the same. When $\epsilon - \phi$ is greater than 90° (which may occur for a leading current, since ϕ is then negative) the voltage at the load end will in general be higher than at the generator end although the impedance drop in the line may be very large. As a fair approximation, when the impedance drop is less than 20 per cent, that is, when z/Z is less than 0.2, the percentage voltage loss may be written

$$D = \frac{100\,z}{Z}\cos(\epsilon - \phi), \tag{36}$$

z and Z being the impedances of the line and load respectively, and ϵ and ϕ the power-factor angles of the line and load respectively.

Example of Calculation by Simple Impedance Method. — Take the case of a three-phase, 60-cycle line 50 miles long, the wires being No. 0000 A.W.G. (or B. & S.) stranded copper spaced symmetrically with 6 feet between centers, and let the load be 15,000 kilowatts at 60,000 volts between wires and at a power factor of 80 per cent with lagging current. The voltage to neutral is then $60{,}000 \div \sqrt{3} = 34{,}600$ and the current per wire $15{,}000 \div (\sqrt{3} \times 60 \times 0.8) = 180$ amperes. The resistance of each wire per mile is 0.269 ohm at 77° F., and the reactance 0.728 ohm. The equivalent impedance of the load per mile of line is $Z = 34{,}600 \div (50 \times 180) = 3.84$. $\cos\phi = 0.8$ and $\sin\phi = \sqrt{1 - 0.8^2} = 0.6$. Whence

$$\text{Per cent power loss} = Q = \frac{100 \times 0.269}{3.84 \times 0.8} = 8.76 \text{ per cent},$$

$$\text{Per cent voltage loss} = D = 100\left[\sqrt{\left(0.8 + \frac{0.269}{3.84}\right)^2 + \left(0.6 + \frac{0.728}{3.84}\right)^2} - 1\right] = 17.5\%.$$

wer factor at generator end = $\cos\phi_0 = \left(\frac{100 + 8.76}{100 + 17.5}\right) \times 0.80 = 74.1$ per cent,

Per cent impedance drop = $\frac{100\sqrt{0.269^2 + 0.728^2}}{3.84} = 20.2$ per cent.

Graphical Determination of Voltage Loss; Mershon's Chart (Fig. 3). — e voltage loss may also be determined by means of the chart shown in Fig. 3, ich was devised by R. D. Mershon. This chart is nothing more than a ans of solving equation (32) graphically. To use the chart calculate

$$\text{the per cent resistance drop} = r\left(\frac{100\,ll}{V}\right), \tag{37}$$

$$\text{the per cent reactance drop} = x\left(\frac{100\,ll}{V}\right), \tag{38}$$

l from the point on the curve marked "0" where this curve cuts the vertical e corresponding to the load power factor lay off horizontally the per cent istance drop, and from the end of this horizontal line lay off vertically upward per cent reactance drop; the per cent voltage loss is then given by the num- on the circle through the end of this vertical line.

Taking the same example as given in the preceding section, $(100\,ll) \div V = 0 \times 50 \times 180) \div 34{,}600 = 26.0$, whence the per cent resistance drop is $0.269 \times 0 = 7.0$ per cent and the per cent reactance drop is $0.728 \times 26.0 = 18.9$ and refore from the chart the per cent voltage loss is 17.6 per cent.

Calculations in Terms of Voltage at Generator End. — When the volts to neutral at the generator end are given instead of the volts to neutral V at the load end, the ulations for a line of total resistance of R ohms per wire, and total reactance of X as per wire for a load of P kilowatts per wire* at a power factor of $\cos\phi$ at the load l may be made in the same manner as above by first finding V by the formula,

$$V = A\sqrt{1 \pm \sqrt{1 - \frac{(R^2 + X^2)\,P^2 \times 10^6}{A^4\cos^2\phi}}}, \tag{39}$$

ere

$$A = V_0\sqrt{\frac{1}{2} - \frac{1000\,P\,(R\cos\phi + X\sin\phi)}{V_0^2\cos\phi}}. \tag{40}$$

e plus or minus sign in the formula for V arises from the fact that for a given amount delivered power and given voltage at the generator end two different voltages at the d end are possible; for an inductive load the voltage corresponding to the minus sign l in general be less than 50 per cent of the voltage at the generator end, and the "minus n" solution is therefore usually of no practical importance. The maximum power ich can be delivered at the load end for a given voltage at the generator end is

$$P_m = \frac{V_0\cos\phi}{2000\,(\sqrt{R^2 + X^2} + R\cos\phi + X\sin\phi)}. \tag{41}$$

Voltage and Power Loss in Two-phase Three-wire Line. — Take the usual se of the three wires in the same plane, with the common wire midway between the o outers. Let r be the resistance per mile of each outer, and r_1 the resistance per mile the common wire, taken from the tables in the article on *Wires and Cables, Bare*, and and x_1 the corresponding reactances per mile taken from the tables in the article on *ductance and Inductive Reactance*, for a spacing equal to the distance between the middle ire and each outer. Let E be the voltage between each outer and the middle wire, I e amperes in each outer, $\cos\phi$ the power factor of the load, and l the length of the line. ssuming a balanced load, then the voltage between the two outers is $\sqrt{2}\,E$ and the rrent in the middle wire is $\sqrt{2}\,I$, and the total power delivered to the load is $(2\,EI\cos$) ÷ 1000 kilowatts. The per cent power loss is then

$$Q = \frac{100\,(r + r_1)\,ll}{E\cos\phi}.$$

* Calling P_t the total kilowatts delivered to the load, then $P = P_t/2$ for a single hase line. $P = P_t/3$ for a three-phase line and $P = P_t/4$ for a two-phase four-wire line

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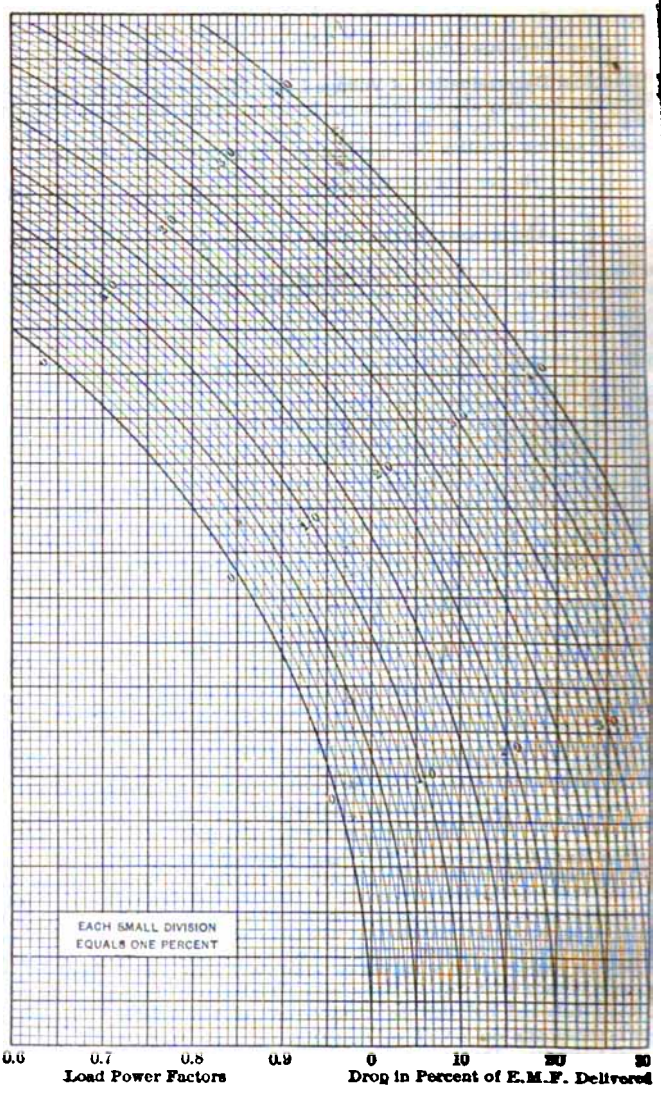


Fig. 3. Mershon's Chart for Calculating Drop in A-C. Line

e equivalent resistances and reactances of the line for the two phases, assuming the rents in the two outer wires to be exactly equal in effective value and to differ in phase exactly 90°, are

$$R_1 = (r + r_1 - x_1 + 0.0014f)\,l, \qquad X_1 = (x + x_1 + r_1)\,l,$$
$$R_2 = (r + r_1 + x_1 - 0.0014f)\,l, \qquad X_2 = (x + x_1 - r_1)\,l,$$

ere f is the frequency in cycles per second. When the wires are transposed only the m $0.0014f$ in the expressions for R_1 and R_2 go out, the other terms in the R's and X's aining unaltered. The voltages at the generator end for the two phases are then

$$E_1 = E\sqrt{\left(\cos\phi + \frac{R_1 I}{E}\right)^2 + \left(\sin\phi + \frac{X_1 I}{E}\right)^2},$$

$$E_2 = E\sqrt{\left(\cos\phi + \frac{R_2 I}{E}\right)^2 + \left(\sin\phi + \frac{X_2 I}{E}\right)^2}.$$

course, if the voltages E_1 and E_2 are maintained equal at the generator end, which is ally the case, the assumptions of equal currents and equal voltages at the load end are orrect, but the above formulas may be used to obtain an approximate value of the tage loss in the two phases. The unbalancing due to the unequal equivalent impedes of the two phases renders the two-phase three-wire system undesirable except for s in which the voltage loss is a small percentage of the voltage at the load, and the alancing therefore small.

DWIGHT'S TRANSMISSION LINE CHART.—The chart given in g. 3A, though approximate only, gives a simple and ordinarily sufficiently urate means for calculating the voltage drop or size of wire for any alterting-current, overhead transmission line which is not over 100 miles long. hen the resistance drop and the reactance drop are each under 15 per cent the line voltage, the error in the voltage drop as calculated by this chart is s than 0.5 per cent of the line voltage.

To use the chart, lay a straight edge across it from the proper spacing int to the proper size of wire, and read on the vertical scale corresponding to the given power factor the volts per mile per ampere; call this V. , vice versa, when the volts drop per mile per ampere V is known, lay straight edge across the chart from the proper spacing point to the given lue of V as read on the vertical scale corresponding to the given power tor, and read the size of wire on the right-hand vertical scale. A value of above the diagonal line on the chart corresponds to a "negative drop," ., an actual voltage rise. Let V = volts drop per mile per ampere, E = lts between wires at the receiver end, U = kilovolt-amperes delivered to e receiver, l = length of line, in miles. Then,

$$\text{Total drop, in per cent of } E = \frac{100{,}000\,U\,L\,V}{E^2} - 100\,K\left(\frac{l}{1{,}000}\right)^2$$

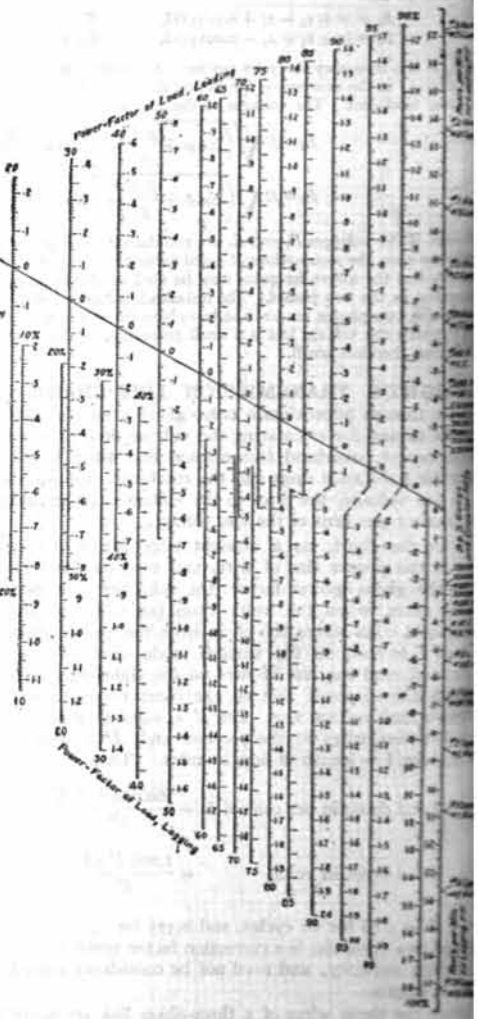
$$\text{Total drop, in volts} = \frac{1{,}000\,U\,l\,V}{E} - E\,K\left(\frac{l}{1{,}000}\right)^2$$

here K = 2.16 for 60 cycles, and 0.375 for 25 cycles. The last term in each these two formulas is a correction factor which takes into account the effect the line capacity, and need not be considered when the line is less than 30 iles in length.

When the three wires of a three-phase line are separated by distances a, b nd c, use as the effective spacing $s = \sqrt[3]{a\,b\,c}$. When the three wires are all the same plane, and the middle wire is at the distance a from each of the thers, use as the effective spacing $s = 1.26\,a$.

The above formulas are for two-phase and three-phase lines. For a single-

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3A. Dwight's Transmission Line Chart.

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Example.—Length of line, 100 miles; effective spacing, 8 feet; No. 3 copper, & S. gauge; load, measured at the receiver end, 3,000 kv-a., 66,000 volts, 90 per cent power-factor lagging, 3-phase, 60 cycles.

Lay a straight edge from the 8-ft. spacing point for copper conductor, 60 cycles, to the point for No. 3 copper on the right-hand vertical scale. It crosses the 90 per cent power-factor line at $V = 1.34$.

$$\text{Per cent drop} = \frac{100{,}000 \times 3{,}000 \times 100 \times 1.34}{66{,}000 \times 66{,}000} - \frac{100 \times 2.16}{100} = 7.07\%$$

The voltage rise at no load is 2.16 per cent.

The regulation at the receiver end, or change in voltage from full load to no load, is 9.23 per cent of E. The exact values of the voltage drop and regulation as calculated by the formulas on page 1786 are 7.08 per cent and 9.40 per cent. If the power factor had been leading instead of lagging, V would have been 0.70, and the drop would have been 2.66 per cent, as against the exact value of 2.51 per cent. In the above example, the errors due to the chart are less than 0.2 per cent of line voltage.

SINGLE END-CONDENSER METHOD. — This method assumes that the total current at the load end is equal to the actual load current plus (vectorially) the charging current which would be taken by a single condenser shunted across the line at the load end, the capacity of this condenser being taken equal to the total capacity of the line. This method gives too low a voltage at the generator end by approximately the same amount that the straight impedance

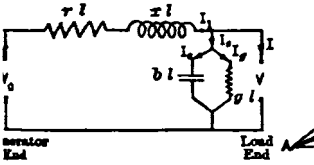


Fig. 4.

$\overline{AH} = I,$
$\overline{AC} = V,$
$\overline{AG} = I \cos \phi,$
$\overline{GH} = I \sin \phi,$
$\overline{HJ} = blV \times 10^{-6},$
$\overline{JK} = glV \times 10^{-6},$
$\overline{HK} = \gamma lV \times 10^{-6},$
$\overline{AK} = I_1 = I_0,$

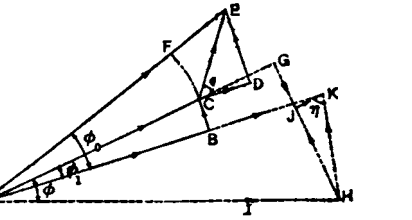


Fig. 4a.

$\overline{AB} = V \cos \phi_1,$
$\overline{BC} = V \sin \phi_1,$
$\overline{CD} = rlI_1,$
$\overline{DE} = xlI_1,$
$\overline{CE} = zlI_1,$
$\overline{AE} = V_0,$
$\overline{FE} = \eta,$

method gives it too high, and also gives the power loss too low by approximately the same amount that the straight impedance method gives it too high. By averaging the losses obtained by the two methods a close approximation to their true values is obtained.

Fig. 4 is a diagram of the circuit and Fig. 4a is a complete vector diagram of the voltage and current; voltages are shown by full lines and currents by dotted lines. The diagrams and formulas are for the general case of a line with leakage, but for nearly all practical cases the leakage may be neglected.

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The effect of the electrostatic capacity of the line is to change both the numerical value and the phase angle of the line current. Or, the condenser and the load may be looked upon as forming together an equivalent load taking a current I_1 at a power factor $\cos\phi_1$ differing from the actual current and power factor of the load. Let

V = volts to neutral at the load end of the line,
I = actual amperes per wire at the load end,
$\cos\phi$ = actual power factor at the load end,
$\sin\phi = \sqrt{1-\cos^2\phi}$ = actual reactive factor at the load end,
l = length of each line wire in miles,
b = capacity susceptance to neutral per mile of line, in micromhos, see tables in the article on *Capacity and Charging Current*,
g = leakage conductance to neutral per mile of line in micromhos, usually taken equal to zero in power lines, as explained above,
$y = \sqrt{g^2+b^2}$ = dielectric admittance to neutral per mile of conductor, in micromhos. Note that for no leakage $y = b$.

The total leakage current, total charging current and total exciting current of the line are then respectively

$$I_g = glV \times 10^{-6}, \qquad I_c = blV \times 10^{-6}, \qquad I_e = \sqrt{I_g^2 + I_c^2}. \tag{42}$$

The total line current, i.e., the resultant of the actual load current and the exciting current, is

$$I_1 = I\sqrt{\left(\cos\phi + \frac{I_g}{I}\right)^2 + \left(\sin\phi - \frac{I_c}{I}\right)^2}. \tag{43}$$

On the assumptions of this method of calculation I_1 is also the current at the generator end.

The power factor of the equivalent load formed by the actual load and the condenser is then

$$\cos\phi_1 = \frac{I\cos\phi + I_g}{I_1}, \tag{44}$$

and the reactance factor of this equivalent load is

$$\sin\phi_1 = \frac{I\sin\phi - I_c}{I_1}. \tag{45}$$

The formulas given above for the straight impedance method are then directly applicable, using for I, $\cos\phi$ and $\sin\phi$ in those formulas the values of I_1, $\cos\phi_1$ and $\sin\phi_1$ just calculated; i.e., the straight impedance method is to be applied not to the actual load but to the equivalent load formed by the actual load and a condenser having an admittance equal to the total admittance of the line.

Example of Calculation by Single End-Condenser Method. — Three-phase line, 50 miles long, No. 0000 A.W.G. stranded copper, 6 feet between centers, frequency 60 cycles, load 15,000 kilowatts, 60,000 volts between wires at load end, 80 per cent power factor at load. This is the same example as used above for the straight impedance method. Then $V = 34{,}600$, $I = 180$, $\cos\phi = 0.8$, $\sin\phi = 0.6$, $l = 50$, $b = 6.03$, $g = 0$, $r = 0.269$, $x = 0.728$. Then,

Charging current $= I_c = 6.03 \times 50 \times 34{,}600 \times 10^{-6} = 10.4$ amperes,

$$\text{Resultant current} = I_1 = 180\sqrt{(0.8)^2 + \left(0.6 - \frac{10.4}{180}\right)^2} = 174 \text{ amperes},$$

$$\text{Power factor of equivalent load} = \cos\phi_1 = \frac{180 \times 0.8}{174} = 0.828.$$

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e factor of equivalent load $= \sin\phi_1 = \dfrac{180 \times 0.6 - 10.4}{174} = 0.561$,

ıce of equivalent load per mile of line $= Z_1 = \dfrac{34{,}600}{50 \times 174} = 3.98$,

power loss $= Q = \dfrac{100 \times 0.269}{3.98 \times 0.828} = 8.16$ per cent,

voltage loss $= D$

$$\sqrt{\left(0.828 + \frac{0.269}{3.98}\right)^2 + \left(0.561 + \frac{0.728}{3.98}\right)^2} - 1 = 16.30 \text{ per cent},$$

ctor at generator end $= \cos\phi_0 = \left(\dfrac{100 + 8.16}{100 + 16.3}\right) \times 0.822 = 76.4$ per cent.

ent power loss and voltage loss obtained by the straight impedance lecting the line capacity are respectively 8.76 and 17.6 per cent. As e the single end-condenser method gives these losses too low (for ads) by approximately the same amount that the straight imped- d gives them too high, whence closer approximations to the true per cent power loss $= (8.16 + 8.76) \div 2 = 8.46$ and per cent voltage $+ 17.6) \div 2 = 17.0$.

ion of Effect of Synchronous Condenser. — Formulas (43) to lirectly to the calculation of the effect of a synchronous condenser f the line taking a current having an in-phase or energy component nd a quadrature leading component equal to I_c. Fig. 4a then repre- ctor relations of the currents and voltages, the vector JK being the nponent of the current taken by the synchronous condenser and HJ ure component.

CONDENSER OR OD. — This method the line may be con- alent to the circuit 5, which represents enser, having a ca- akage conductance ively to the total eakage conductance hunted across the

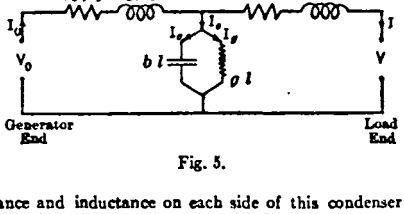


Fig. 5.

ddle point, the resistance and inductance on each side of this condenser spectively to half the total conductor resistance and inductance.

on of Fig. 5 will show that the half of the line nearest the load is represented mpedance in series with the load. Hence the voltage, current and power niddle point of the line may be figured by the straight impedance method Then, considering the voltage, current and power factor thus calculated ad at the middle point of the line, the second half of the line may be cal- single end-condenser method just described.

proper values (which are somewhat complicated functions of the actual and the frequency) to the constants of the "T" circuit shown in Fig. 5, y be made *exactly equivalent*, as far as the relations between the voltage, wer at the two ends are concerned, *to a line of any length and for any fre-* orrected" constants are entirely independent of the voltage, current and the load; see p. 1683.

the "T" Circuit in Symbolic Notation. — The solution of the circuit is also given below in terms of complex quantities (*see under Symbolic article on Alternating Currents*). Let

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V = numerical value of volts to neutral at the load end of the line,
I = amperes per wire at the load end of the line, taken as the vector of reference,
$\cos\phi$ = power factor at the load end of the line,
$\dot{V} = V\cos\phi + jV\sin\phi$ = volts to neutral at the load end of the line, referred to the current at the load end,
$\dot{z} = r + jx$ = conductor impedance in ohms per mile of wire, r being the resistance per mile and x the reactance per mile,
$\dot{y} = g + jb$ = dielectric admittance, one wire to neutral, in micromhos per mile of line, where g is the leakage conductance per mile and b the capacity susceptance per mile,
l = length of each wire in miles.

Put

$$\dot{M} = 10^{-6}\dot{y}\dot{z}l^2 = [(gr - bx) + j(br + gx)]\,10^{-6}l^2. \qquad (a)$$

Then the current at the generator end, in symbolic notation, is

$$\dot{I}_0 = (1 + \tfrac{1}{2}\dot{M})\,I + 10^{-6}\dot{y}\dot{V}, \qquad (c)$$

and the volts to neutral at the generator end, in symbolic notation, are

$$\dot{V}_0 = (1 + \tfrac{1}{2}\dot{M})\,\dot{V} + \dot{z}l\,(1 + \tfrac{1}{4}\dot{M})I. \qquad (d)$$

Calling I_0' and I_0'' the real and "j" components respectively of the current $\dot{I}_0$, and V_0' and V_0'' the real and "j" components of the voltage $\dot{V}_0$, then the numerical values of the current and voltage at the generator end are

$$I_0 = \sqrt{(I_0')^2 + (I_0'')^2}, \quad \text{and} \quad V_0 = \sqrt{(V_0')^2 + (V_0'')^2}, \qquad (e)$$

and the power input per wire at the generator end is

$$P_0 = V_0'I_0' + V_0''I_0''. \qquad (f)$$

In applying this last formula particular attention must be paid to the signs of the quantities involved, e.g., if $\dot{V}_0 = 1000 + j\,300$ and $\dot{I}_0 = 100 - j\,20$, then $V_0' = 1000$, $V_0'' = 300$, $I_0' = 100$ and $I_0'' = -20$, and $P_0 = 1000 \times 100 - 300 \times 20$. The power factor at the generator end is

$$\cos\phi_0 = \frac{P_0}{V_0I_0}. \qquad (g)$$

SPLIT-CONDENSER OR "π" OR "U" METHOD. — This method assumes that the line may be considered equivalent to the circuit shown in Fig. 6, which represents a single impedance in series with the load, the resistance and inductance of this impedance being equal respectively to the total conductor resistance and inductance of the line, and a condenser shunted across the line at each end, each condenser having a capacity and leakage conductance equal respectively to half the total capacity and half the total leakage conductance of the line.

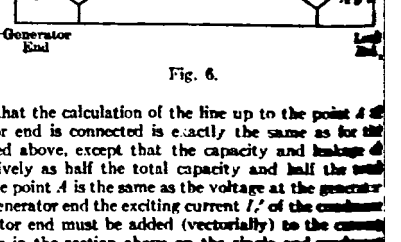


Fig. 6.

An inspection of Fig. 6 will show that the calculation of the line up to the point A at which the condenser at the generator end is connected is exactly the same as for the single end-condenser method described above, except that the capacity and leakage of the end condenser are taken respectively as half the total capacity and half the total leakage of the line. The voltage at the point A is the same as the voltage at the generator end, but to find the current I_0 at the generator end the exciting current I_1' of the condenser shunted across the line at the generator end must be added (vectorially) to the current I_1 at A. Using the same notation as in the section above on the single end-condenser method, the total generator current is then

$$I_0 = I_1\sqrt{\left(\cos\phi_0 + \frac{I_1'}{I_1}\right)^2 + \left(\sin\phi_0 - \frac{I_1''}{I_1}\right)^2},$$

where

$$I_1' = \tfrac{1}{2}gV_0 \times 10^{-6} \quad \text{and} \quad I_1'' = \tfrac{1}{2}bV_0 \times 10^{-6}.$$

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e case of the "T" circuit, a "π" circuit, such as shown in Fig. 6, may be given ected" constants as will make it exactly equivalent for any one frequency, as terminal conditions are concerned, to a line of any length whatever no matter his frequency may be; see p. 1787.

of the "π" Circuit in Symbolic Notation. — Using the same notation ction above on the *Solution of the "T" Circuit in Symbolic Notation*, and cal- e quantity M by the same formula, viz., equation (46), the current and voltage rator end in symbolic notation are respectively

$$\dot{I}_0 = (1 + \tfrac{1}{2}\dot{M})\,\dot{I} + 10^{-6}\dot{y}\,(1 + \tfrac{1}{4}\dot{M})\,\dot{V}, \qquad (52)$$

$$\dot{V}_0 = (1 + \tfrac{1}{2}\dot{M})\,\dot{V} + z\dot{I}. \qquad (53)$$

ical values of these quantities, the power and the power factor are then to be n the same manner as for the "T" circuit, viz., by formulas (49) to (51).

CALCULATION OF A-C. LINES OF ANY LENGTH AND NCY.* — The charging current (and also the leakage current) for any a transmission through only on of the line between the ient and the end. The ex- ination of the , voltage and y point there- es that this ken into ac- other words y and leak- line are dis- d not lumped in the above calculation. shown three elements of a line, a re- tral of zero being also omplete the s method of rately each ine is fully ove, p. 1668.

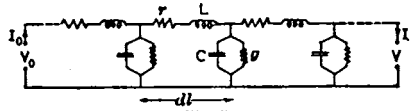


Fig. 7.

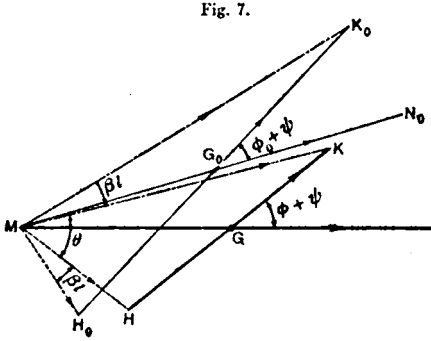


Fig. 7a.

$\overline{MN} = I,$	$\overline{MK}_0 = Ae^{\alpha l},$
$\overline{HK} = YV,$	$\overline{MH}_0 = Be^{-\alpha l},$
$\overline{MK} = A,$	$\overline{MN}_0 = I_0,$
$\overline{MH} = B,$	$\overline{H_0K}_0 = YV_0.$

o make clear the physical meaning of the various terms employed, olution is first given in terms of instantaneous values. Following the working formulas (1) in terms of exponentials, viz., ϵ^x and ϵ^{-x}, of real hyperbolic functions, and (3) in terms of hyperbolic func- lex angles.

uations of Transmission Line. — Let l = the distance in miles of any ransmisaion line, measured from any arbitrarily chosen point (say from let i = the instantaneous current in amperes in the conductor at this sitive in the direction *opposite* to that in which l is measured (i.e., positive load end); let v = the potential drop in volts between this point and the t r = the conductor resistance in ohms per mile, L = the inductance of n henries per mile, C = the capacity to neutral in microfarads per mile

s section is abstracted from the lecture notes of Dr. H. Pender.

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and g = the leakage conductance to neutral in micromhos per mile. The following relations then hold at any point along the line, t being time in seconds measured from an arbitrarily chosen instant:

$$\frac{dv}{dl} = ri + L\frac{di}{dt}, \tag{5}$$

$$10^6\frac{di}{dl} = gv + C\frac{dv}{dt}. \tag{6}$$

If the circuit is composed of two or more sections of different constants (e.g., an overhead section and an underground section, or a circuit formed by a step-up transformer, transmission line and a step-down transformer) then a similar set of equations holds for each section of the circuit, the constants r, L, g, and C being in general different for the several sections.

The complete solution of any two equations of the form given by (54) and (55) consists of an infinite series of terms for both v and i, corresponding terms in the two series having the following values:

$$i = \sqrt{\frac{2}{}}\, e^{-(\alpha-\epsilon)t}\left[Ae^{\alpha l}\sin(\omega t+\beta l+\theta_1) + Be^{-\alpha l}\sin(\omega t-\beta l+\theta_2)\right], \tag{5'}$$

$$v = \frac{\sqrt{2}}{Y} e^{-(\alpha-\epsilon)t}\left[Ae^{\alpha l}\sin(\omega t+\beta l+\theta_1-\psi) - Be^{-\alpha l}\sin(\omega t-\beta l+\theta_2-\psi)\right]. \tag{6'}$$

Physical Interpretation and Names Given to the Various Constants. — The constant ω in equations (56) and (57) is equal to $2\pi f$, where f is the frequency of the oscillation represented by these equations. In the most general case any change in the circuit conditions, such as closing or opening a switch, or a lightning stroke in the vicinity of the circuit, may set up an infinite number of oscillations of different frequencies, their frequency being determined by the initial conditions at the instant the change is made. The current and voltage set up by each oscillation is represented by a set of terms of the form given by (56) and (57), and the resultant current and voltage will be respectively the sum of all the current terms and the sum of all the voltage terms. The oscillation of any given frequency, however, may be considered separately, as it is uninfluenced by the presence of the other oscillations. Moreover, in the case of a composite circuit, consisting say of a step-up transformer, transmission line and step-down transformer, if an oscillation of frequency f is set up in one part of the circuit it will also appear in all other sections of the circuit, though it may be greatly damped in these sections and therefore produce no appreciable effect.

Attenuation Constant (α), Wave Length Constant (β), Wave Length λ and Velocity of Propagation (U). — Referring to equations (56) and (57) each oscillation sets up in each section of the circuit two waves, each of which has a wave length $\lambda = \frac{2\pi}{\beta}$; the constant β is therefore called the "wave length constant;" it is a function of the frequency and of the constants r, L, g and C of the circuit. The two waves travel along the line in opposite directions each with a velocity $U = \frac{\omega}{\beta}$; in a composite circuit this velocity U is in general different for each section of the circuit. One wave may be looked upon as the "incident" and the other as the "reflected" wave. The amplitude of each wave diminishes by the factor e^{α} as the wave travels unit distance; the factor e^{α} is called the "attenuation factor" and the constant α is called the "attenuation constant." The attenuation constant is a function of the frequency and the constants r, L, g and C of the circuit; see p. 1784.

Surge Admittance (Y) and its Power-factor Angle (ψ). — The constant Y, which is equal to the quotient of the amplitude (or r.m.s. value) of the incident current wave by the incident voltage wave, is called the "surge admittance" and its reciprocal is called the "surge impedance"; it is a function of the frequency and the constants r, L, g and C of the circuit; see p. 1784. The constant ψ, which is equal to the angle by which the incident current wave leads the incident voltage wave, is called the "power-factor angle of the surge admittance"; it is a function of the frequency and the constants r, L, g and C, see p. 1785.

Amplitude Constants (A and B) and Phase-Angle Constants (θ_1 and θ_2). — The constants are equal to the amplitudes of the incident and reflected current waves at the point from which the distance l is measured, and the constants θ_1 and θ_2 give the

ese two waves at this point ($l = 0$) at the instant from which time is measured ote that the incident current wave at $l = 0$ leads the reflected current wave le $\theta = \theta_1 - \theta_2$. The determination of these constants for steady state condi- en on p. 1785.

ural Damping Constant (u), Energy Transfer Constant (s) and Com- nping Constant ($u - s$). — In the general case of a natural oscillation in circuit the amplitude of each wave diminishes in unit time by the factor factor is called the "composite damping factor," and the constant $(u - s)$ e "composite damping constant." The composite damping constant, like cy f, is the same for all sections of a composite circuit. In the case of a line onstants throughout, not connected to any terminal apparatus, it can readily hat $s = 0$, in which case the amplitude of the oscillations diminishes in unit factor ϵ^{u}; this factor is therefore called the "natural damping factor" and u, which for a section having the constants r, L, g and C per unit length,

$$u = \frac{1}{2}\left(\frac{r}{L} + \frac{g}{C}\right), \tag{58}$$

natural damping constant." Any section of a composite circuit for which the ng $\epsilon^{(u-s)}$ is less than the natural damping ϵ^{u} must receive energy from some ; consequently a positive value of s for a given section means that energy into this section from some other section of the circuit. Similarly, a nega- s for a given section means that energy is transferred from this section to ection. The constant s may therefore be called the "energy transfer con- e the voltage and current in the circuit cannot increase indefinitely the er constant s can never have a positive value greater than u.

composite damping constant $(u - s)$ is the same for all sections of a circuit, t the transfer of energy from one section to another by oscillations in a com- will always be into the section in which u is the larger from the section in e smaller. Neglecting the leakage conductance g, this means that energy will into section 1 from section 2, when $\frac{r_1}{L_1}$ is greater than $\frac{r_2}{L_2}$, that is, energy from the section of the larger "time constant" $\left(\frac{L_2}{r_2}\right)$ to that of the smaller nt" $\left(\frac{L_1}{r_1}\right)$. When the resistances are small, this means that in the limiting nergy ($= \frac{1}{2} L_2 I^2$) of the magnetic field of the second section may go into nergy ($= \frac{1}{2} C_1 V^2$) in the first section, producing therefore a very high volt- ction point when the inductance L_1 of the second section is large compared city C_1 of the first section. This accounts for the very high voltages some- luring switching operations at the junction point of an overhead line with d line, or in a transformer connected to a long overhead line.

tate" Conditions in a Transmission Line. — From the above discussion at when a sufficient time (usually a small fraction of a second) has elapsed ge in the circuit conditions, the only terms left in the general equations ion line for a given impressed sine-wave voltage of frequency f are those , viz.,*

$$\sqrt{2}\left[A\epsilon^{\alpha l}\sin(\omega t + \beta l) + B\epsilon^{-\alpha l}\sin(\omega t - \beta l - \theta)\right] \tag{59}$$

$$\frac{\sqrt{2}}{Y}\left[A\epsilon^{\alpha l}\sin(\omega t + \beta l - \psi) - B\epsilon^{-\alpha l}\sin(\omega t - \beta l - \theta - \psi)\right]. \tag{60}$$

alue of the current at any point is then equal to the sum of two vectors ths $A\epsilon^{\alpha l}$ and $B\epsilon^{-\alpha l}$, the former leading the latter by the angle $(\alpha\beta l + \beta)$, e value of the voltage is equal to the difference of these same two vectors The phase angle between the voltage and current is equal to the phase he sum and difference of the A and B vectors less the angle ψ.

state conditions time may be counted from any arbitrarily chosen interval, ons (56) and (57) may be put equal to zero, and for convenience $-\theta$ may

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Notation for Steady State Conditions. — These relations are clearly shown in the vector diagram, Fig. 7a, which is a complete vector diagram of a transmission line with distributed capacity and leakage. The four constants α, β, Y and ψ are constants of the line, independent of the load, and are expressed in terms of the ordinary line constants as follows: Let

f = frequency in cycles per second,

r = conductor resistance per mile, in ohms; see tables in article on *Wire and Cables, Bare*,

$x = 2\pi fL$ = conductor reactance per mile, in ohms, corresponding to the impressed frequency f; see tables in article on *Inductance and Inductive Reactance*,

$z = \sqrt{r^2 + x^2}$ = conductor impedance per mile, in ohms,

g = leakage conductance to neutral per mile of line, in micromhos; see above, p. 1667. For power lines g is usually taken equal to zero.

$b = 2\pi fC$ = capacity susceptance to neutral per mile of line, in micromhos, corresponding to the impressed frequency f; see tables in article on *Capacity and Charging Current*,

$y = \sqrt{g^2 + b^2}$ = dielectric admittance per mile, in micromhos; when $g = 0$, then $y = b$,

$\alpha = 10^{-3}\sqrt{\dfrac{yz - bx + gr}{2}}$ = the attenuation constant; for r and g small compared with x and b this reduces to $\dfrac{10^{-3}}{2}\left(r\sqrt{\dfrac{C}{L}} + g\sqrt{\dfrac{L}{C}}\right)$.

$\beta = 10^{-3}\sqrt{\dfrac{yz + bx - gr}{2}}$ = the wave length constant; for r and g small respectively compared with x and b this reduces to $2\pi f \times 10^{-3}\sqrt{LC}$, which for an overhead line equals approximately $\dfrac{2\pi f}{180{,}000}$,

$Y = 10^{-3}\sqrt{\dfrac{y}{z}}$ = surge admittance; for r and g small respectively compared with x and b, this reduces to $10^{-3}\sqrt{\dfrac{C}{L}}$. The reciprocal of the surge admittance is called the "surge impedance,"

$\psi = \tan^{-1}\sqrt{\dfrac{yz - bx - rg}{yz + bx + rg}}$ = the power-factor angle of the surge admittance, taken positive for $gx < br$ and negative for $gx > br$. For r and g small compared with x and b, then $\psi = 28.7\left(\dfrac{r}{x} - \dfrac{g}{b}\right)$ degrees.

$U = \dfrac{2\pi f}{\beta}$ = velocity of propagation in miles per second; for a frequency sufficiently high to make r negligible compared with x, and g negligible compared with b, this reduces to $\dfrac{10^3}{\sqrt{LC}}$, which for an overhead line with wires far apart is equal to the velocity of light in air, viz., 180,000 miles per second, approximately,

$\lambda = \dfrac{2\pi}{\beta} = \dfrac{U}{f}$ = wave length of each wave in miles; for a frequency f sufficiently high to make r negligible compared with x, and g negligible

compared with b, this reduces to $\frac{10^5}{f\sqrt{LC}}$, which for an overhead line is equal approximately to $\frac{180{,}000}{f}$ miles.*

a the vector diagram and in the formulas given below, let

l = length of the line in miles,
I = effective (r.m.s.) value of the amperes per wire at the load end,
V = effective (r.m.s.) value of the volts to neutral at the load end,
ϕ = the power-factor angle at the load end, i.e., $\cos\phi$ is the power factor at the load end. ϕ is taken positive for a lagging and negative for a leading current,
I_0, V_0, ϕ_0 = corresponding quantities at the generator end.

Solution by Vector Diagram (Fig. 7a). — Having calculated the constants α, β, Y and ψ, and knowing the current I, voltage V and power-factor le ϕ of the load,

Lay off $\overline{MN} = I$ as the base line, and bisect it at G,

At the angle $(\phi + \psi)$ ahead of $\overline{MN}$ lay off the line $\overline{HK}$ equal in length to YV, so that it is also bisected by G,

Then measure off $\overline{MK} = A$ and $\overline{MH} = B$,

Lay off at the angle 57.3 βl degrees ahead of A the line $\overline{MK_0}$ equal in length† to $Ae^{\alpha l}$,

Lay off at the angle 57.3 βl degrees behind B the line $\overline{MH_0}$ equal in length to $Be^{-\alpha l}$,

Bisect H_0K_0 at G_0.

Then the line $\overline{MN_0} = 2\,\overline{MG_0}$ is equal to the current at the generator end,

The line $\overline{H_0K_0}$ divided by Y is equal to the voltage at the generator end,

The angle between $\overline{G_0N_0}$ and $\overline{G_0K_0}$ less the angle ψ is the power-factor angle at the generator end.

Note that the voltage at the load end if drawn in the diagram would be at angle ψ behind the vector $\overline{GK}$, and at the generator end would be at the le ψ behind $G_0\overline{K_0}$.

Algebraic Solution for Steady-state Conditions. — The vector diam may be solved algebraically as follows: Calculate first the constants A, nd θ from the formulas:

$$A = \tfrac{1}{2}\sqrt{I^2 + (YV)^2 + 2\,YVI\cos(\phi+\psi)}, \tag{61}$$

$$B = \tfrac{1}{2}\sqrt{I^2 + (YV)^2 - 2\,YVI\cos(\phi+\psi)}, \tag{62}$$

$$\theta = \tan^{-1}\left[\frac{2\,YVI\sin(\phi+\psi)}{I^2 - (YV)^2}\right]. \tag{63}$$

te that $\sin\theta$ has the same algebraic sign as the numerator of this fraction l $\cos\theta$ his the same algebraic sign as the denominator of this fraction; this s the quadrant in which θ lies.

Put $$A_0 = Ae^{\alpha l}, \quad \text{and} \quad B_0 = Be^{-\alpha l}. \tag{64}$$

* The above formulas for s, y, α, β, Y, ψ, U and λ also hold for the transient or free illations in a single circuit, and also for each section of a composite circuit, provided hese formulas $r_1 = r\,(u - s)\,L$ is substituted for r and $g_1 = g + (u - s)\,C$ is substied for g.

† See the table in the article on *Exponential Functions* for values of e^x and e^{-x}, where x any number.

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The current, voltage and power-factor angle at the generator end are, then, expressing all angles in degrees,

$$I_0 = \sqrt{A^2 + B^2 + 2AB\cos(114.6\beta l + \theta)},$$

$$V_0 = \frac{1}{Y}\sqrt{A^2 + B^2 - 2AB\cos(114.6\beta l + \theta)},$$

$$\phi_0 = \tan^{-1}\left[\frac{2AB\sin(114.6\beta l + \theta)}{A^2 - B^2}\right] - \psi.$$

Note that the quadrant in which $(\phi_0 + \psi)$ lies is determined by the algebraic signs of the numerator and denominator of the fraction in the brackets, just as in the case of the angle θ.

Solution of Steady State Conditions in Terms of Hyperbolic Functions.[1] — The above expressions for the current, voltage and power factor at the generator may also be put in the form,

$$I_0 = I\sqrt{\frac{\cosh(2\alpha l + \gamma) + \cos(114.6\beta l + \theta)}{\cosh\gamma + \cos\theta}},$$

$$V_0 = V\sqrt{\frac{\cosh(2\alpha l + \gamma) - \cos(114.6\beta l + \theta)}{\cosh\gamma - \cos\theta}},$$

$$\phi_0 = \tan^{-1}\left[\frac{\sin(114.6\beta l + \theta)}{\sinh(2\alpha l + \gamma)}\right] - \psi,$$

where θ and γ are given by the formulas

$$\gamma = \tanh^{-1}\left[\frac{2YVI\cos(\phi + \psi)}{I^2 + (YV)^2}\right],$$

$$\theta = \tan^{-1}\left[\frac{2YVI\sin(\phi + \psi)}{I^2 - (YV)^2}\right].$$

The other quantities are as above defined. Note that θ is the same angle as given by equation (63) and the quadrant in which it lies is to be determined as described in the note under (63). Also note that the constant γ given by (71) may be expressed in terms of A and B, given by (61) and (64), by means of the formula

$$\gamma = \log_e\left(\frac{A}{B}\right) = 2.302\log_{10}\left(\frac{A}{B}\right).$$

Formulas for Open Circuit and Short Circuit at Load End. — When the line is open at the load end, $I = 0$, whence from equations (61) to (63), $A = \frac{1}{2}VY$, $B = \frac{1}{2}VY$, and $\theta = 180°$ (since the denominator of the fraction is negative). When the line is short-circuited at the load end, $V = 0$, and $A = \frac{1}{2}I$, $B = \frac{1}{2}I$, and $\theta = 0°$ (since the denominator of the fraction is positive). The current, voltage and power-factor angle at any point along the line may then be found in either case by substituting these values in equations (65) to (67) which reduce to the simple hyperbolic forms:

On open circuit	On short circuit
$I_0 = YV\sqrt{\sinh^2(\alpha l) + \sin^2(57.3\beta l)}$	$I_0 = I\sqrt{1 + \sinh^2(\alpha l) - \sin^2(57.3\beta l)}$
$V_0 = V\sqrt{1 + \sinh^2(\alpha l) - \sin^2(57.3\beta l)}$	$V_0 = \frac{I}{Y}\sqrt{\sinh^2(\alpha l) + \sin^2(57.3\beta l)}$
$\phi_0 = -\tan^{-1}\left[\frac{\sin(114.6\beta l)}{\sinh(2\alpha l)}\right] - \psi$	$\phi_0 = +\tan^{-1}\left[\frac{\sin(114.6\beta l)}{\sinh(2\alpha l)}\right] - \psi$

[1] Tables of hyperbolic functions are given in the article on *Hyperbolic Functions*.

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lution of Steady-state Equations in Complex Hyperbolic Functions.* — all quantities other than the length l in symbolic notation (*see Alternating* the equations of the transmission line for *steady state conditions only*, may

$$\dot{I}_0 = \dot{I} \frac{\sinh (l\sqrt{\dot{y}\dot{z}} + \dot{B})}{\sinh \dot{B}}, \tag{74}$$

$$\dot{V}_0 = \dot{V} \frac{\cosh (l\sqrt{\dot{y}\dot{z}} + \dot{B})}{\cosh \dot{B}}, \tag{75}$$

ymbols other than $\dot{B}$ have the same meanings as above, except that they are l as complex quantities and

$$\dot{B} = \tanh^{-1} \left(\frac{\dot{I}}{\dot{V}} \sqrt{\frac{\dot{z}}{\dot{y}}} \right) \tag{76}$$

t of $\sqrt{\dot{y}\dot{z}}$ is the attenuation constant and the imaginary or "j" part is the constant.

rously Equivalent "T" and "π" Circuits. — As noted above the middle "T" circuit, Fig. 5, or the split condenser or "π" circuit, Fig. 6, is rigorously the actual transmission line when proper values are assigned to the constants nits. The corrected values z' and y' of the impedance per mile and of the er mile are, in symbolic notation, as follows:

"T" circuit	"π" circuit
$\dot{z}' = \dot{z} \dfrac{\tanh \left(\frac{l\sqrt{\dot{y}\dot{z}}}{2} \right)}{\frac{l\sqrt{\dot{y}\dot{z}}}{2}}$	$\dot{z}' = \dot{z} \dfrac{\sinh (l\sqrt{\dot{y}\dot{z}})}{l\sqrt{\dot{y}\dot{z}}}$
$\dot{y}' = \dot{y} \dfrac{\sinh (l\sqrt{\dot{y}\dot{z}})}{l\sqrt{\dot{y}\dot{z}}}$	$\dot{y}' = \dot{y} \dfrac{\tanh \left(\frac{l\sqrt{\dot{y}\dot{z}}}{2} \right)}{\frac{l\sqrt{\dot{y}\dot{z}}}{2}}$

ly's tables above referred to are given tables of these correction fractions.

S AFFECTING THE MECHANICAL DESIGN. — In design- ssion line the following factors, in addition to the line losses, must l: (1) right-of-way, (2) telephone circuits, (3) ground wires, (4) ;) type of supporting structure, (6) type of insulators, (7) con- emperature range, (9) collection of ice, (10) wind velocity and wind ie requirements imposed by these several conditions are noted be- ler mentioned; this is followed by the formulas and curves neces- the required calculations.

ınd Width of Right-of-way. — The right-of-way should be as straight as practicable. Its width for a single line should be equal of space over which the conductors normally hang, plus twice the conductors under maximum wind, plus twice the safe clearance or to possible buildings adjacent to the right-of-way. In com- e swing allowance must be made for swing of suspension insula- ing of conductor should be based on the longest span ordinarily

bles and charts of such functions have been published by Prof. A. E. Ken- *Complex Hyperbolic and Circular Functions*, Harvard University Press,

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used, and extra width should be secured wherever extraordinarily long spans are made. For telephone lines on separate poles extra width will be required unless the power wires are high enough to swing safely over them. Where two power lines are on one right-of-way the towers for the two lines should be located directly opposite each other, especially on long spans, since the two lines may then be placed close together with less danger of the wires of the two lines swinging together. However, it is usually desirable to have the lines far enough apart so that the towers of one line may fall without striking those of the other line. The right-of-way should be passable (or at least accessible) for patrolling as well as for construction.

When it is necessary that the right-of-way cross railroads, roads or other lines the length of crossing should be reduced to a minimum by making the crossing at as near right angles as practicable. Rights-of-way through swamps often require expensive road building and expensive tower foundations, though small swamps (up to about 1000 feet across) can often be crossed in a single span. Steep side hills require extra expense for foundations and tower extensions, and introduce a hazard of injury to tower from sliding earth, rocks, trees or snow. A right-of-way through forests requires expensive clearing.

It is usually advantageous to own and fence the right-of-way. However, when the right-of-way passes through farm lands, it is sometimes advantageous not to fence it in, but to have it cultivated and kept free from brush. Instead of purchasing a right-of-way, it is often sufficient to obtain easements covering the location of towers and suspension of wires. Easements should include the right to remove and trim trees under and adjacent to the line.

Telephone Circuits for Power Lines. — When the line voltage does not exceed 66,000 volts, the telephone circuits are usually carried on the same poles or towers as the power circuits, being placed below the power conductors. A separate line of wooden poles on the same right-of-way is usually employed when the voltage is higher than 66,000.

Where the telephone wires are on the same supporting structure as the power wires, sufficient clearance between the power and telephone circuits must be allowed to make the telephone line accessible for repairs and also to prevent the two circuits touching under abnormal conditions. On wood pole lines of short span (100 to 125 feet) the vertical clearance at the poles or towers ranges from 4 feet for 22,000 volts to 6 feet for 66,000 volts. On long span lines greater spacing is necessary to allow for safe clearance in the middle of the longest span due to the change in the sag of the power and telephone wires under all conditions of unequal ice loading and all variations of side deflection due to wind.

Telephone wires are ordinarily of copper, though copper-clad steel is sometimes used for long spans. For spans up to 125 feet No. 10 B. & S. copper may be used (though No. 8 is preferable) while for longer spans larger sizes (usually No. 8 or No. 6 or even No. 4) are necessary to allow for sleet load. A spacing of 12 inches between wires may be used for 125-foot spans, but a wider spacing is necessary for longer spans. Where inadequate spacing is used the telephone lines will frequently become crossed by the wind, unless they are strung with little sag, in which case they are overloaded and broken by sleet. With wide spacing and large sag higher poles must be used.

Ground Wires. — Grounded cables or wires are placed above the transmission line circuits to protect the latter from lightning discharges (*see Lightning Protectors*). They are usually grounded at each supporting structure except where short spans are used. The same care must be exercised to obtain clearances between conductors and ground cables or wires, as outlined above under telephone circuits. For tower lines having flexible towers and single-circuit towers having conductors arranged in a horizontal plane, two ground cables are

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le, but for double-circuit tower lines either one or two may be used. As l rule a line drawn through the ground cable and any conductor should : an angle of more than 45 degrees with the vertical.

nces. — The following clearances require determination: conductor d; to edge of right-of-way; to tower; to ground wire; to telephone other conductors.

inimum clearance from the high-voltage wires to the surface of the ordinarily 20 feet or more, and from the telephone wires on towers igh-voltage wires is 18 feet to ground. The minimum clearance from to the edge of the right-of-way or to the tower, under maximum swing ors and cables in the wind, should exceed the striking distance corre- to the arc-over voltage of the insulators used. The minimum clear- een conductors, under extreme conditions of unequal ice loading (*see* uld exceed the striking distance of the normal voltage by a factor of at least two. The normal clearance between conductors should be ter than this, and is ordinarily from 10 inches to 1 foot per 10,000 volts ires.

Supporting Structure. — (*See also Poles for Overhead Lines; Cross ms.*) Wood poles are usually the cheapest form of supporting r lines up to about 66,000 volts. Most lines of voltage over 66,000 ines of lower voltage are supported on steel towers.

line of poles or towers may support one, two and occasionally more Where several circuits are required two or more single-circuit tower conductors arranged in a horizontal plane have the advantage that of an accident will usually be confined to one circuit, and that one safely be repaired with another circuit alive, but this arrangement maximum width of right-of-way. Where it is important to use the economically two-circuit towers having the conductors of each cir- d in vertical planes on each side of the tower are used.

es are ordinarily placed from 100 to 200 feet apart and steel towers 800 feet apart. The span for steel tower lines is ordinarily chosen ler the sum of the costs of all of the items a minimum, and is usually within the limits mentioned.

or towers ordinarily used where the line is straight are designed to ight of the conductors with sleet and the side pressure of wind on ot to resist the tension in the conductors which is assumed to be rtially balanced. Such towers are called standard, straight line l towers. Heavier towers designed to resist the unbalanced tension ables (which may occur if the cables are broken on the other side of called anchor or dead-end towers, are used at intervals of from pans where the line is straight. Heavier towers designed to resist ed lateral resultant of the tension in the cables are also used at re known as angle towers. For economy in design and manufac- and angle towers (for any angle up to about 60°) are usually made ble. Where towers are not very high, economy is often secured by towers intermediate between square anchor and angle towers. On nes extra strong poles guyed or braced in all four directions, with arms and double pins and insulators, are used for anchoring the line

nsulators. — (*See also Insulators.*) Pin insulators are usually used p to 50,000 and suspension insulators for higher voltages. Suspen- s are sometimes used for lower voltage where a high factor of safety or the lower voltages the cost of the line is usually less for pin than n insulators. The suspension insulator requires a higher tower

than the pin insulator, for the conductor is below the cross arm, and a longe cross arm is also required to allow for the swing of the insulators in the wind

Conductors for Overhead Lines. — (*See also Wires and Cables.*) Copper, aluminum or steel, or combinations of the two former with steel, are used for line conductors. The use of an all-steel conductor is limited to those cases where great mechanical strength is required, although some economy is claimed for it when high voltages are used and a conductor of large diameter is required on account of corona (*see Corona*). Conductors consisting of a steel center with copper or aluminum outside are used where long spans are desirable and mechanical strength of conductor is required, and may also be used where large diameter is required to prevent corona formation. The maximum stress in wires and cables should not exceed the elastic limit. This condition is ordinarily met if a factor of safety of two, based on the ultimate strength, is used.

Distribution of Stress in Stranded Conductors. — Conductors for long spans are usually stranded when larger than No. 6 B. & S. gage, on account of the tendency to crystallize at the points of support, due to swinging in the wind. However, the maximum size of solid conductor which may be used is dependent largely upon the kind of support; if these are designed to prevent sharp bending, solid conductors, larger than No. 6, may be used. One difficulty in the use of a stranded cable is that for a given total tension in the cable the wires in the various layers are not all stressed equally. In particular, the center wire or core, if of metal, takes more than its share of the tension. On this account the actual sag in the cable when suspended may differ from that calculated, unless an allowance is made for the unequal tension in the various wires composing the cable. One method of avoiding this difficulty is to stress the cable, before stringing it, to a tension per square inch corresponding to the elastic limit of the component wires; the center wire will then be given a permanent set and when the cable is again stressed each of the component wires will tend to take the same proportion of the total tension.

Cables having centers or cores of a different material than the outside strands should be so designed that both materials share the stress over the operating range of temperatures, to such extent as is possible. The properties of steel-core aluminum cables and the method of considering stresses therein are given in the article on Wires and Cables, Bare.

The distribution of stress among the wires of which conductors may be composed applies more particularly to long spans where clearances are important and it is necessary to use small deflections compared to lengths of spans. For all ordinary construction, having spans of 500 to 600 feet or less, a very slight change in either thickness of ice or amount of wind pressure on the conductor will affect results as much as the error resulting from not taking into consideration the distribution of stresses in conductors.

Mechanical Characteristics of Conductor Materials. — For purposes of design both elastic limit and modulus of elasticity of cables should be obtained from tests on samples of the cables actually to be used, since errors in these materially affect the accuracy of the calculations of deflections in spans. The modulus of elasticity of cables varies widely with the number of wires and their pitch or lay in the different layers. Table I shows the values of these quantities and also of the other mechanical properties of conductors commonly used in design, when specific test results are not available. See also the articles on *Aluminum; Copper; Strength and Elasticity; Wires and Cables, Bare.*

Temperature Range. — The maximum and minimum air temperatures which have occurred in any locality for a period of years can be obtained from the records of the United States Weather Bureau, or from similar records for other countries. The minimum air temperature recorded (which may be as

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TABLE I

ACTERISTICS OF WIRES AND CABLES

Copper	Aluminum	Steel
,000	25,000–50,000	60,000–80,000
	11,000–14,000	35,000–40,000
	7×10^6–10×10^6	22×10^6–28×10^6
	12.8×10^{-6}	6.6×10^{-6}
3.09	0.92	2.67

me of the northern states) will be the minimum temperature ctor may be expected to reach. However, since the conduc- d to the direct rays of the sun, they will reach a maximum temper- e summer considerably in excess of the Weather Bureau records, ve the temperatures in the shade.

ther important temperature which should be determined is that of the when coated with ice. As noted below, a sleet storm is usually followed by ll in temperature, and although the ice forms at 32° F., the wire may reach uch lower temperature while the ice is on it.

The following temperature ranges have been used in the design of certain es:

	Maximum	Minimum
Eastern Canada	+ 120° F.	− 40° F.
Mississippi Valley	+ 120° F.	− 20° F.
Southern California	+ 140° F.	+ 10° F.

Collection of Ice on Wires. — Investigation of the records of the Weather ureau leads to the conclusion that sleet and ice storms are generally followed by lling temperatures and high winds, and transmission lines should be designed meet these conditions. Records indicate that under favorable conditions ice d sleet will collect on wires and cables to the same amount in any climate where ezing temperatures are obtained. Mild, moderate and cold climates differ the frequency with which conditions are favorable. In general, sleet storms e most frequent in the moderate climates, since precipitation takes place more ten at freezing temperatures. Destructive sleet storms occur in the eastern art of the United States at least as far south as Atlanta. One-half inch ickness of solid ice on wires and cables is generally assumed in designing ansmission lines, but thicknesses of one-quarter and three-quarter inch are lso assumed in the more favorable and unfavorable localities.

Ice and sleet generally collect quite uniformly on wires throughout their ngth. The collection is sometimes in the form of icicles but more often is g-shaped in cross section, with the wire in the small end of the section. It equently falls off non-uniformly in sections.

Clear solid ice weighs 57 pounds per cubic foot or 0.033 pound per cubic inch, ut sleet or frozen snow such as often collects on wires weighs much less, some- imes as little as 8 pounds per cubic foot.

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Effect of Surface and Electric Potential on Collection of Ice. — Local observations of single ice or sleet storms have shown that ice will sometimes collect on one wire or cable and not on an adjoining one. This has led to the conclusion that ice will not collect on certain kinds of wires, but more extensive observations indicate that ice will collect on any kind of wire under favorable conditions. Observations on wires carrying sufficient current to heat them and wires having potential near the critical corona voltage are not sufficiently extensive to warrant the conclusion that they will not collect ice and sleet.

Wind Velocity and Wind Pressure on Wires. — As noted in the article on *Wind Pressure*, the records of the United States Weather Bureau give nominal average velocities for five minute intervals, the true average velocities differing from the recorded velocities as follows:

Recorded velocity in miles per hour	10	20	30	40	50	60	70	80	90	100
Actual velocity in miles per hour	9.6	17.8	25.7	33.3	40.8	48.0	55.2	62.2	69.2	76.1

The Weather Bureau records give no indication of the "gust" velocities which may occur during the five minute periods, and which may greatly exceed the average velocity. Tests with a Dines pressure tube anemometer have shown that the extreme maximum is about 50 per cent greater than the average for short periods.

The extreme maximum wind velocity observed in Chicago in the whole thirty-six year period from 1873 to 1910 was 84 miles per hour (uncorrected) in February, 1894. A velocity of 76 miles per hour (uncorrected) was observed once in November, 1898, and a velocity of 72 miles per hour (uncorrected) was observed seven times. During the ten year period from 1894 to 1903 the maximum wind velocity in a few other representative localities was as follows, all velocities being the observed or uncorrected velocities: Bismark, N. D., 72; Eastport, Me., 78; Buffalo, N. Y., 90; New York City, N. Y., 78; Galveston, Tex., 84; Savannah, Ga., 76; Salt Lake City, Utah, 60. All the maxima range between 60 miles and 90 miles per hour.

The wind pressure on a cable is usually calculated from the formula

$$p = KV^2, \qquad (1)$$

where p is the pressure in pounds per square foot of the projected area of the cable (including sleet and insulation, if any), and V is the actual velocity of the wind in miles per hour blowing perpendicularly across the span. The projected area, in square feet, of a one-foot length of cable is equal to the over-all diameter in inches divided by 12, where by over-all diameter is meant the diameter over the ice and insulation, if any. Buck's formula (*see article on Wind Pressure*) gives a value of 0.0025 for the constant K, whereas a value of 0.002 derived from the work of the Weather Bureau and experiments of Borda is also used.

Maximum Loading. — There is considerable difference of opinion as to what should be taken as the maximum loading in designing a transmission line. The Committee on Overhead Line Construction of the N.E.L.A. have proposed three different loadings, viz.: (A) No ice and a wind pressure of 15 pounds per square foot; (B) ice ½-inch thick and a wind pressure of 8 pounds per square foot; and (C) ice ¾-inch thick and a wind pressure of 11 pounds per square foot. Class B loading gives greater stress than Class A loading for all sizes of wire in use. The difference is greatest for small sizes.

Several important lines have been designed on the assumption of a maximum loading of ½ inch of ice and wind pressure at 6 pounds per square foot, the temperature corresponding to this loading being taken as 0° F. In these same lines the clearance under unequal loadings was calculated on the assumption of five

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s between anchor towers, with no ice on the third span of the lower con-
or, and no ice on the first, second, fourth and fifth spans of the upper
uctor, but with a loading of ¼ inch of ice on all other spans the tempera-
being taken as 32° F. and no wind assumed.

ERTICAL AND TRANSVERSE FORCES ON A SUSPENDED LE. — The resultant force acting on one foot of a suspended wire is in gen-
made up of three components, viz.:

= weight of the conductor (including insulation, if any) per foot length, in pounds;
= weight of the ice coating per foot length of the conductor, in pounds;
= wind pressure per foot length of the conductor, in pounds.

weight of the conductor per foot length may be taken directly from the es in the articles on *Wires and Cables, Bare*, as can also the diameter of the luctor (over the insulation, if any). Let d be this diameter in inches and let the thickness of the ice coating, then the weight of the ice coating per foot th of the conductor is

$$i = 1.24\, t\,(d + t). \tag{2}$$

p be the wind pressure per square foot of projected area, assumed or calcu-d from equation (1); then the wind pressure per foot length of the conductor, the horizontal component of the resultant force, is

$$h = \frac{p\,(d + 2t)}{12}. \tag{3}$$

vertical component of the resultant force per foot length of conductor, which qual to the resultant force for no wind, is

$$v = c + i. \tag{4}$$

lues of v and h for various ice thicknesses and various sizes of wires are given Table II. The values of h are given in the table for a wind pressure of 10 unds per square foot; these values of h are designated h_0; for any other wind ssure of say p pounds multiply these values by $\frac{p}{10}$. Knowing v and h the ultant force w for any combination of wind and ice loads is readily determined the formula

$$w = \sqrt{v^2 + h^2}. \tag{5}$$

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TABLE II. VERTICAL AND HORIZONTAL LOADING FORCES*

Pounds per Foot of Conductor

The horizontal component h_0 is given for a wind pressure of 10 lb. per s., for any other wind pressure of p lb. per sq. ft., $h = \frac{ph_0}{10}$.

The resultant force for any ice thickness and wind pressure is $w = \sqrt{v^2 + h^2}$

Wire, size, B. & S. (A. W. G.) and circular mils		No Ice		¼-inch ice		½-inch ice		¾-inch ice	
		Vertical v	Horizontal h_0	Vertical v	Horizontal h_0	Vertical v	Horizontal h_0	Vertical v	Horizontal h
Aluminum, stranded									
	500,000	0.460	0.679	0.791	1.096	1.280	1.511	1.919	1.[illegible]
	450,000	0.414	0.643	0.731	1.060	1.205	1.476	1.834	1.[illegible]
	400,000	0.368	0.604	0.670	1.021	1.130	1.438	1.744	1.[illegible]
	350,000	0.322	0.566	0.610	0.983	1.055	1.399	1.655	1.[illegible]
	300,000	0.276	0.517	0.546	0.934	0.973	1.351	1.555	1.[illegible]
	250,000	0.230	0.473	0.483	0.890	0.894	1.306	1.459	1.[illegible]
0000	211,600	0.195	0.435	0.434	0.852	0.831	1.269	1.382	1.[illegible]
000	167,800	0.155	0.387	0.376	0.804	0.755	1.220	1.288	1.[illegible]
00	133,100	0.122	0.345	0.328	0.762	0.691	1.179	1.208	1.[illegible]
0	105,500	0.097	0.307	0.289	0.724	0.637	1.140	1.140	1.[illegible]
1	83,690	0.077	0.273	0.256	0.690	0.592	1.106	1.082	1.[illegible]
2	66,370	0.061	0.243	0.229	0.660	0.533	1.076	1.032	1.[illegible]
3	52,640	0.049	0.217	0.207	0.634	0.522	1.051	0.992	1.[illegible]
4	41,740	0.039	0.193	0.188	0.610	0.494	1.026	0.954	1.[illegible]
Copper, stranded									
	500,000	1.525	0.683	1.856	1.100	2.345	1.516	2.989	1.[illegible]
	450,000	1.373	0.642	1.689	1.059	2.165	1.475	2.791	1.[illegible]
	400,000	1.220	0.607	1.523	1.024	1.984	1.440	2.599	1.[illegible]
	350,000	1.068	0.566	1.356	0.983	1.801	1.399	2.401	1.[illegible]
	300,000	0.915	0.525	1.188	0.942	1.618	1.359	2.203	1.[illegible]
	250,000	0.762	0.492	1.022	0.909	1.440	1.325	2.012	1.[illegible]
0000	211,600	0.645	0.442	0.887	0.859	1.286	1.275	1.831	1.[illegible]
000	167,800	0 513	0.392	0.736	0.809	1.116	1.225	1.651	1.[illegible]
00	133,100	0.406	0.350	0.614	0.767	0.978	1.184	1.498	1.[illegible]
0	105,500	0.322	0.313	0.516	0.728	0.866	1.146	1.372	1.[illegible]
1	83,690	0.255	0.275	0.435	0.692	0.771	1.109	1.263	1.[illegible]
2	66,370	0.203	0.243	0.371	0.660	0.695	1.076	1.174	1.[illegible]
3	52,640	0.160	0.217	0.318	0.634	0.633	1.051	1.103	1.[illegible]
4	41,740	0.127	0.193	0.276	0.610	0.582	1.026	1.042	1.443
5	33,100	0.101	0.172	0.242	0.589	0.540	1.005	0.992	1.422
6	26,250	0.080	0.153	0.215	0.570	0.505	0.986	0.951	1.403

* This table is in agreement with the *Report of the Committee on Overhead Line Construction*, Proc. N.E.L.A., May, 1910, Vol. [illegible], p. 472; the diameters used are slightly greater than those given in the article on *Wires and Cables, Bare*.

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TABLE II. — VERTICAL AND HORIZONTAL LOADING FORCES — *Continued*

Wire, size, B. & S. A. W. G.) nd circular mils		No ice		¼-inch ice		½-inch ice		¾-inch ice	
		Vertical v	Horizontal h_0	Vertical v	Horizontal h_0	Vertical v	Horizontal h_0	Vertical v	Horizontal h_0
Copper, solid bare									
00	211,600	0.641	0.383	0.911	0.800	1.238	1.216	1.770	1.634
00	167,800	0.509	0.341	0.713	0 758	1.074	1.175	1.591	1.591
00	133,100	0.403	0.304	0.594	0.724	0.940	1.138	1.443	1.554
0	107,500	0.320	0.271	0.498	0.688	0.833	1.104	1.323	1.521
1	83,690	0.253	0.241	0.420	0.658	0.744	1.075	1.223	1.491
2	66,370	0.202	0.215	0.359	0.632	0.673	1.048	1.142	1.465
3	52,640	0.159	0.191	0.308	0.608	0.613	1.025	1.073	1.441
4	41,740	0.126	0.170	0.267	0.587	0.564	1 004	1.016	1.425
5	33.100	0.100	0.151	0.234	0.568	0.524	0.985	0.969	1.402
6	26.250	0.079	0.135	0.207	0.552	0.491	0.969	0.930	1.385
opper, solid, riple braid, eatherproof									
00	211.600	0.767	0.533	1.043	0.950	1.476	1.366	2.064	1.783
00	167,800	0.629	0.494	0.890	0.911	1.309	1.328	1.882	1.744
00	133,100	0.502	0.429	0.759	0.846	1.133	1.263	1.682	1.679
0	105,500	0.407	0.417	0.639	0.834	1.029	1.250	1.573	1.666
1	83,690	0.316	0.378	0.534	0.795	0.909	1.210	1.438	1.627
2	66,370	0.260	0.364	0.473	0.781	0.843	1.198	1.367	1.614
3	52,640	0.199	0.338	0.403	0.755	0.763	1.171	1.278	1.588
4	41,740	0.164	0.299	0.353	0.716	0.698	1.133	1.199	1.549
5	33,100	0.135	0.287	0.319	0.704	0.660	1.120	1.146	1.536
6	26,250	0.112	0.273	0.291	0.690	0.627	1.106	1.118	1.523
Steel, stranded, galvanized									
¼ in.	575,000	1.540	0.730	1.888	1.147	2.393	1.563	3.050	1.980
5/16	500,000	1.336	0.677	1.666	1.094	2.151	1.510	2.789	1.927
⅜	425,000	1 138	0.625	1.448	1 042	1.903	1.459	2.533	1.875
7/16	357,000	0 958	0.572	1.249	0 989	1.694	1 406	2 295	1.822
½	295,000	0.791	0.522	1.062	0 939	1.489	1.351	2.070	1.772
9/16	250,000	0 688	0.469	0.920	0.886	1.392	1.303	1 889	1.719
⅝	190,000	0.510	0.417	0.742	0.834	1.132	1.250	1.672	1.667
11/16	145,000	0.415	0.364	0 628	0 781	0.998	1.198	1.519	1.614
¾	106,000	0.295	0.312	0 489	0.779	0.839	1 146	1.341	1.562
13/16	74,000	0.210	0.260	0.384	0.677	0.715	1.094	1.200	1.510

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CALCULATION OF SAG AND TENSION. — A wire or cable suspend between towers takes the form of a catenary curve. In transmission line pr tice the maximum deflection or sag is always small compared to the span, th is, the curve is very flat. The shape of such a flat catenary curve does not di appreciably from a parabola and, as the approximate parabolic formulas much simpler than the more exact catenary formulas, they are used inste The flatness of the curve allows of some further simplifications even in the p bolic formulas, viz., (1) the tension is considered uniform throughout the the slight excess of tension at the ends over that at middle being neglected, the change of length of the wire due to elastic stretch or temperature expan is taken as equal to the change of length of a wire equal in length to the h zontal distance between the points of support.

Notation Used in Sag-tension Formulas. — The following notation, alphabetically, will be used throughout the discussion of sag and tension

A = cross section of the conductor (actual metal cross section) in circ inches = square of diameter in inches; 1 circular inch = 1,000 circular mils.

a = coefficient of linear expansion of the conductor per ° F.; see Table above.

D = deflection, in feet, of the lowest point of the conductor when suspend from two points of support at the same elevation and at a distance apart. (D is measured in the direction of the resultant transv force.)

e = difference in elevation of the two points of support, in feet.

F = longitudinal horizontal component of the stress in the conductor, pounds. (The resultant stress in the wire at the insulator is equal $\sqrt{F^2 + H^2 + V^2}$, where V is the weight of the conductor and ice fr the insulator to the lowest point of the span, and H is the total w pressure on half the length of span; H and V in this expression usually negligible compared with F.)

h = wind pressure in pounds per foot length of conductor assumed perpe dicular to the vertical plane through the two points of support. s equation (3) and Table II above.

L = length of span in feet, i.e., the horizontal distance between the two post of support in feet.

l = length in feet of the arc of the curve in which the conductor hangs, i the length of stretched conductor between the two points of suppor

M = modulus of elasticity of the conductor in pound-inch units; see Table above.

$S = \frac{vD}{w}$ = sag of the lowest point of the conductor below the horizontal lin through the lower point of support; for no wind $S = D$.

T_0 = maximum allowable tension in the conductor in pounds per square inch of its cross section; T_0 is usually taken as one-half the ultimate strength of the conductor; see Table I.

v = vertical force in pounds on a one-foot length of the conductor, including the weight of conductor and the weight of the ice, if any, on it; s equation (4) and Table II above.

$w = \sqrt{v^2 + h^2}$ = resultant load in pounds on a one-foot length of the con ductor.

$Z = \frac{hD}{w}$ = side swing, in feet, of the middle point of the conductor, measured perpendicularly to the vertical plane through the two points of support.

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arious symbols with the subscript "o" will be used to designate the
the various quantities under the conditions of maximum assumed
see paragraph above on *Maximum Loading*.

mental Equations of a Wire Span. — As noted above, a perfectly
ire suspended between two points of support hangs in a catenary.
mption that the wire hangs in a parabola instead of in a catenary is
y accurate for all practical calculations of wire spans, the error in the
ated on this assumption being less than 2 per cent of its true value
sag is less than 0.06 times the length of the span (e.g., less than 60 feet
-foot span), and the error in the length of the wire calculated on this
n being less than 0.002 per cent of its true value for the same limiting
. The formulas given below are all based on the assumption of a

flection, Sag and Side Swing. — For a given length of span L,
and stress F, the deflection D for the points of support at the same
s given by the relation

$$D = \frac{wL^2}{8F}. \tag{6}$$

e is no wind this is also equal to the vertical sag, that is $S = D$. When
nd, w is greater than the vertical loading v, and the vertical sag for the
upport at the same elevation is

$$S = \frac{vD}{w} = \frac{vL^2}{8F}. \tag{7}$$

ion (7) has the value given by equation (6). When one point of
at an elevation e above the other, then the vertical sag of the lowest
e conductor below the lower point of support is

$$S' = S\left(1 - \frac{e}{4S}\right)^2, \tag{8}$$

given by equation (7). The horizontal distance of the lowest point
luctor from the lower point of support is

$$L' = \frac{L}{2}\left(1 - \frac{e}{4S}\right). \tag{9}$$

swing Z of the middle point of the conductor, which is the point
flected the maximum distance from the vertical plane through the
of support, is

$$Z = \frac{hD}{w} = \frac{hL^2}{8F}. \tag{10}$$

on (10) has the value given by equation (6).

th of Stretched Conductor. — The length of conductor between
nts of support for a given length of span L, loading w, stress F and
elevation e, is

$$l = L + \frac{8}{3}\frac{D^2}{L} + \frac{e^2}{2L}, \tag{11}$$

the value given by equation (6), that is, D is the deflection for the
of span, loading and tension, but for the points of support at the
on.

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Effect of Changes in Loading and Temperature. — When the loading or the temperature changes, the stress in the conductor will change to some new value, F_0 say, and the deflection will change to some new value, say D. Let the new loading be w_0 and the new temperature be t_0, the initial temperature being t; also let a be the coefficient of linear expansion, M the modulus of elasticity, and A the cross section of the conductor in millions of circular mils. Then, when the points of support remain fixed, the following relation must hold

$$\frac{8}{3L^2}(D^2 - D_0^2) = a(t - t_0) + \frac{1.273}{MA}(F - F_0).$$

The D's in this equation are the same as given by equation (6) for a loading w and w_0 respectively and stresses of F and F_0 respectively. Note that equation (12) is independent of the difference in elevation of the two points of support; also that the two sets of symbols, with and without the subscripts, refer to *any* two sets of conditions.

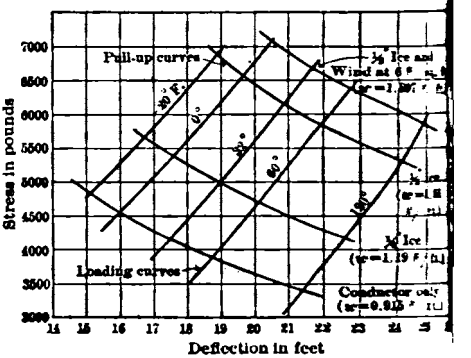


Fig. 8. Stress-Deflection Chart for a 300,000-Circular-Mil 19-Strand Copper Conductor on an 800-ft. Span

Stress - Deflection Charts (Fig. 8). — In order to apply the above equations to the calculation of clearances under various conditions equation (6), namely

$$D = \frac{wL^2}{8F}, \qquad (13)$$

and equation (12), which may be written

$$F = F_0 - \frac{2.10\,MA}{L^2}D_0^2 - \frac{MAa}{1.273}(t - t_0) + \frac{2.10\,MA}{L^2}D^2, \qquad (14)$$

may be plotted for any given length of span as shown in Fig. 8, with deflection D as abscissas and the stress F as ordinates.

Pull-up Curves. — The curves representing the relation between D and F in equation (13) are equilateral hyperbolas, as many of these curves being drawn as there are loadings to be considered. These hyperbolas may be called "pull-up" curves, since they give the stress to which the wire must be pulled up for any given deflection. In Fig. 8 four pull-up curves are shown, one for the conductor only ($w = 0.915$), conductor coated with ¼ inch of ice but no wind ($w = 1.19$), conductor coated with ½ inch of ice but no wind ($w = 1.61$), and conductor coated with ½ inch of ice and a wind pressure of 6 pounds per foot of projected area of wire ($w = 1.807$), this last being taken as the maximum loading.

Loading Curves. — The curves representing the relation between D and F in equation (14) are parabolas with vertical axes, as many of these curves being drawn as there are temperatures to be considered. These parabolas may be called "loading curves," since for a change in loading (at constant temperature) they give the relation which must exist between the new stress and new deflection produced. In order to plot these curves it is necessary to assume a maximum allowable tension, say T_0 pounds per square inch, a maximum load-

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d the minimum temperature t_0 at which this loading is assumed to ten

$$F_0 = \frac{AT_0}{1.273} \qquad \text{and} \qquad D_0 = \frac{w_0 L^2}{8 F_0},$$

r given temperature t all the terms in the right-hand member of (14) its except the last term, which varies as D^2. In Fig. 8 the maximum ension T_0 is taken as 30,000 pounds per square inch, the maximum is 1.807 pounds per foot length, and the minimum temperature under oading as 0° F. Then $F_0 = 7065$ pounds and $D_0 = 20.5$, which fixes n the 0° loading curve, and the other points on this curve are calcu- ly from (14) by putting $t = 0$. For any other temperature, equation he same shaped parabola as for 0°, but each point of the curve is ically downward a distance $\frac{MAa}{1.273}$ for each degree increase of tempera- e it is only necessary to calculate the 0° loading curve, and the load- r any other temperature can be readily plotted by the use of a pair

Stresses and Deflections. — In stringing cable it is essential that deflection be correct for the stringing temperature, otherwise the tress will be safe or the ground less ue to maxi- tion exceed- ned amount. oper string- of tempera- d tempera- are plotted ss-deflection se curves are and no ice. such curves -foot span Fig. 8. For he cable is F., then it en a deflec- ıl sag) of rovided the port are at ation, or at 00 pounds,

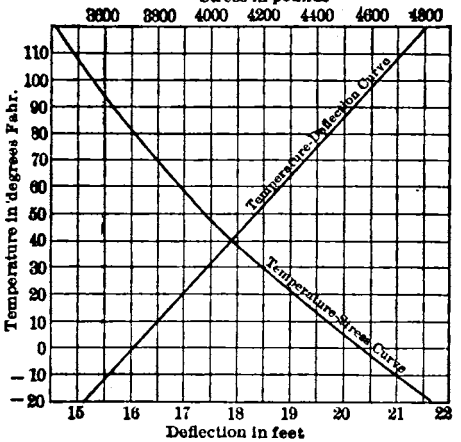


Fig. 9. Stringing Chart

ing independent of the difference of elevation of the two points of there is a difference of elevation of 30 feet, say, between the two port, then from equation (8a), the cable should be drawn up until lowest point below the lower point of support is

$$S' = 19.25\left(1 - \frac{30}{4 \times 19.25}\right)^2 = 7.17 \text{ feet},$$

s will then be 3800 pounds.

lculation of Change in Deflection and Stress with Loading ature.* — When for F in equation (12) is substituted its value

* From Lecture Notes by Dr. H. Pender.

TABLE III.—VALUES OF y IN TERMS OF x

$b_1 > (b_2 \times b_3)$

x	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.0000	0.0013	0.0025	0.0036	0.0047	0.0057	0.0067	0.0076	0.0084	0.009
0.1	0.0099	0.0106	0.0113	0.0119	0.0125	0.0130	0.0135	0.0140	0.0145	0.015
0.2	0.0154	0.0158	0.0162	0.0166	0.0170	0.0174	0.0178	0.0182	0.0185	0.018
0.3	0.0191	0.0194	0.0197	0.0200	0.0203	0.0206	0.0209	0.0212	0.0215	0.021
0.4	0.0221	0.0224	0.0227	0.0229	0.0231	0.0233	0.0235	0.0237	0.0239	0.024
0.5	0.0243	0.0245	0.0247	0.0249	0.0251	0.0253	0.0255	0.0257	0.0259	0.026
0.6	0.0263	0.0265	0.0267	0.0269	0.0271	0.0273	0.0275	0.0277	0.0279	0.028
0.7	0.0283	0.0285	0.0287	0.0289	0.0291	0.0293	0.0295	0.0297	0.0299	0.030
0.8	0.0303	0.0304	0.0305	0.0306	0.0307	0.0308	0.0309	0.0310	0.0311	0.031
0.9	0.0313	0.0314	0.0315	0.0316	0.0317	0.0318	0.0319	0.0320	0.0321	0.032

x	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	0.0327	0.0340	0.0352	0.0363	0.0373	0.0383	0.0392	0.0401	0.0410	0.041
2	0.0426	0.0434	0.0442	0.0449	0.0456	0.0463	0.0470	0.0477	0.0484	0.049
3	0.0496	0.0502	0.0508	0.0514	0.0520	0.0526	0.0532	0.0537	0.0542	0.054
4	0.0552	0.0557	0.0562	0.0567	0.0572	0.0577	0.0582	0.0587	0.0591	0.059
5	0.0599	0.0603	0.0607	0.0611	0.0615	0.0619	0.0623	0.0627	0.0631	0.063
6	0.0639	0.0643	0.0647	0.0651	0.0655	0.0659	0.0663	0.0666	0.0669	0.067
7	0.0675	0.0678	0.0681	0.0684	0.0687	0.0690	0.0693	0.0696	0.0699	0.070
8	0.0705	0.0708	0.0711	0.0714	0.0717	0.0720	0.0723	0.0726	0.0729	0.073
9	0.0735	0.0738	0.0741	0.0744	0.0747	0.0750	0.0753	0.0756	0.0759	0.076

x	0	1	2	3	4	5	6	7	8	9
10	0.0765	0.0789	0.0812	0.0834	0.0855	0.0875	0.0894	0.0913	0.0931	0.094

from equation (13) there results a cubic equation in D. This cubic equation can be solved directly by means of Tables III and IV given herewith. (Pender, *Electrical World, Vol. 66, p. 344, 1015.*) The procedure is as follows: using the same notation as above, calculate,

$$b_1 = \frac{1273\,F_0}{MA},$$

$$b_3 = \left(\frac{w_0 L}{0.155\,F_0}\right)^2,$$

$$b_2 = 1000\,a(t - t_0),$$

$$b = \frac{1273\,wL}{MA},$$

B = numerical value of $[b_1 - (b_2 + b_3)]$,

$$x = \frac{b}{B\sqrt{B}}$$

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TABLE IV.—VALUES OF y IN TERMS OF x

$b_1 < (b_2 + b_3)$

0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
.0194	0.0200	0.0205	0.0210	0.0215	0.0220	0.0224	0.0228	0.0232	0.0236
.0239	0.0242	0.0245	0.0248	0.0252	0.0255	0.0258	0.0261	0.0263	0.0266
.0269	0.0272	0.0274	0.0277	0.0279	0.0281	0.0283	0.0286	0.0288	0.0290
.0292	0.0295	0.0297	0.0299	0.0300	0.0302	0.0304	0.0306	0.0308	0.0310
.0312	0.0314	0.0316	0.0318	0.0320	0.0322	0.0323	0.0325	0.0327	0.0329
.0330	0.0332	0.0333	0.0335	0.0337	0.0338	0.0340	0.0341	0.0343	0.0345
.0346	0.0348	0.0349	0.0350	0.0352	0.0353	0.0354	0.0355	0.0358	0.0359
.0360	0.0361	0.0362	0.0363	0.0365	0.0366	0.0368	0.0369	0.0370	0.0371
.0372	0.0373	0.0374	0.0375	0.0377	0.0378	0.0379	0.0380	0.0381	0.0383
.0384	0.0385	0.0386	0.0387	0.0388	0.0390	0.0319	0.0392	0.0393	0.0394

0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
.0395	0.0406	0.0416	0.0425	0.0434	0.0443	0.0451	0.0460	0.0467	0.0475
.0482	0.0490	0.0497	0.0504	0.0510	0.0516	0.0522	0.0528	0.0534	0.0539
.0544	0.0560	0.0566	0.0571	0.0577	0.0581	0.0586	0.0591	0.0596	0.0590
.0595	0.0600	0.0604	0.0609	0.0613	0.0617	0.0621	0.0625	0.0629	0.0633
.0637	0.0641	0.0645	0.0649	0.0653	0.0657	0.0660	0.0663	0.0667	0.0670
.0673	0.0677	0.0681	0.0685	0.0689	0.0692	0.0695	0.0698	0.0701	0.0704
.0708	0.0711	0.0714	0.0717	0.0720	0.0723	0.0726	0.0729	0.0732	0.0735
.0738	0.0741	0.0743	0.0747	0.0749	0.0751	0.0754	0.0757	0.0760	0.0762
.0765	0.0768	0.0771	0.0773	0.0776	0.0779	0.0781	0.0784	0.0787	0.0789

0	.1	2	3	4	5	6	7	8	9
.0792	0.0817	0.0840	0.0861	0.0881	0.0900	0.0919	0.0937	0.0954	0.0970

ke y from table.

en the deflection is

$$D = yL\sqrt{B},$$

the stress is,

$$F = \frac{wL^2}{8D}.$$

ote that b_1 may be greater or less than (b_2+b_3); in either case B is to be n *positive* and equal to the numerical value of $b_1-(b_2+b_3)$. Also note that is the elongation, in feet per 1000 feet, of a straight wire when subjected stress of F_0 pounds.

is the number of feet per 1000 feet of wire, by which the length of the wire degrees and loading w_0 exceeds the horizontal distance between the points ipport (when these are at the same elevation).

is the elongation, in feet per 1000 feet of wire, due solely to a change in perature from t_0 to t degrees.

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b is the elongation, in feet per 1000 feet of wire, due to a stress equal wL (= its own weight plus the total ice and wind, if any, at the temperature

Example. — To find the sag at which a No. 0 B. & S. stranded copp wire must be strung at 60° F. on a 400-ft. span so that the wire will have a fac of safety of two at 0° F. when loaded with ice 0.5 in. thick all around the w and with a wind pressure of 8 lb. per square foot of projected area. The brea ing strength of the wire is 4980 lb., cross-section 105,500 circ. mils, modulus elasticity 16×10^6, and coefficient of expansion 9.6×10^{-6}.

The data and calculations are then as follows:

$$F_0 = 2490 \qquad M = 16\times10^6,$$

$$w = 0.323, \qquad L = 400.$$

$$w_0 = 1.26, \qquad t - t_0 = 60$$

$$A = 0.1055, \qquad a = 9.6\times10^{-6}.$$

Then

$$b_1 = \frac{1273\times2490}{16\times10^6\times0.1055} = 1.878,$$

$$b_2 = \left(\frac{1.26\times400}{0.0155\times2490}\right)^2 = 1.705,$$

$$b_3 = 1000\times9.6\times10^{-6}60 = 0.576,$$

$$b = \frac{1273\times0.323\times400}{16\times10^6\times0.1055} = 0.0975.$$

Noting that b_1 is less than (b_2+b_3),

$$B = 1.705+0.576-1.878 = 0.403,$$

$$x = \frac{0.0975}{0.403\sqrt{0.403}} = 0.382,$$

and, from Table IV, $y = 0.0308$. Whence

$$D = 0.0308\times400\sqrt{0.403} = 7.82 \text{ ft.}$$

This is the sag at 60° F. with no ice or wind.

The sag at 0° F. with no ice or wind is found in exactly the same way, not that for these conditions $b_3 = 0$, and b_1 is greater than (b_2+b_3), giving for B value

$$1.878-1.705 = 0.173,$$

and for x the value

$$\frac{0.0975}{0.173\sqrt{0.173}} = 1.355,$$

and y from Table III is then 0.0367, and

$$D = 0.0367\times400\sqrt{0.173} = 6.10 \text{ ft.}$$

Stress and Deflection in Spans of Unequal Length. — By stringing cab according to the stress determined for each particular length of span, the main

owable tension will be reached in all spans under maximum loading s. Under other loading conditions the tension will be unequal where ths are not the same. This is shown in Fig. 10 which is plotted for the ditions as stated in the title of Fig 8, but for spans of from 600 to n length. Fig. 11 shows the corresponding deflections.

equal stresses on the two sides of the insulator will tend to bend the nsulator pin, but any motion of the point of support will tend to equalize es. When suspension insulators are used, the stresses are practically since the is free to should be t the motion ulator neces- equalize the small. When insulators the cable is strung at a orresponding erage length When the thus strung under min- perature and loading will ceed the as- sion in the ins and be be assumed the longer larly, under emperature the longer have a sag f the value on the as- f the maxi- ble tension

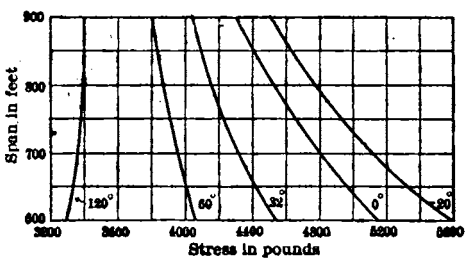


Fig. 10.

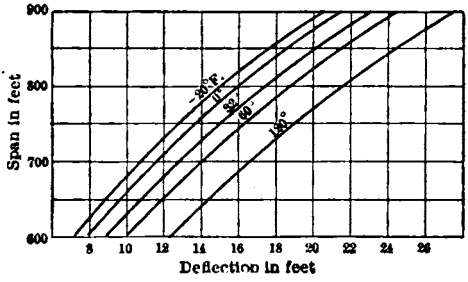


Fig. 11.

ed with maximum loading, and the shorter spans will have a sag ie calculated value. The actual stresses and deflections can be y the method given in the following section.

on of Stresses in Unequally Loaded Spans.* — When suspen- ors are used, any tendency of the stresses in two adjacent spans to qual will produce such a deflection of the insulator, in the direction with greater stress, as will establish equilibrium in the line. This irs will occur (1) when adjacent spans carry unequal ice loads, (2) re on one side of the insulator breaks, and (3) to a slight extent with mperature when the adjacent spans are unequal in length, as noted following method of calculating the "equilibrium" stresses in the orresponding sags is applicable to all cases of initially unbalanced spective of their cause. The method may also be used to calcu- ss and sag in spans supported on pin insulators, provided the mo- ling of the pin and of the pole or tower is known or can be calculated.

* From lecture notes by Dr. H. Pender.

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Change of Stress Due to Change in Length of Span. — When the length L of the span (i.e., distance between points of support) increases by λ inches, due to a horizontal displacement of the insulators (without slipping of the wire), the stress in the wire is increased by the same amount as would be produced by a fall in temperature of

$$t - t' = \frac{\lambda}{12\,aL} \qquad \text{or} \qquad t' = t - \frac{\lambda}{12\,aL}, \tag{15}$$

degrees Fahrenheit, where t is the actual temperature and t' may be called the "equivalent" temperature corresponding to the change in length λ. In the equation λ is the actual increase in the distance between the points of support in inches, a the temperature coefficient of linear expansion per ° F., and L the original length of the span in feet. For example, in an 800-foot span of copper wire an increase of 1 inch in L corresponds to a drop of temperature of $1 \div (12 \times 9.6 \times 10^{-6} \times 800) = 10.85$ degrees, and an increase in length of λ inches corresponds to a drop of temperature of $t - t' = 10.85\,\lambda$ degrees.

Hence the stress-deflection chart for any given length of span, see Fig. 8, may be used directly to determine the stress in the wire after any change in the length of the span, due to the deflection of the insulator. For example, consider an 800-foot span of 300,000-circular-mil, bare, copper conductor, at 32° F., without ice or wind, initially stressed to 4170 pounds, and let the length of the span be increased 4 inches as the result of the deflection of the insulators by this amount. This increase in length of span will then give the same stress in the wire as would be produced if the temperature fell from 32° to $t' = 32 - 4 \times 10.85 = -11.4$°. The point at which the loading curve (Fig. 8) corresponding to a temperature of -11.4° crosses the pull-up curve for conductor only gives the new stress, viz., 4700 pounds.

Horizontal Pull of Insulator. — Referring to Fig. 12, let m = the horizontal distance in inches (measured along the span) which any insulator is deflected from the vertical, taken positive when to the right, say, and negative when to the left. Let x = the length of the insulator string in inches, i.e., distance from point of attachment to tower to point of attachment to wire. V = total weight of wire and ice between the lowest point of the wire in the span to the left of the insulator and the lowest point of the wire in the span to the right of the insulator plus one-half the weight of the insulator; H = total wind pressure on the length of wire between the middle points of the two adjacent spans, plus half the wind pressure on the insulator; and put $W = \sqrt{V^2 + H^2}$. Then the horizontal component of the pull of the insulator toward the left along the line of the span is *

$$P = \frac{m}{\sqrt{x^2 - m^2}} \cdot W. \tag{16}$$

For example, consider two adjacent spans of 300,000-circular-mil copper, each 800 feet long and with points of support at the same elevation. Let the span to the left be free of ice and let the one to the right have a ½-inch ice coating; assume the insulator to be 60 inches long and to weigh 100 pounds. Then for no wind $H = 0$, $V = 1.19 \times 400 + 0.915 \times 400 + 100/2 = 892$ pounds. Whence for deflections of the insulator of less than 12 inches the horizontal pull of the insulator is $P = (892 \times m) \div 60 = 14.9\,m$, or 14.9 pounds per inch deflection.

* When m is less than 10 per cent of x this may be written, with an error of less than 2 per cent,

$$P = \frac{m}{x} W. \tag{16a}$$

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Stresses in a Series of Spans When Points of Support are not ed. — Referring to Fig. 12, let the left-hand end of span No. 1 be anchored, assume the insulator at the right-hand end to be deflected a horizontal dis-ce of m_1 inches, due, for example, to a change in the loading on the succeeding

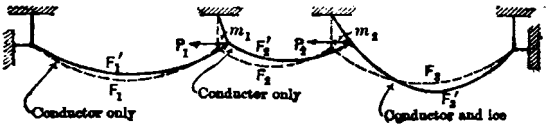


Fig. 12.

ns (or to a change in temperature when the spans are of unequal length). m equation (15) calculate the "equivalent" temperature t_1' corresponding this change in length, and from the pull-up curve in Fig. 8 corresponding assumed loading w_1 of this span find the stress on this curve corresponding a temperature of t_1' degrees; call this stress F_1'.

Next calculate the transverse and vertical loads on the insulator, viz., H_1 and and the resultant load $W_1 = \sqrt{V_1^2 + H_1^2}$, as explained in the preceding sec-n. Then from equation (16) or (16a) calculate the horizontal pull P_1 of the ulator. The stress in the second span, assuming the value of m_1 chosen at start is correct, must then be

$$F_2' = F_1' + P_1. \tag{17}$$

is then determined from F_2' on the pull-up curve. From equation (15) the responding increase in the length of span No. 2 must then be

$$\lambda_2 = 12\,aL_2\,(t - t_2'), \tag{18}$$

ere L_2 is the length of the second span. The corresponding deflection of the ulator at the right-hand end of span No. 2 must then be

$$m_2 = m_1 + \lambda_2, \tag{19}$$

rays taking the insulator deflection positive when to the right, say.

Using the values of λ_2 and m_2 thus found, calculate the λ_3 and m_3 in exactly e same manner as λ_2 and m_2 were calculated, and similarly for the succeeding ans until the next anchor tower is reached. For the anchor tower at the right-nd end of the n-th span, say, the deflection of the insulator must be zero, viz.,

$$m_n = 0. \tag{20}$$

m_n as calculated comes out greater than zero, then the assumed value of m_1 is o great; if m_n comes out less than zero the assumed value of m_1 is too small. y calculating m_n for two or three assumed values of m_1, and plotting m_n as dinates against m_1 as abscissas, the correct value of m_1 will be where this rve crosses the axis of abscissas. Using this correct value of m_1, the stresses d deflections in each span may then be accurately calculated by the process st given, using the Stress-Deflection Chart, Fig. 8. The complete process is st shown by an example.

Example. — Consider the case of three spans between anchor towers, ig. 12) all of the same length, 800 feet, and all supports at the same elevation, 0,000-circular-mil copper being used for the conductor. Let the temperature e 32° F., and let the middle span have a ¼-inch ice coating but the other two pans have no ice on them; also assume no wind. The Stress-Deflection Chart iven in Fig. 8 then applies directly, provided the wires are strung in accordance herewith. Assume that each insulator weighs 100 pounds and has a length of

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60 inches. Then for an increase of λ inches in the length of any span, the "equivalent" temperature is, from equation (15),

$$t' = 32 - 10.85\lambda$$

or if the equivalent temperature rise t' is known

$$\lambda = 0.092\,(32 - t').$$

The horizontal pull of any insulator for a deflection of m inches (small compared with the length of the insulator) is, from equation (16a),

$$P = 14.9\,m.$$

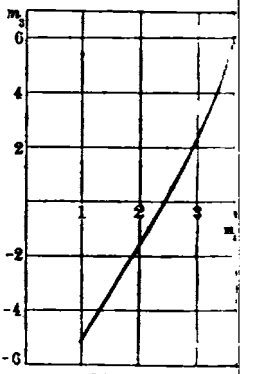


Fig. 13.

In the following table are given the calculations for assumed values of m_1 of 1, 2, 3 and 4 inches, and in Fig. 13 are plotted the corresponding calculated values of m_2 against m_1. It is seen that the relation between m_2 and m_1 is practically a straight line cutting the horizontal axis at $m_1 = 2.4$, which is therefore the correct value of m_1. The calculations for $m_1 = 2.4$ inches are given in the last column of the table. Hence the stresses and deflections in the two end spans (without ice) are $F_1' = F_3' = 4460$ pounds and $D_1' = D_3' = 16.3$ feet respectively, and the stress and deflection in the middle span loaded with ½-inch of ice are $F_2' = 4496$ pounds and $D_2' = 21.1$ feet respectively, the deflections being read directly from Fig. 8 corresponding to the proper stresses and loadings (w).

m_1	= assumed	1	2	3	4	2.4
t_1'	$= 32 - 10.85\,m_1$	21.1	10.3	−0.6	−11.4	6
F_1'	From Fig. 8 ($w = 0.915$)	4300	4410	4550	4700	4460
P_1	$= 14.9\,m_1$	15	30	45	60	36
F_2'	$= F_1' + P_1$	4315	4440	4595	4760	4496
t_2'	From Fig. 8 ($w = 1.19$)	105	90	74	55	84
λ_2	$= 0.092\,(32 - t_2')$	−6.72	−5.33	−3.86	−2.12	−4.78
m_2	$= m_1 + \lambda_2$	−5.72	−3.33	−0.86	1.88	−2.38
P_2	$= 14.9\,m_2$	−85	−50	−13	28	−36
F_3'	$= F_2' + P_2$	4230	4390	4582	4788	4460
t_3'	From Fig. 8 ($w = 0.915$)	26	13	−3	−16	1
λ_3	$= 0.092\,(32 - t_3')$	0.55	1.75	3.22	4.42	2.86
m_3	$= m_1 + \lambda_3$	−5.17	−1.58	2.36	6.30	0.46

LOCATION OF TOWERS AND DETERMINATION OF CLEARANCES.—The height of towers is determined so as to give some specified minimum clearance from conductor to ground for some length of span chosen as a nominal standard on the basis of level ground. In practice the ground is rarely level and the towers are actually located to conform to the irregularities of the ground. In locating towers of a given height the spans are made as long as possible consistent with maintaining the ground clearance. The irregularities of the ground are ordinarily advantageous and permit of slightly longer spans on the average than could be obtained with the same height of towers on level ground.

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and Plan of Right-of-Way. — In order to locate towers properly sary to have a profile of the right-of-way. Profiles are conveniently standard ruled profile section paper to a vertical scale of 20 feet to the . horizontal scale of 200 feet to the inch. Three profiles are desirable, the center of the tower line and one on each side, say at each edge of ıy, as shown on Fig. 14 at *A*, *B* and *C*. The two side profiles indicate t and direction of the slope of the ground across the line, which must l for in determining ground clearance and foundation or tower

f the right-of-way is of course also necessary for determining the con- t angles in the line, and the clearances from the conductor to the edge ıt-of-way when the conductor is deflected horizontally by the wind. n is shown at the bottom of Fig. 14.

tes for Locating Towers. — Three templates are required, one for ırance with maximum sag, marked *M* in Fig. 14, one for uplift at inimum sag, marked *N*, and one for maximum side swing, marked *Z*. ut from thin celluloid and are to the same horizontal and vertical ed for the profile and plan of the right-of-way.

curvature of the catenary or parabola in which the wire hangs de- on the tension and loading and not on the length of the span or on ce in elevation of the points of support, all spans having the same l loading can be drawn (for any one predetermined scale) from a late, irrespective of their lengths or of the differences in elevation of of support. However, when the elevations of the points of support same, the lowest point of the curve is shifted from the middle of the l the lower support, but the axis of the curve remains vertical.

struction of Maximum Sag Template *M*. — The maximum sag ım the Stress-Deflection Chart, Fig. 8, and may be the deflection ıg to the maximum temperature, and conductor only, e.g., 21.4 feet may be the deflection corresponding to 32° F. and the maximum Wind will increase this deflection but will not increase the *vertical* S_m this maximum sag. Then the equation of the maximum sag template *M*, is

$$y = \left(\frac{4\,S_m}{L^2}\right) x^2, \qquad (21)$$

he length of the particular span for which the maximum sag is S_m, in of the curve is its lowest point and the axis of y is vertical; all ıre in feet. Three parabolic curves are given by this template; the presents the position of the cable and is drawn on the basis of the ı under the maximum load; the middle curve is a similar parabola pper curve a distance equal to the minimum allowable clearance to bottom curve is another similar parabola below the upper curve e equal to the height of cable above ground at the support.

truction of Minimum Sag Template *N*. — The minimum sag is rom the Stress-Deflection Chart, and is usually the deflection cor- o the minimum temperature and conductor only, e.g., 15.1 feet in l this sag S_n; then the equation of the minimum sag template, or is

$$y = \left(\frac{4\,S_n}{L^2}\right) x^2. \qquad (22)$$

truction of Maximum Side-swing Template *Z*. — The maxi- wing occurs at time of maximum wind pressure and may be at

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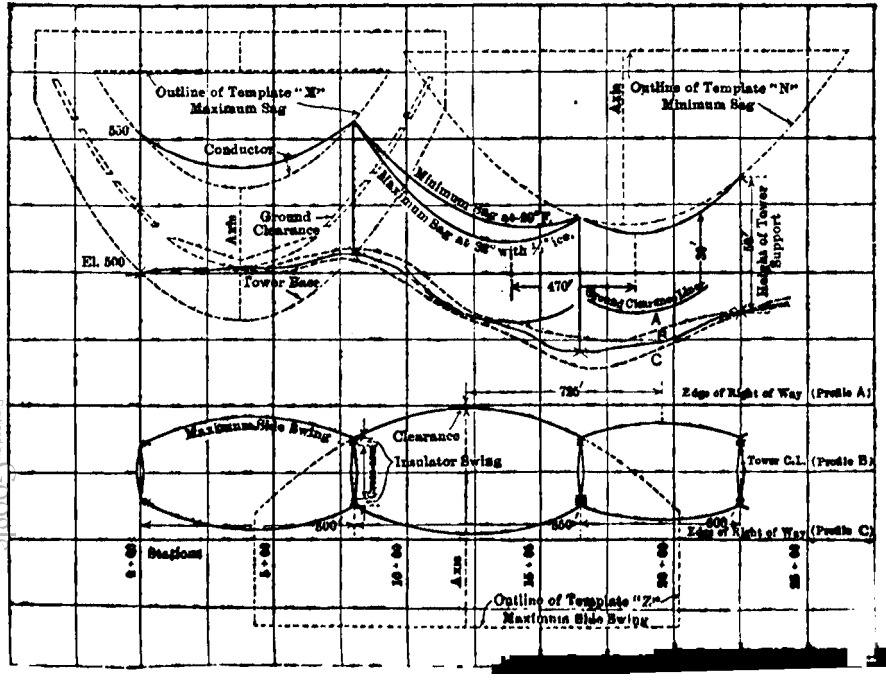


Fig. 14. Chart Showing Use of Templates in Locating Towers and Determining Clearances

imum temperature or may be at 32° F. when covered with ice. In the ter case the side swing depends on the shape (circular or elliptical) of the covering and its specific gravity. For a circular covering of solid ice one ·ular thickness (usually but not necessarily the maximum thickness) gives greatest side swing. For example, in Fig. 8, the maximum side swing occurs $D = 21.7$ and $w = 1.807$, and its value is, see equation (16), $Z = (0.815 \times 21.7)$ $1.807 = 9.8$ feet, 0.815 being the wind pressure per foot of wire. Calling the aximum side swing Z_m, then the equation of the side swing template, or tem- ate Z, is

$$y = \left(\frac{4\,Z_m}{L^2}\right)x^2. \qquad (23)$$

Locating Towers by Means of Template M. — Choose a starting point, as own for example in Fig. 14, at station 0 + 00, elevation 500.0 feet for the first wer location. The template M is then placed over the profile and shifted until axis is vertical and the lower curve is at station 0 + 00, elevation 500.0 feet, and e middle curve is tangent to the ground profile as shown. The proper loca- on for the second tower is at the point where the lower curve again intersects e ground profile, or at station 8 + 00, elevation 506.0 feet, in the example. ie operation is then repeated for the next tower. Adjustments in length of an are usually necessary to meet local conditions, in order to avoid locating wers in roads or swamps and to bring towers at angle points. Adjustments ich increase the ground clearance are of course allowable.

The position of the conductors with maximum sag may be drawn on the profile om the top curve of the template.

Uplift on Insulator; Use of Template N. — An insulator sustains the ight of the lengths of conductor from the insulator to the lowest point of the an on each side. If the conductor leaves the insulator horizontally on one le, the lowest point of that span is at the insulator, which then sustains no ight due to that span. If the conductor has an upward inclination where it ives an insulator, it is exerting an uplift equal to the weight of a length of nductor extending from the insulator along the span produced in the reverse rection to the lowest point of the parabola. Where the conductor has a down- ard inclination on one side and upward on the other side of the insulator, there ll be a weight or uplift on the insulator equal to the difference between the ight of conductor on one side and uplift on the other.

Suspension insulators when used hanging downward to sustain weight are capable of resisting uplift. Where uplift occurs the conductor may be dead ded or may be tied down or weighted down.

The method used for locating towers ordinarily precludes uplift under the ading which gives maximum sag, but uplift may occur when the loading is less.) determine this the minimum sag is drawn on the profile with template N. ie minimum sag curve is drawn between points of support, keeping the axis the parabola vertical as before.

Side Swing of Suspension Insulators. — Let l_1 = the length of conductor tween the lowest point in the span to the left of the insulator and the lowest int in the span to the right of the insulator, and let l_2 = the distance between e middle points of these two spans, both in feet. Also let v = the weight of e conductor and ice per foot length, and h = the wind pressure per foot length ee Table II). Then the vertical pull on the insulator is vl_1 and the transverse rizontal force is hl_2. Also let v_1 = the weight of the insulator and h_1 = the tal wind pressure on it. Then the insulator is deflected sidewise from the rtical by approximately the angle

$$\theta = \tan^{-1}\left[\frac{hl_2 + 0.5\,h_1}{vl_1 + 0.5\,v_1}\right]. \qquad (24)$$

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Usually the weight of the insulator and the wind pressure on it are negligible compared with the weight and wind pressure on the conductor, in which case

$$\theta = \tan^{-1}\left(\frac{hl_2}{wl_1}\right). \tag{12a}$$

When the points of support are at the same elevation $l_1 = l_2$ and

$$\theta = \tan^{-1}\frac{h}{w}. \tag{12b}$$

Calling X the length of the insulator in feet then the transverse horizontal deflection of the insulator is $X \sin \theta$ feet.

For example, consider the side swing of the third insulator (from the left) in Fig. 14. Then $l_1 = 470$, $l_2 = 850/2 + 600/2 = 725$, $w = 1.61$ (for 300,000-circular-mil conductor with ½ inch of ice), and $h = 0.82$ (for wind pressure of 8 pounds per square foot). Whence, neglecting the weight of the insulator and the wind pressure on it,

$$\theta = \tan^{-1}\frac{0.82 \times 725}{1.61 \times 470} = 38°.$$

If the insulator is 5 feet long, the transverse horizontal deflection is then $5 \sin 38° = 3.1$ feet.

If the angle of swing as thus determined is excessive the cables and insulators will be lifted up into the cross arms at times of low temperatures and high winds. The remedy is the same as in case of direct uplift.

Side Clearance; Use of Template Z. — Where a right-of-way of definite width is obtained it is necessary to determine whether the conductor will swing beyond the edge of the right-of-way. Therefore after the towers have been located by the use of the profile they should be marked on the plan and the side swing marked in from template Z, as shown in Fig. 14. In determining side swing, the swing of the insulator (if suspension type) must be allowed for, as well as the side swing of the conductor. Adequate margin should be allowed between the extreme position of conductor and the edge of the right-of-way, so that a safe clearance will be preserved from any structures erected adjacent thereto. Where extraordinarily long spans must be used, an adequate extra width of right-of-way should be obtained in the first place.

Loss of Clearance Between Conductors Due to Unequal Ice Loading. — Where one span is loaded with ice and the one immediately below it is not, the clearance is reduced. This condition may sometimes arise due to the ice falling off the lower wire before it falls off the upper wire. Where the wires are directly over each other the normal clearance must be great enough to prevent the crossing of wires under these conditions. For ice loading without wind, clearance under unequal loading is most easily obtained by offsetting the wires horizontally for the required clearance instead of increasing the vertical clearance. However, to prevent crossing of the unequally loaded wires when deflected by wind pressure, this horizontal offset must be considerable, as the clearance must then be obtained between the wires in their inclined positions.

If the conductors to which Fig. 8 refer are normally 10 feet apart vertically on an 800-foot span, the sag would be 17.5 feet without ice at 32° F., 19.0 feet with ¼-inch ice, and 20.9 feet with ½-inch ice at 32° F. Consequently, if two cables are used one above the other, and ice should form on the upper but not on the lower, then, assuming fixed points of support (pin insulators), the clearance would be reduced by 3.4 feet for ½-inch ice, and 1.5 feet for ¼-inch ice, making the clearances 6.6 feet and 8.5 feet respectively, instead of 10 feet.

Where suspension insulators are used the reduction of clearance fro
loading is greater. If one span is loaded with ice and the adjacen
same wire are not loaded, the sag of the loaded span will be increas
insulators will swing toward that span. Similarly if one span is
d adjacent spans are loaded,
sag will be decreased. The
nimum clearance occurs where
ly one span of the upper wire
loaded and is immediately
er the only unloaded span of
lower wire. The actual re-
ction is readily calculated by
method given above in the
tion on *Calculation of Stresses Unequally Loaded Spans*, p.
3. The amount of reduction
ends on the number of spans
ween anchor towers, and the
tance from the anchor towers
which the unbalanced loading
urs. For a 300,000-circular-mil copper cable on 800-foot spans
h unequal loadings on sections of one, two, three and five spans (s
assumed conditions of unequal loading and the loss of clearar
ows:

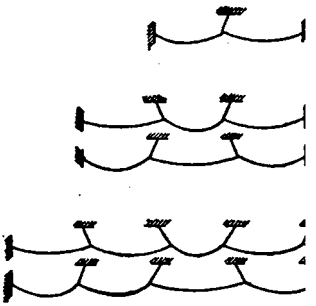


Fig. 16.

Number of spans between anchor towers	1	2	3
pper conductor; ¼-inch ice on spans Nos. :*	1	1	2
ower conductor; ¼-inch ice on spans Nos. :*	...	2	1, 3
ag of middle span of upper conductor, feet	19.0	20.5	21.1
ag of middle span of lower conductor, feet	17.5	15.9	15.5
oss of clearance in middle span, feet	1.5	4.6	5.6

* The other spans assumed to have no ice load.

Stresses and Deflections Due to Broken Conductors. — Wl
ctor breaks in a span supported by suspension insulators, the insu
ent to the broken span swing up into line with the cable, throwing
ck into the unbroken part of the cable equal to the length of the
is slack divides between the unbroken spans, increasing the de
h. The stresses and deflections of the unbroken spans may be d
the method given above in the section on *Calculation of Stresses in
ded Spans*, p. 1803, calling the span in which the break occurs sp

ERECTION OF TRANSMISSION LINES. — The preliminar
nstructing a transmission line includes the clearing of the right-of-
of buildings (if necessary), building roads, bridges, fences, gate
ke the right-of-way passable. If the telephone line is to be sup
arate structures, this is generally built in advance of the main line
ring the rest of the construction.

After the towers are in place and the insulators placed, the wires
-strung. The reels are distributed and spaced according to the
le on each. The reels of heavy cable are supported on reel ja
ter wire and cable is usually drawn out on the ground and carried
on the supporting structures. Heavy cables are drawn over rollers
ached to the towers at approximately the final point of support. T

out of wires and cables is usually done with horses, but under favorable conditions a traction engine or hoisting engine can be used. Where lines parallel railroads they have been pulled out successfully with locomotives. Care should be taken in drawing out the cable so as not to scratch or injure it by sharp bends or faulty cable grips, or by dragging it over sharp stones. See also the article on *Wires and Cables, Bare.*

After the cable is drawn out and is in place on the sheaves on the towers, it should be adjusted to the proper sag by using dynamometers for measuring the tension. In order to have uniform tension in all spans when pulling several at one time, the cable should be free to move at all points of support. Wires and cables should be clamped or tied in place while under the proper tension corresponding to the temperature at time of stringing. Wind loads on cables or wires are generally not of an amount during wire stringing to require allowance for additional tension. Splicing sleeves are twisted by hand wrenches in the smaller sizes and by splicing machines for the larger sizes.

At anchor towers loose jumpers must be bent to shape and not left so that they may ground on the tower due to twist of cable, pressure of wind or weight of sleet.

Where ground wires or telephone wires are also on the tower, it is equally important that they be strung at the proper tension; otherwise they may cross and ground the conductors.

Suspension towers (i.e., those intermediate between the dead-end towers) are ordinarily not strong enough to stand the strain of dead-ended cables during high winds and heavy sleet storms; consequently care must be used if cables are temporarily dead ended on them during construction.

Transposition of Transmission Lines. — (*See also Telephone Lines.*) Transpositions are not necessary for the proper operation of an isolated transmission line, but are used to diminish the inductive effects of the transmission line on neighboring circuits. The number of transpositions required depends principally on the sensitiveness and proximity of other circuits, especially telephone lines and on the distance that such lines parallel the transmission line, and also to a lesser degree on the current and voltage of the transmission line.

Where the voltage of transmission is 2200 or less the length of exposure (i.e., distance between two successive transposition points) is usually insufficient to require transpositions and, when the voltage is over 60,000, the lines are often at sufficient distance from nearest telephone line to make transpositions unnecessary. For voltages above 2200 and not over 60,000 a telephone line is ordinarily run the whole distance on the same poles or towers with a transmission line, thereby making transpositions necessary. Transpositions on such transmission lines are ordinarily located three miles or more apart, the telephone line also being transposed every 500 or 600 feet.

Each transposition of a three-phase line ordinarily consists of a spiral of one-third of a turn. Three transpositions give a complete spiral and bring the phases back to their original position. A line is ordinarily transposed by giving it one or more complete spirals, the transpositions being located so as to divide the line into approximately equal sections. For one complete spiral two transpositions dividing the line into thirds are sufficient, though the equivalent of a third transposition is necessary at one end if the phases are to have the same relative position in the station wiring at each end.

Special poles or towers are usually necessary at transposition points.

TESTS AND INSPECTION OF TRANSMISSION LINES. — Tests on transmission lines include testing of the several parts; conductors, insulators, pins, clamps, ties, towers, etc., and are described in the articles on *Wire and*

ulators for Overhead Lines; Poles for Overhead Lines, Cross Arms;
he efficiency and other electrical characteristics of transmission lines
puted with such certainty that tests are not necessary to determine
es, though the calculations are occasionally checked by observations
g actual operation.
ne is completed it should be carefully inspected to see that all joints
nade, all insulators put on, etc. Moreover, before starting continu-
n, it is advisable to apply voltage in order to make sure that the
pen circuited, short-circuited or grounded.
) or more transmission lines are to be in parallel, or where a new line
) points already connected by other lines, it is necessary to test out
sponding phases before connecting in multiple, especially if any of
'e transpositions.

ION. — Patrolmen are usually located between ten and twenty
depending on the character of the country. The coöperation of
along the line must be obtained in order to prevent damage by
insulators, throwing wires over the conductors, blasting rocks or
the line, etc. Patrolmen should inspect the line regularly and keep
and inflammable material away from the poles and towers. They
he condition of the foundations, towers, poles, insulators and con-
addition they should make minor and emergency repairs on the

tches are often installed at each patrolman's house. By manipu-
witches any section of line may then be tested for faults.
maintenance of a line includes resetting foundations that have
ing of foundations with earth to proper depth after heavy rains;
towers before they are affected by rust; renewal of rusted ground
ement of cracked or partially defective insulators that have not
ing sag of any cable where sag has changed due to stretch of cable,
gth during emergency repairs, etc.

Connections. — A good telephone line is essential and the patrol-
:port by telephone at regular intervals. As a convenience in
phones are installed or connections are provided for a portable
it intervals of three or four miles along the line. For the higher
protection must be provided for the person using telephone.
:tion includes insulated stools, telephone insulating transformers,
telephone lightning arresters and fuses.

TRANSMISSION LINES. — To obtain an accurate estimate
transmission line the cost of the various elements should be sepa-
ned. The following over-all costs based on before-the-war
1 as a rough guide in preliminary estimating.

ht-of-Way. — The cost of the right-of-way for a low-voltage line
ominal amount for a line on public roads, to $10,000 per mile or
ate right-of-way in thickly settled districts. A right-of-way 100
res approximately 12 acres per mile, which for farming land at
amounts to $2400 per mile. Land values may be expected to
rably higher for right-of-way than for farming, especially if a
desired crossing a farm diagonally.
way for high-voltage tower lines should be estimated liberally as
l have long spans and few angles, and cannot be diverted around
rty and obstructions as readily as short-span wooden-pole lines.

ize and Cost of Conductor on Total Cost. — The size and
of conductors greatly affect the cost of a line. A circuit of 3

No. 0000 cables costs about $1500 per mile with copper at 14.4 cents per p and $2000 per mile at 19.2 cents per pound. The cost of smaller cables i portionally less; No. 0 being about one-half, No. 3 about one-fourth and about one-eighth the cost of No. 0000. Thus the copper cost of a thre line will range from about $205 per mile for No. 6 at 15.6 cents per pou $2000 per mile for No. 0000 at 19.2 cents per pound.

For the same power loss in the line aluminum conductors usually cost 10 per cent less than copper.

Total Structural Cost of Wooden Pole Lines. — The structural co wooden-pole transmission line ordinarily ranges from about $1500 per mi 11,000-volt line with 3 No. 6 wires to about $4000 per mile for a 55,000-v with 3 No. 0000 wires, excluding the cost of right-of-way. To the stru cost and cost of right-of-way should be added the charges for engine contractor's services, superintendence, tools and equipment, etc., which amount to from 20 to 40 per cent of the structural cost.

Total Structural Cost of Tower Lines. — The cost of light tower lin 55,000 volts with 3 No. 0000 wires may be as low as for a wooden pole lin about $4000 per mile. For 110,000 volts with three 300,000-circular-m the cost may be about $8000 per mile or more. The cost of towers proper greatly according to the views of the designers as to what risks are pro design, that is, the severity of assumed wind and ice loadings, and the f of safety. The cost of foundations is very small when simple steel stat used in very firm ground, but foundations add greatly to the cost of a line concrete or steel structures are used, so designed as to make the strength ity and holding power of the foundations actually equal to the strength tower under reasonably unfavorable conditions of ground. See artic *Towers for Transmission Lines*.

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Reports: *Report of Engineering Data Committee of the A.I.E.E.*, pres at the annual convention of the A.I.E.E., June 1914 (contains a large am of important data on all features of the transmission lines of a number of hydroelectric plants); *Transmission Line Crossings, Joint Report of the mittee on Overhead Line Construction*, N.E.L.A., and *Report of Committ Transmission Line Crossings*, A.R.E.A.

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NOMETRIC FUNCTIONS. — (*See also Derivatives; Integrals; thematical; Trigonometry.*) The trigonometric functions of an angle are o one another of the various sides of a right triangle having the given e of its angles. Referring to Fig. 1, let B, P and H be the three sides le. Then the trigonometric functions of the angle x are

bbreviated $\sin x = \frac{P}{H}$; cotangent of x, abbreviated $\cot x = \frac{B}{P}$;

abbreviated $\cos x = \frac{B}{H}$; secant of x, abbreviated $\sec x = \frac{H}{B}$;

r, abbreviated $\tan x = \frac{P}{B}$; cosecant of x, abbreviated $\csc x = \frac{H}{P}$.

and H are limited to the three sides of a right triangle, the above re directly applicable only to angles lying between 0 and 90°. The however, may be extended by considering the point A (Fig. 2) as

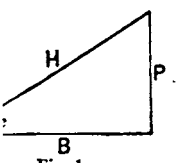


Fig. 1.

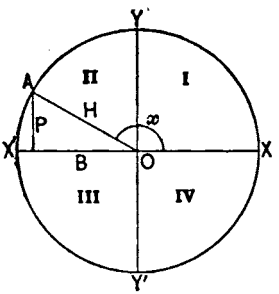


Fig. 2.

rcle of radius OA with the center at O. Let XX' be the horizontal YY' the vertical diameter of this circle, and call P the perpendicu- rom A to the line XX' and B the horizontal distance from A to be considered positive when A lies above XX', negative when considered positive when A is to the right of YY' and negative ft. The four quarters of the circle are called quadrants, and are the first, second, third and fourth quadrants as indicated. The o lie in the quadrant in which the point A lies. In Fig. 2 the he second quadrant.

ALGEBRAIC SIGNS OF THE FUNCTIONS

	Sine	Cosine	Tangent
quadrant	+	+	+
d quadrant	+	−	−
quadrant	−	−	+
quadrant	−	+	−

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Period. — From the above definitions it is evident that adding 2π radians, 360° to an angle does not change the value of any of its functions, that is, the functions repeat themselves every time the angle increases by the 2π radians or 360°. They are therefore said to have a period equal to 2π radians or 36

Functions of Angles in Any Quadrant in Terms of Angles in First Quadrant.—

$$\sin(-x) = -\sin x, \qquad \sin(90+x) = \cos x,$$
$$\cos(-x) = \cos x, \qquad \cos(90+x) = -\sin x,$$
$$\tan(-x) = -\tan x, \qquad \tan(90+x) = -\cot x,$$

$$\sin(180-x) = \sin x, \qquad \sin(180+x) = -\sin x,$$
$$\cos(180-x) = -\cos x, \qquad \cos(180+x) = -\cos x,$$
$$\tan(180-x) = -\tan x, \qquad \tan(180+x) = \tan x,$$

$$\sin(270-x) = -\cos x, \qquad \sin(270+x) = -\cos x,$$
$$\cos(270-x) = -\sin x, \qquad \cos(270+x) = \sin x,$$
$$\tan(270-x) = \cot x, \qquad \tan(270+x) = -\cot x.$$

Table of Trigonometric Functions. — By making use of the above relati the functions of any angle may be obtained from a table giving the values of t functions for angles between 0 and 90°. Such a table is given below. For t cot, sec and csc take the reciprocals of the tan, cos and sin respectively.

Example of Use of Table. — $\sin 21.6° = 0.3681$, $\cos 21.6° = 0.$ $\tan 21.6° = 0.3959$; $\sin 107° = \sin(180° - 107°) = \sin 73° = 0.9563$, $\cos 107° =$ $\cos 73° = -0.2924$, $\tan 107° = -\tan 73° = -3.2709$.

TRIGONOMETRIC FUNCTIONS 0.0°-6

Angle in degrees	Name of function	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.
	sin	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0
0	cos	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0
	tan	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0
	sin	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0
1	cos	0.9998	0.9998	0.9998	0.9997	0.9997	0.9997	0.9996	0.9996	0.9995	0
	tan	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0
	sin	0.0349	0.0366	0.0384	0.0401	0.0419	0.0436	0.0454	0.0471	0.0488	0
2	cos	0.9994	0.9993	0.9993	0.9992	0.9991	0.9990	0.9990	0.9989	0.9988	0
	tan	0.0349	0.0367	0.0384	0.0402	0.0419	0.0437	0.0454	0.0472	0.0489	0
	sin	0.0523	0.0541	0.0558	0.0576	0.0593	0.0610	0.0628	0.0645	0.0663	0
3	cos	0.9986	0.9985	0.9984	0.9983	0.9982	0.9981	0.9980	0.9979	0.9978	0
	tan	0.0524	0.0542	0.0559	0.0577	0.0594	0.0612	0.0629	0.0647	0.0664	0
	sin	0.0698	0.0715	0.0732	0.0750	0.0767	0.0785	0.0802	0.0819	0.0837	0
4	cos	0.9976	0.9974	0.9973	0.9972	0.9971	0.9969	0.9968	0.9966	0.9965	0
	tan	0.0699	0.0717	0.0734	0.0752	0.0769	0.0787	0.0805	0.0822	0.0840	0
	sin	0.0872	0.0889	0.0906	0.0924	0.0941	0.0958	0.0976	0.0993	0.1011	0
5	cos	0.9962	0.9960	0.9959	0.9957	0.9956	0.9954	0.9952	0.9951	0.9949	0
	tan	0.0875	0.0892	0.0910	0.0928	0.0945	0.0963	0.0981	0.0998	0.1016	0
	sin	0.1045	0.1063	0.1080	0.1097	0.1115	0.1132	0.1149	0.1167	0.1184	0
6	cos	0.9945	0.9943	0.9942	0.9940	0.9938	0.9936	0.9934	0.9932	0.9930	0
	tan	0.1051	0.1069	0.1086	0.1104	0.1122	0.1139	0.1157	0.1175	0.1192	0

GONOMETRIC FUNCTIONS 7.0°–20.9°

de e- es	Name of function	Value of function for each tenth of a degree									
		.0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	sin	0.1219	0.1236	0.1253	0.1271	0.1288	0.1305	0.1323	0.1340	0.1357	0.1374
7	cos	0.9925	0.9923	0.9921	0.9919	0.9917	0.9914	0.9912	0.9910	0.9907	0.9905
	tan	0.1228	0.1246	0.1263	0.1281	0.1299	0.1317	0.1334	0.1352	0.1370	0.1388
	sin	0.1392	0.1409	0.1426	0.1444	0.1461	0.1478	0.1495	0.1513	0.1530	0.1547
8	cos	0.9903	0.9900	0.9898	0.9895	0.9893	0.9890	0.9888	0.9885	0.9882	0.9880
	tan	0.1405	0.1423	0.1441	0.1459	0.1477	0.1495	0.1512	0.1530	0.1548	0.1566
	sin	0.1564	0.1582	0.1599	0.1616	0.1633	0.1650	0.1668	0.1685	0.1702	0.1719
9	cos	0.9877	0.9874	0.9871	0.9869	0.9866	0.9863	0.9860	0.9857	0.9854	0.9851
	tan	0.1584	0.1602	0.1620	0.1638	0.1655	0.1673	0.1691	0.1709	0.1727	0.1745
	sin	0.1736	0.1754	0.1771	0.1788	0.1805	0.1822	0.1840	0.1857	0.1874	0.1891
0	cos	0.9848	0.9845	0.9842	0.9839	0.9836	0.9833	0.9829	0.9826	0.9823	0.9820
	tan	0.1763	0.1781	0.1799	0.1817	0.1835	0.1853	0.1871	0.1890	0.1908	0.1926
	sin	0.1908	0.1925	0.1942	0.1959	0.1977	0.1994	0.2011	0.2028	0.2045	0.2062
1	cos	0.9816	0.9813	0.9810	0.9806	0.9803	0.9799	0.9796	0.9792	0.9789	0.9785
	tan	0.1944	0.1962	0.1980	0.1998	0.2016	0.2035	0.2053	0.2071	0.2089	0.2107
	sin	0.2079	0.2096	0.2113	0.2130	0.2147	0.2164	0.2181	0.2198	0.2215	0.2232
2	cos	0.9781	0.9778	0.9774	0.9770	0.9767	0.9763	0.9759	0.9755	0.9751	0.9748
	tan	0.2126	0.2144	0.2162	0.2180	0.2199	0.2217	0.2235	0.2254	0.2272	0.2290
	sin	0.2250	0.2267	0.2284	0.2300	0.2317	0.2334	0.2351	0.2368	0.2385	0.2402
3	cos	0.9744	0.9740	0.9736	0.9732	0.9728	0.9724	0.9720	0.9715	0.9711	0.9707
	tan	0.2309	0.2327	0.2345	0.2364	0.2382	0.2401	0.2419	0.2438	0.2456	0.2475
	sin	0.2419	0.2436	0.2453	0.2470	0.2487	0.2504	0.2521	0.2538	0.2554	0.2571
4	cos	0.9703	0.9699	0.9694	0.9690	0.9686	0.9681	0.9677	0.9673	0.9668	0.9664
	tan	0.2493	0.2512	0.2530	0.2549	0.2568	0.2586	0.2605	0.2623	0.2642	0.2661
	sin	0.2588	0.2605	0.2622	0.2639	0.2656	0.2672	0.2689	0.2706	0.2723	0.2740
5	cos	0.9659	0.9655	0.9650	0.9646	0.9641	0.9636	0.9632	0.9627	0.9622	0.9617
	tan	0.2679	0.2698	0.2717	0.2736	0.2754	0.2773	0.2792	0.2811	0.2830	0.2849
	sin	0.2756	0.2773	0.2790	0.2807	0.2823	0.2840	0.2857	0.2874	0.2890	0.2907
6	cos	0.9613	0.9608	0.9603	0.9598	0.9593	0.9588	0.9583	0.9578	0.9573	0.9568
	tan	0.2867	0.2886	0.2905	0.2924	0.2943	0.2962	0.2981	0.3000	0.3019	0.3038
	sin	0.2924	0.2940	0.2957	0.2974	0.2990	0.3007	0.3024	0.3040	0.3057	0.3074
7	cos	0.9563	0.9558	0.9553	0.9548	0.9542	0.9537	0.9532	0.9527	0.9521	0.9516
	tan	0.3057	0.3076	0.3096	0.3115	0.3134	0.3153	0.3172	0.3191	0.3211	0.3230
	sin	0.3090	0.3107	0.3123	0.3140	0.3156	0.3173	0.3190	0.3206	0.3223	0.3239
8	cos	0.9511	0.9505	0.9500	0.9494	0.9489	0.9483	0.9478	0.9472	0.9466	0.9461
	tan	0.3249	0.3269	0.3288	0.3307	0.3327	0.3346	0.3365	0.3385	0.3404	0.3424
	sin	0.3256	0.3272	0.3289	0.3305	0.3322	0.3338	0.3355	0.3371	0.3387	0.3404
9	cos	0.9455	0.9449	0.9444	0.9438	0.9432	0.9426	0.9421	0.9415	0.9409	0.9403
	tan	0.3443	0.3463	0.3482	0.3502	0.3522	0.3541	0.3561	0.3581	0.3600	0.3620
	sin	0.3420	0.3437	0.3453	0.3469	0.3486	0.3502	0.3518	0.3535	0.3551	0.3567
0	cos	0.9397	0.9391	0.9385	0.9379	0.9373	0.9367	0.9361	0.9354	0.9348	0.9342
	tan	0.3640	0.3659	0.3679	0.3699	0.3719	0.3739	0.3759	0.3779	0.3799	0.3819

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Angle in degrees	Name of function	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0
	sin	0.3584	0.3600	0.3616	0.3633	0.3649	0.3665	0.3681	0.3697	0.3714	0
21	cos	0.9336	0.9330	0.9323	0.9317	0.9311	0.9304	0.9298	0.9291	0.9285	0
	tan	0.3839	0.3859	0.3879	0.3899	0.3919	0.3939	0.3959	0.3979	0.4000	0
	sin	0.3746	0.3762	0.3778	0.3795	0.3811	0.3827	0.3843	0.3859	0.3875	0
22	cos	0.9272	0.9265	0.9259	0.9252	0.9245	0.9239	0.9232	0.9225	0.9219	0
	tan	0.4040	0.4061	0.4081	0.4101	0.4122	0.4142	0.4163	0.4183	0.4204	0
	sin	0.3907	0.3923	0.3939	0.3955	0.3971	0.3987	0.4003	0.4019	0.4035	0
23	cos	0.9205	0.9198	0.9191	0.9184	0.9178	0.9171	0.9164	0.9157	0.9150	0
	tan	0.4245	0.4265	0.4286	0.4307	0.4327	0.4348	0.4369	0.4390	0.4411	0
	sin	0.4067	0.4083	0.4099	0.4115	0.4131	0.4147	0.4163	0.4179	0.4195	0
24	cos	0.9135	0.9128	0.9121	0.9114	0.9107	0.9100	0.9092	0.9085	0.9078	0
	tan	0.4452	0.4473	0.4494	0.4515	0.4536	0.4557	0.4578	0.4599	0.4621	0
	sin	0.4226	0.4242	0.4258	0.4274	0.4289	0.4305	0.4321	0.4337	0.4352	0
25	cos	0.9063	0.9056	0.9048	0.9041	0.9033	0.9026	0.9018	0.9011	0.9003	0
	tan	0.4663	0.4684	0.4706	0.4727	0.4748	0.4770	0.4791	0.4813	0.4834	0
	sin	0.4384	0.4399	0.4415	0.4431	0.4446	0.4462	0.4478	0.4493	0.4509	0
26	cos	0.8988	0.8980	0.8973	0.8965	0.8957	0.8949	0.8942	0.8934	0.8926	0
	tan	0.4877	0.4899	0.4921	0.4942	0.4964	0.4986	0.5008	0.5029	0.5051	0
	sin	0.4540	0.4555	0.4571	0.4586	0.4602	0.4617	0.4633	0.4648	0.4664	0
27	cos	0.8910	0.8902	0.8894	0.8886	0.8878	0.8870	0.8862	0.8854	0.8846	0
	tan	0.5095	0.5117	0.5139	0.5161	0.5184	0.5206	0.5228	0.5250	0.5272	0
	sin	0.4695	0.4710	0.4726	0.4741	0.4756	0.4772	0.4787	0.4802	0.4818	0
28	cos	0.8829	0.8821	0.8813	0.8805	0.8796	0.8788	0.8780	0.8771	0.8763	0
	tan	0.5317	0.5340	0.5362	0.5384	0.5407	0.5430	0.5452	0.5475	0.5498	0
	sin	0.4848	0.4863	0.4879	0.4894	0.4909	0.4924	0.4939	0.4955	0.4970	0
29	cos	0.8746	0.8738	0.8729	0.8721	0.8712	0.8704	0.8695	0.8686	0.8678	0
	tan	0.5543	0.5566	0.5589	0.5612	0.5635	0.5658	0.5681	0.5704	0.5727	0
	sin	0.5000	0.5015	0.5030	0.5045	0.5060	0.5075	0.5090	0.5105	0.5120	0
30	cos	0.8660	0.8652	0.8643	0.8634	0.8625	0.8616	0.8607	0.8599	0.8590	0
	tan	0.5774	0.5797	0.5820	0.5844	0.5867	0.5890	0.5914	0.5938	0.5961	0
	sin	0.5150	0.5165	0.5180	0.5195	0.5210	0.5225	0.5240	0.5255	0.5270	0
31	cos	0.8572	0.8563	0.8554	0.8545	0.8536	0.8526	0.8517	0.8508	0.8499	0
	tan	0.6009	0.6032	0.6056	0.6080	0.6104	0.6128	0.6152	0.6176	0.6200	0
	sin	0.5299	0.5314	0.5329	0.5344	0.5358	0.5373	0.5388	0.5402	0.5417	0
32	cos	0.8480	0.8471	0.8462	0.8453	0.8443	0.8434	0.8425	0.8415	0.8406	0
	tan	0.6249	0.6273	0.6297	0.6322	0.6346	0.6371	0.6395	0.6420	0.6445	0
	sin	0.5446	0.5461	0.5476	0.5490	0.5505	0.5519	0.5534	0.5548	0.5563	0
33	cos	0.8387	0.8377	0.8368	0.8358	0.8348	0.8339	0.8329	0.8320	0.8310	0
	tan	0.6494	0.6519	0.6544	0.6569	0.6594	0.6619	0.6644	0.6669	0.6694	0
	sin	0.5592	0.5606	0.5621	0.5635	0.5650	0.5664	0.5678	0.5693	0.5707	0
34	cos	0.8290	0.8281	0.8271	0.8261	0.8251	0.8241	0.8231	0.8221	0.8211	0
	tan	0.6745	0.6771	0.6796	0.6822	0.6847	0.6873	0.6899	0.6924	0.6950	0

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GONOMETRIC FUNCTIONS 35.0°-48.9°

le-	Name of function	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	sin	0.5736	0.5750	0.5764	0.5779	0.5793	0.5807	0.5821	0.5835	0.5850	0.5864
5	cos	0.8192	0.8181	0.8171	0.8161	0.8151	0.8141	0.8131	0.8121	0.8111	0.8100
	tan	0.7002	0.7028	0.7054	0.7080	0.7107	0.7133	0.7159	0.7186	0.7212	0.7239
	sin	0.5878	0.5892	0.5906	0.5920	0.5934	0.5948	0.5962	0.5976	0.5990	0.6004
6	cos	0.8090	0.8080	0.8070	0.8059	0.8049	0.8039	0.8028	0.8018	0.8007	0.7997
	tan	0.7265	0.7292	0.7319	0.7346	0.7373	0.7400	0.7427	0.7454	0.7481	0.7508
	sin	0.6018	0.6032	0.6046	0.6060	0.6074	0.6088	0.6101	0.6115	0.6129	0.6143
7	cos	0.7986	0.7976	0.7965	0.7955	0.7944	0.7934	0.7923	0.7912	0.7902	0.7891
	tan	0.7536	0.7563	0.7590	0.7618	0.7646	0.7673	0.7701	0.7729	0.7757	0.7785
	sin	0.6157	0.6170	0.6184	0.6198	0.6211	0.6225	0.6239	0.6252	0.6266	0.6280
8	cos	0.7880	0.7869	0.7859	0.7848	0.7837	0.7826	0.7815	0.7804	0.7793	0.7782
	tan	0.7813	0.7841	0.7869	0.7898	0.7926	0.7954	0.7983	0.8012	0.8040	0.8069
	sin	0.6293	0.6307	0.6320	0.6334	0.6347	0.6361	0.6374	0.6388	0.6401	0.6414
9	cos	0.7771	0.7760	0.7749	0.7738	0.7727	0.7716	0.7705	0.7694	0.7683	0.7672
	tan	0.8098	0.8127	0.8156	0.8185	0.8214	0.8243	0.8273	0.8302	0.8332	0.8361
	sin	0.6428	0.6441	0.6455	0.6468	0.6481	0.6494	0.6508	0.6521	0.6534	0.6547
0	cos	0.7660	0.7649	0.7638	0.7627	0.7615	0.7604	0.7593	0.7581	0.7570	0.7559
	tan	0.8391	0.8421	0.8451	0.8481	0.8511	0.8541	0.8571	0.8601	0.8632	0.8662
	sin	0.6561	0.6574	0.6587	0.6600	0.6613	0.6626	0.6639	0.6653	0.6665	0.6678
1	cos	0.7547	0.7536	0.7524	0.7513	0.7501	0.7490	0.7478	0.7466	0.7455	0.7443
	tan	0.8693	0.8724	0.8754	0.8785	0.8816	0.8847	0.8878	0.8910	0.8941	0.8972
	sin	0.6691	0.6704	0.6717	0.6730	0.6743	0.6756	0.6769	0.6782	0.6794	0.6807
2	cos	0.7431	0.7420	0.7408	0.7396	0.7385	0.7373	0.7361	0.7349	0.7337	0.7325
	tan	0.9004	0.9036	0.9067	0.9099	0.9131	0.9163	0.9195	0.9228	0.9260	0.9293
	sin	0.6820	0.6833	0.6845	0.6858	0.6871	0.6884	0.6896	0.6909	0.6921	0.6934
3	cos	0.7314	0.7302	0.7290	0.7278	0.7266	0.7254	0.7242	0.7230	0.7218	0.7206
	tan	0.9325	0.9358	0.9391	0.9424	0.9457	0.9490	0.9523	0.9556	0.9590	0.9623
	sin	0.6947	0.6959	0.6972	0.6984	0.6997	0.7009	0.7022	0.7034	0.7046	0.7059
4	cos	0.7193	0.7181	0.7169	0.7157	0.7145	0.7133	0.7120	0.7108	0.7096	0.7083
	tan	0.9657	0.9691	0.9725	0.9759	0.9793	0.9827	0.9861	0.9896	0.9930	0.9965
	sin	0.7071	0.7083	0.7096	0.7108	0.7120	0.7133	0.7145	0.7157	0.7169	0.7181
5	cos	0.7071	0.7059	0.7046	0.7034	0.7022	0.7009	0.6997	0.6984	0.6972	0.6959
	tan	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319
	sin	0.7193	0.7206	0.7218	0.7230	0.7242	0.7254	0.7266	0.7278	0.7290	0.7302
6	cos	0.6947	0.6934	0.6921	0.6909	0.6896	0.6884	0.6871	0.6858	0.6845	0.6833
	tan	1.0355	1.0392	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686
	sin	0.7314	0.7325	0.7337	0.7349	0.7361	0.7373	0.7385	0.7396	0.7408	0.7420
7	cos	0.6820	0.6807	0.6794	0.6782	0.6769	0.6756	0.6743	0.6730	0.6717	0.6704
	tan	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067
	sin	0.7431	0.7443	0.7455	0.7466	0.7478	0.7490	0.7501	0.7513	0.7524	0.7536
8	cos	0.6691	0.6678	0.6665	0.6652	0.6639	0.6626	0.6613	0.6600	0.6587	0.6574
	tan	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463

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TRIGONOMETRIC FUNCTIONS

Angle in degrees	Name of function	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	sin	0.7547	0.7559	0.7570	0.7581	0.7593	0.7604	0.7615	0.7627	0.7638	0.7
49	cos	0.6561	0.6547	0.6534	0.6521	0.6508	0.6494	0.6481	0.6468	0.6455	0.6
	tan	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1
	sin	0.7660	0.7672	0.7683	0.7694	0.7705	0.7716	0.7727	0.7738	0.7749	0.7
50	cos	0.6428	0.6414	0.6401	0.6388	0.6374	0.6361	0.6347	0.6334	0.6320	0.6
	tan	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2
	sin	0.7771	0.7782	0.7793	0.7804	0.7815	0.7826	0.7837	0.7848	0.7859	0.7
51	cos	0.6293	0.6280	0.6266	0.6252	0.6239	0.6225	0.6211	0.6198	0.6184	0.6
	tan	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2
	sin	0.7880	0.7891	0.7902	0.7912	0.7923	0.7934	0.7944	0.7955	0.7965	0.7
52	cos	0.6157	0.6143	0.6129	0.6115	0.6101	0.6088	0.6074	0.6060	0.6046	0.6
	tan	1.2799	1.2846	1.2892	1.2938	1.2985	1.3032	1.3079	1.3127	1.3175	1.3
	sin	0.7986	0.7997	0.8007	0.8018	0.8028	0.8039	0.8049	0.8059	0.8070	0.8
53	cos	0.6018	0.6004	0.5990	0.5976	0.5962	0.5948	0.5934	0.5920	0.5906	0.5
	tan	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3
	sin	0.8090	0.8100	0.8111	0.8121	0.8131	0.8141	0.8151	0.8161	0.8171	0.8
54	cos	0.5878	0.5864	0.5850	0.5835	0.5821	0.5807	0.5793	0.5779	0.5764	0.5
	tan	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4124	1.4176	1.4
	sin	0.8192	0.8202	0.8211	0.8221	0.8231	0.8241	0.8251	0.8261	0.8271	0.8
55	cos	0.5736	0.5721	0.5707	0.5693	0.5678	0.5664	0.5650	0.5635	0.5621	0.5
	tan	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4
	sin	0.8290	0.8300	0.8310	0.8320	0.8329	0.8339	0.8348	0.8358	0.8368	0.8
56	cos	0.5592	0.5577	0.5563	0.5548	0.5534	0.5519	0.5505	0.5490	0.5476	0.5
	tan	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5224	1.5282	1.5
	sin	0.8387	0.8396	0.8406	0.8415	0.8425	0.8434	0.8443	0.8453	0.8462	0.8
57	cos	0.5446	0.5432	0.5417	0.5402	0.5388	0.5373	0.5358	0.5344	0.5329	0.5
	tan	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5
	sin	0.8480	0.8490	0.8499	0.8508	0.8517	0.8526	0.8536	0.8545	0.8554	0.8
58	cos	0.5299	0.5284	0.5270	0.5255	0.5240	0.5225	0.5210	0.5195	0.5180	0.5
	tan	1.6003	1.6066	1.6128	1.6191	1.6255	1.6319	1.6383	1.6447	1.6512	1.6
	sin	0.8572	0.8581	0.8590	0.8599	0.8607	0.8616	0.8625	0.8634	0.8643	0.8
59	cos	0.5150	0.5135	0.5120	0.5105	0.5090	0.5075	0.5060	0.5045	0.5030	0.5
	tan	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7
	sin	0.8660	0.8669	0.8678	0.8686	0.8695	0.8704	0.8712	0.8721	0.8729	0.8
60	cos	0.5000	0.4985	0.4970	0.4955	0.4939	0.4924	0.4909	0.4894	0.4879	0.4
	tan	1.7321	1.7391	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7
	sin	0.8746	0.8755	0.8763	0.8771	0.8780	0.8788	0.8796	0.8805	0.8813	0.8
61	cos	0.4848	0.4833	0.4818	0.4802	0.4787	0.4772	0.4756	0.4741	0.4726	0.4
	tan	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8
	sin	0.8829	0.8838	0.8846	0.8854	0.8862	0.8870	0.8878	0.8886	0.8894	0.8
62	cos	0.4695	0.4679	0.4664	0.4648	0.4633	0.4617	0.4602	0.4586	0.4571	0.4
	tan	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9

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gle de- ees	Name of func- tion	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	sin	0.8910	0.8918	0.8926	0.8934	0.8942	0.8949	0.8957	0.8965	0.8973	0.8980
63	cos	0.4540	0.4524	0.4509	0.4493	0.4478	0.4462	0.4446	0.4431	0.4415	0.4399
	tan	1.9626	1.9711	1.9797	1.9883	1.9970	2.0057	2.0145	2.0233	2.0323	2.0413
	sin	0.8988	0.8996	0.9003	0.9011	0.9018	0.9026	0.9033	0.9041	0.9048	0.9056
64	cos	0.4384	0.4368	0.4352	0.4337	0.4321	0.4305	0.4289	0.4274	0.4258	0.4242
	tan	2.0503	2.0594	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348
	sin	0.9063	0.9070	0.9078	0.9085	0.9092	0.9100	0.9107	0.9114	0.9121	0.9128
65	cos	0.4226	0.4210	0.4195	0.4179	0.4163	0.4147	0.4131	0.4115	0.4099	0.4083
	tan	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2148	2.2251	2.2355
	sin	0.9135	0.9143	0.9150	0.9157	0.9164	0.9171	0.9178	0.9184	0.9191	0.9198
66	cos	0.4067	0.4051	0.4035	0.4019	0.4003	0.3987	0.3971	0.3955	0.3939	0.3923
	tan	2.2460	2.2566	2.2673	2.2781	2.2889	2.2998	2.3109	2.3220	2.3332	2.3445
	sin	0.9205	0.9212	0.9219	0.9225	0.9232	0.9239	0.9245	0.9252	0.9259	0.9265
67	cos	0.3907	0.3891	0.3875	0.3859	0.3843	0.3827	0.3811	0.3795	0.3778	0.3762
	tan	2.3559	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4383	2.4504	2.4627
	sin	0.9272	0.9278	0.9285	0.9291	0.9298	0.9304	0.9311	0.9317	0.9323	0.9330
68	cos	0.3746	0.3730	0.3714	0.3697	0.3681	0.3665	0.3649	0.3633	0.3616	0.3600
	tan	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5782	2.5916
	sin	0.9336	0.9342	0.9348	0.9354	0.9361	0.9367	0.9373	0.9379	0.9385	0.9391
69	cos	0.3584	0.3567	0.3551	0.3535	0.3518	0.3502	0.3486	0.3469	0.3453	0.3437
	tan	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7034	2.7179	2.7326
	sin	0.9397	0.9403	0.9409	0.9415	0.9421	0.9426	0.9432	0.9438	0.9444	0.9449
70	cos	0.3420	0.3404	0.3387	0.3371	0.3355	0.3338	0.3322	0.3305	0.3289	0.3272
	tan	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8397	2.8556	2.8716	2.8878
	sin	0.9455	0.9461	0.9466	0.9472	0.9478	0.9483	0.9489	0.9494	0.9500	0.9505
71	cos	0.3256	0.3239	0.3223	0.3206	0.3190	0.3173	0.3156	0.3140	0.3123	0.3107
	tan	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	3.0415	3.0595
	sin	0.9511	0.9516	0.9521	0.9527	0.9532	0.9537	0.9542	0.9548	0.9553	0.9558
72	cos	0.3090	0.3074	0.3057	0.3040	0.3024	0.3007	0.2990	0.2974	0.2957	0.2940
	tan	3.0777	3.0961	3.1146	3.1334	3.1524	3.1716	3.1910	3.2106	3.2305	3.2506
	sin	0.9563	0.9568	0.9573	0.9578	0.9583	0.9588	0.9593	0.9598	0.9603	0.9608
73	cos	0.2924	0.2907	0.2890	0.2874	0.2857	0.2840	0.2823	0.2807	0.2790	0.2773
	tan	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646
	sin	0.9613	0.9617	0.9622	0.9627	0.9632	0.9636	0.9641	0.9646	0.9650	0.9655
74	cos	0.2756	0.2740	0.2723	0.2706	0.2689	0.2672	0.2656	0.2639	0.2622	0.2605
	tan	3.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062
	sin	0.9659	0.9664	0.9668	0.9673	0.9677	0.9681	0.9686	0.9690	0.9694	0.9699
75	cos	0.2588	0.2571	0.2554	0.2538	0.2521	0.2504	0.2487	0.2470	0.2453	0.2436
	tan	3.7321	3.7583	3.7848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812
	sin	0.9703	0.9707	0.9711	0.9715	0.9720	0.9724	0.9728	0.9732	0.9736	0.9740
76	cos	0.2419	0.2402	0.2385	0.2368	0.2351	0.2334	0.2317	0.2300	0.2284	0.2267
	tan	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972

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TRIGONOMETRIC FUNCTIONS 77.0°–89

Angle in degrees	Name of function	Value of function for each tenth of a degree									
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	sin	0.9744	0.9748	0.9751	0.9755	0.9759	0.9763	0.9767	0.9770	0.9774	0.9
77	cos	0.2250	0.2232	0.2215	0.2198	0.2181	0.2164	0.2147	0.2130	0.2113	0.2
	tan	4.3315	4.3662	4.4015	4.4374	4.4737	4.5107	4.5483	4.5864	4.6252	4.6
	sin	0.9781	0.9785	0.9789	0.9792	0.9796	0.9799	0.9803	0.9806	0.9810	0.9
78	cos	0.2079	0.2062	0.2045	0.2028	0.2011	0.1994	0.1977	0.1959	0.1942	0.1
	tan	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0
	sin	0.9816	0.9820	0.9823	0.9826	0.9829	0.9833	0.9836	0.9839	0.9842	0.9
79	cos	0.1908	0.1891	0.1874	0.1857	0.1840	0.1822	0.1805	0.1788	0.1771	0.1
	tan	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6
	sin	0.9848	0.9851	0.9854	0.9857	0.9860	0.9863	0.9866	0.9869	0.9871	0.9
80	cos	0.1736	0.1719	0.1702	0.1685	0.1668	0.1650	0.1633	0.1616	0.1599	0.1
	tan	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2
	sin	0.9877	0.9880	0.9882	0.9885	0.9888	0.9890	0.9893	0.9895	0.9898	0.9
81	cos	0.1564	0.1547	0.1530	0.1513	0.1495	0.1478	0.1461	0.1444	0.1426	0.1
	tan	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0
	sin	0.9903	0.9905	0.9907	0.9910	0.9912	0.9914	0.9917	0.9919	0.9921	0.9
82	cos	0.1392	0.1374	0.1357	0.1340	0.1323	0.1305	0.1288	0.1271	0.1253	0.1
	tan	7.1154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0
	sin	0.9925	0.9928	0.9930	0.9932	0.9934	0.9936	0.9938	0.9940	0.9942	0.9
83	cos	0.1219	0.1201	0.1184	0.1167	0.1149	0.1132	0.1115	0.1097	0.1080	0.1
	tan	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3
	sin	0.9945	0.9947	0.9949	0.9951	0.9952	0.9954	0.9956	0.9957	0.9959	0.9
84	cos	0.1045	0.1028	0.1011	0.0993	0.0976	0.0958	0.0941	0.0924	0.0906	0.0
	tan	9.5144	9.6768	9.8448	10.02	10.20	10.39	10.58	10.78	10.99	11.2
	sin	0.9962	0.9963	0.9965	0.9966	0.9968	0.9969	0.9971	0.9972	0.9973	0.9
85	cos	0.0872	0.0854	0.0837	0.0819	0.0802	0.0785	0.0767	0.0750	0.0732	0.0
	tan	11.43	11.66	11.91	12.16	12.43	12.71	13.00	13.30	13.62	13.9
	sin	0.9976	0.9977	0.9978	0.9979	0.9980	0.9981	0.9982	0.9983	0.9984	0.9
86	cos	0.0698	0.0680	0.0663	0.0645	0.0628	0.0610	0.0593	0.0576	0.0558	0.0
	tan	14.30	14.67	15.06	15.46	15.89	16.35	16.83	17.34	17.89	18.4
	sin	0.9986	0.9987	0.9988	0.9989	0.9990	0.9990	0.9991	0.9992	0.9993	0.9
87	cos	0.0523	0.0506	0.0488	0.0471	0.0454	0.0436	0.0419	0.0401	0.0384	0.0
	tan	19.08	19.74	20.45	21.20	22.02	22.90	23.86	24.90	26.03	27.2
	sin	0.9994	0.9995	0.9995	0.9996	0.9996	0.9997	0.9997	0.9997	0.9998	0.9
88	cos	0.0349	0.0332	0.0314	0.0297	0.0279	0.0262	0.0244	0.0227	0.0209	0.0
	tan	28.64	30.14	31.82	33.69	35.80	38.19	40.92	44.07	47.74	52.0
	sin	0.9998	0.9999	0.9999	0.9999	0.9999	1.000	1.000	1.000	1.000	1.0
89	cos	0.0175	0.0157	0.0140	0.0122	0.0105	0.0087	0.0070	0.0052	0.0035	0.0
	tan	57.29	63.66	71.62	81.85	95.49	114.6	143.2	191.0	286.5	573.0

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nctions. — If $a = \sin x$, then x is the angle whose sine is a; this may sed symbolically $x = \sin^{-1}a$, which is read "x equals the angle whose The angle x is also called the "anti-sine" or the "inverse sine" of r notation is used for the other functions; for example, $x = \cos^{-1}b$ express the relation that x is the angle whose cosine is b. At least functions" must be known to completely determine the quadrant in ngle lies; for example, if $x = \sin^{-1} 0.5$ then x may be either 30° or if we also have $x = \cos^{-1} 0.866$, then x must equal 30°, while if $x =$ .866), then x must equal 150°.

ctions may be taken from the table given above by finding the angle in corresponding to the function in the table. *Example:* $\sin^{-1} 0.319$ $180° - 18.6° = 161.4°$.

— The expression $(1 - \cos x)$ is called the "versine" of x.

s Among Functions of the Same Angle. —

$$x = \frac{\sin x}{\cos x} = \frac{1}{\cot x}, \qquad \sin^2 x + \cos^2 x = 1,$$

$$x = \frac{1}{\cos x}, \qquad 1 + \tan^2 x = \frac{1}{\cos^2 x},$$

$$x = \frac{1}{\sin x}, \qquad 1 + \cot^2 x = \frac{1}{\sin^2 x},$$

$$)-x) = \cos x, \qquad \sin(-x) = -\sin x,$$

$$)-x) = \sin x, \qquad \cos(-x) = \cos x,$$

$$)-x) = \cot x, \qquad \tan(-x) = -\tan x.$$

Difference of Two Angles. —

$$\sin(x+y) = \sin x \cos y + \cos x \sin y,$$
$$\cos(x+y) = \cos x \cos y - \sin x \sin y,$$
$$\tan(x+y) = \frac{\tan x + \tan y}{1 - \tan x \tan y},$$
$$\sin(x-y) = \sin x \cos y - \cos x \sin y,$$
$$\cos(x-y) = \cos x \cos y + \sin x \sin y,$$
$$\tan(x-y) = \frac{\tan x - \tan y}{1 + \tan x \tan y}.$$

the Functions of Two Angles. —

$$\sin x \sin y = \tfrac{1}{2}[\cos(x-y) - \cos(x+y)],$$
$$\sin x \cos y = \tfrac{1}{2}[\sin(x+y) + \sin(x-y)],$$
$$\cos x \sin y = \tfrac{1}{2}[\sin(x+y) - \sin(x-y)],$$
$$\cos x \cos y = \tfrac{1}{2}[\cos(x+y) + \cos(x-y)].$$

f Twice an Angle. —

$$\text{in } 2x = 2 \sin x \cos x, \qquad \cos 2x = \cos^2 x - \sin^2 x,$$

$$\tan 2x = \frac{2 \tan x}{1 - \tan^2 x}.$$

f Half an Angle. —

$$\frac{-\cos x}{2}, \qquad \cos\frac{x}{2} = \sqrt{\frac{1+\cos x}{2}}, \qquad \tan\frac{x}{2} = \sqrt{\frac{1-\cos x}{1+\cos x}}$$

Three Times an Angle. —

$$x = 3 \sin x - 4 \sin^3 x, \qquad \cos 3x = 4 \cos^3 x - 3 \cos x,$$

$$\tan 3x = \frac{3 \tan x - \tan^3 x}{1 - 3 \tan^2 x}.$$

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TRIGONOMETRY. — (*See also Trigonometric Functions.*) Any triangle completely defined when, (1) two sides and the included angle are kno (2) one side and two angles are known, (3) three sides are known. Let t sides and angles of a triangle be designated as in Fig. 1.

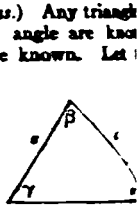


Fig. 1.

1. **Given two sides a and b, and the included angle γ.** Then

$$c = \sqrt{a^2 + b^2 - 2ab\cos\gamma}$$

$$\sin\alpha = \frac{a}{c}\sin\gamma$$

$$\beta = 180 - \alpha - \gamma.$$

2. **Given the side a and the two angles β and γ. Then**

$$\alpha = 180 - \beta - \gamma$$

$$b = a\frac{\sin\beta}{\sin\alpha}$$

$$c = a\frac{\sin\gamma}{\sin\alpha}.$$

3. **Given the three sides a, b and c.** Put

$$s = \tfrac{1}{2}(a + b + c)$$

Then

$$\sin\alpha = \frac{2}{bc}\sqrt{s(s-a)(s-b)(s-c)}$$

$$\sin\beta = \frac{b}{a}\sin\alpha$$

$$\gamma = 180 - \alpha - \beta.$$

Relations Between Sides and Angles. — The following relations bet the sides and angles of a triangle are sometimes useful:

$$\frac{a}{\sin\alpha} = \frac{b}{\sin\beta} = \frac{c}{\sin\gamma}$$

$$\cos\alpha = \frac{b^2 + c^2 - a^2}{2bc}$$

$$\sin\frac{\alpha}{2} = \sqrt{\frac{(s-b)(s-c)}{bc}}$$

$$\cos\frac{\alpha}{2} = \sqrt{\frac{s(s-a)}{bc}}$$

and similar relations for the other two angles.

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Y SYSTEMS, OVERHEAD. — (*See also Cars, Electric; Cross motives, Electric; Poles for Overhead Lines; Rails, Track and Third; lectric, Traction Systems for; Railways, Location and Permanent Way ail Systems; Transmission Lines; Trolley Systems, Underground; Cables, Bare.*) The following is a brief table of contents of this

ns	p. 1825
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y wire is usually of hard-drawn copper but sometimes of steel, ɔended from insulators some 16 to 30 feet above the ground, and ɔntinuous contact surface to a trolley wheel or bow attached to ock. There are two classes of trolley construction, the span wire bracket; each may have either simple or catenary suspension.

e and Side-bracket Construction. — In the simple span wire the trolley wire is supported by wires stretched across the tracks s or building walls. The side-bracket construction resembles the :ept that instead of the supporting wire being stretched between is stretched between two supports on the same pole. In both of : construction, the trolley wire is supported at intervals of 100 feet sags considerably between supports, making it necessary for the n constant vertical vibration as the cars move.

Construction. — The speed attained upon modern electric roads cult to obtain satisfactory service with a trolley wire which dips support and sags and sways with every impulse. The catenary was devised to meet this condition. In general, it consists of a er trolley wire suspended horizontally from a sagging messenger is suitably insulated and firmly held in place. The supporting erably employed for interurban single- or double-track roads is of et type, but for some conditions cross-span construction becomes he latter method of support differs only in the substitution of a s span for the bracket arm and doubling the number of poles ngle track.

'IONS OF VARIOUS TYPES OF CONSTRUCTION. — The :y system is used on urban railways, wherever the unsightliness or :xposed construction is not considered objectionable. It is used and suburban lines wherever the current taken by the trains is not economically carried on copper wires. In recent years it has been ction with the alternating-current systems of electric traction on lines.

construction is the most sightly for double-track city railways, namental brackets are used, side-pole construction being gener- ngle-track lines. Span-wire construction is used where, for any practicable to have the poles near the tracks or where, as is com- in Europe, the span wires are supported from the walls of build- e against overhead lines is often due to the excessive loading of both unsightly and dangerous.

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ELECTRICAL DESIGN OF CONDUCTORS. — In designing the tr system careful attention must be given to both the electrical and mechan features. In this section will be treated the electrical features, and in the lowing section the mechanical features. The electrical design of railway tribution systems involves the consideration of potential drop, heatin conductors and feeder economy. The heating of conductors is seldom important factor in railway feeder design, as it is usually necessary to u low current density to keep down the drop of potential. A discussion o heating of conductors will be found under *Wires and Cables, Bare*. The fe system being sufficient to meet the conditions imposed by the all potential drop (*see below*), it will be economical to make it greater i saving in the cost of energy which will result, is greater than the increa interest and other charges on the additional investment.

Allowable Potential Drop. — The total potential drop is limited by necessity of running the cars at a certain speed and by the need of keepin car lights brilliant. The potential drop in the ground conductors, i.e., the tr rails and bare negative feeders, is further limited by the danger of electro by current leaking into the earth (*see article on Electrolysis*).

The drop in the grounded conductors under maximum-load condition limited by law in Great Britain to 7 volts between any two points of the sy In Germany the maximum drop in the grounded conductors is limited to 1 per kilometer (1.61 volts per mile). In the United States the legal limit i matter of local option and is, in general, less severe than in Europe.

Calculation of Potential Drop. — The method of calculation of pote drop depends upon the following conditions: (1) whether the current is dir alternating; (2) whether the load is concentrated at one point, sparsely dis uted or evenly distributed; (3) the distribution of metal in the feeder cir and (4) whether the section is being fed by one or by two or more substat Calculations for alternating-current lines differ from those for direct-cur lines only in taking into account the inductance, as described below. On railways it is usual to assume the load to be evenly distributed, it being st as a given number of amperes per foot (*see article on Railways, Energy Re ments and Motor Capacity for*). If the load is actually concentrated a equidistant points, the drop will exceed that calculated on the assumption uniform distribution by about $\frac{100}{\pi}$ per cent. On interurban and trunk li the cars are usually concentrated at one or two points between substati making the assumption of uniform distribution impracticable. In such c the loads should be located so as to give the worst conditions, and calculati made as for any network.

Where electrolytic damage is to be guarded against, the drop of potenti the track rails themselves has to be calculated, as well as the total drop i rails and feeders.

Resistance of Trolley and Track. — Values of the resistance of tr wires to direct current will be found in the article on *Wires and Cables, B* and values of the resistance of rails to direct current will be found in the ar on *Rails, Steel*. It should be noted that the resistances of the trolley and p tive feeders are in parallel and that the track rails and negative feeders ar parallel. Also note that in the case of high-voltage systems a considera portion of the current returns through the earth and not through the rails a consequently the drop in the rails is due only to that part of the current wh returns through them. For preliminary calculations, however, the full curre may be assumed as returning through the rails.

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mulas for Direct-current Trolley Circuits. — The following formulas to certain typical circuits which frequently occur in practice. Let

I = total current in amperes taken by all cars on section considered,
L = total length of section in 1000 feet,
$_p$ = total drop in volts, in positive conductors between substation bus and far end of line,
$_n$ = total drop in volts in negative conductors between substation bus and far end of line,
$V = V_p + V_n$ = total drop in volts in both positive and negative conductors,
$_p$ = resistance in ohms of all the positive conductors in multiple per 1000 feet of line,
$_n$ = resistance in ohms of all the negative conductors in multiple per 1000 feet of line,
$r = r_p + r_n$ = total resistance in ohms per 1000 feet of line,
l = distance in 1000 feet, from far end of line to any point P,
v = drop to the point P, subscripts used as for V.

Uniformly Distributed Load, Uniform Conductor, Fed from One tation. — Then

$$v = \frac{rIl^2}{2L},$$

$$V = \frac{rIL}{2}.$$

e formulas are applicable to either the positive or negative conductors idered separately or to both in series.

Uniformly Distributed Load, Conductor Tapered to give Mini- Weight of Metal, Fed from One Substation. — For minimum ht the tapering must be such that at any point P

$$r = \frac{3V}{2I\sqrt{L}\sqrt{l}},$$

the cross-section, if all the conductors are of the same metal, must increase tly as the square root of l. drop to the point P is

$$v = \frac{V\sqrt{l^3}}{L^3}.$$

e formulas also apply to r the positive or negative luctors separately or to both ries.

Uniformly Distributed d, Conductor Divided into tions (Fig. 1); Each Sec- of Constant Resistance, from One Substation. he drop from P_n to the far of line is

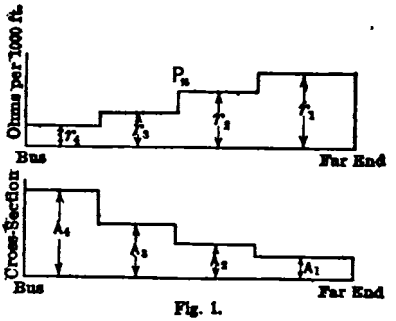


Fig. 1.

$$\frac{I}{2L}\sum_{s=1}^{s=n} r_s[l^2_s - l^2_{(s-1)}].$$

s formula is applicable to either the positive or negative conductors. The script s is here the general form of the subscript corresponding to each ion represented by 1, 2, 3 and 4 in Fig. 1.

Concentrated Load, Section Fed from One End.—Fig. 2 shows 4-track road with 4 trolley wires and 3 feeders with the tracks cross-bonded intervals. The solution given below is a general one, and may be applied any case from 1 track and 1 trolley wire up. Let all distances be expressed in 1000 feet and let

N_f = number of feeders in section considered, e.g., for the section AB, $N_f = 3$, and for the section BD, $N_f = 2$,

N_c = number of contact conductors, trolley wires or third rails in section considered, e.g., four are shown in Fig. 2,

N_t = number of tracks in section considered,

R_f = resistance of each feeder per 1000 feet,

R_c = resistance of each contact conductor per 1000 feet,

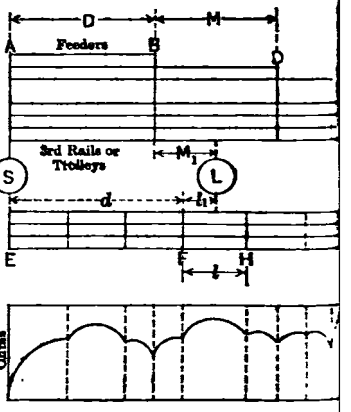


Fig. 2.

R_t = resistance of each track per 1000 feet (1 rail or 2 rails in multiple depending upon whether 1 or 2 rails are used for return conductor),

$$n = N_c + \frac{R_c}{R_f} N_f \qquad \text{for the section considered.}$$

Then for the section in which the load may be, the resistance of the positive conductors from the load to the end of that section in the direction of the substation, e.g., the resistance from L to B, is

$$R_c M_1 \left[1 - \frac{(n-1) M_1}{nM} \right].$$

The resistance of the positive conductors in any section such as BA is

$$\frac{R_c D}{n}.$$

(Note that the value of n for this section is not the same as for the section BD.)

The resistance of the negative conductors from the load to the first cross bond in the direction of the substation, e.g., the resistance from L to F, is

$$R_t l_1 \left[1 - \frac{(N_t - 1) l_1}{N_t l} \right].$$

The resistance of the remaining portion of the negative conductors, e.g., from F to E, is

$$\frac{R_t d}{N_t}.$$

(Note that if negative feeders are used, each negative feeder having a resistance of R_f' per 1000 feet, then for N_t in the last two formulas substitute $n' = N_t + \frac{R_t}{R_f'} N_f'$, where N_f' is the number of negative feeders for that section.)

The total resistance from the load to the substation is the sum of the resistances as above calculated.

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Concentrated Load, Section Fed from Both Ends, Substation tage at the Two Ends the Same. — The most convenient method of ıting such problems is to plot an "equivalent-resistance-distance" curve h as shown in Figs. 2 to 5. By "equivalent resistance" is here meant that stance by which the total current taken by the load must be multiplied give the total drop in voltage between the load and either substation. For mple, if the substation voltage is 600 at each end, the voltage across the l is 550 and the current taken by the load is 200 amperes, then the equivalent stance is $R = \frac{600 - 550}{200} = 0.25$. This method avoids the determination of distribution of the current in the various parts of the network, and the stance when once determined can be applied to any load.

. In Fig. 3 is shown a single track and single trolley. S_1 and S_2 are sub-tions; L is a load placed itrarily between correspond-points P_1 and P_2 on the pos-e and negative conductors pectively. Let

a = resistance of the conductors between the points $S_1P_1P_2S_1$;

b = resistance of the conductors between the points $S_2P_1P_2S_2$.

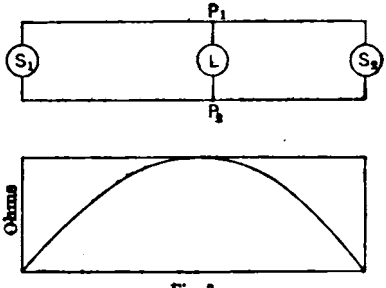


Fig. 3.

ese resistances are the resist-es of the transmitting con-tors and do not include the rnal resistances of the substations and load. Then the equivalent resist-e is

$$R = \frac{ab}{a+b}.$$

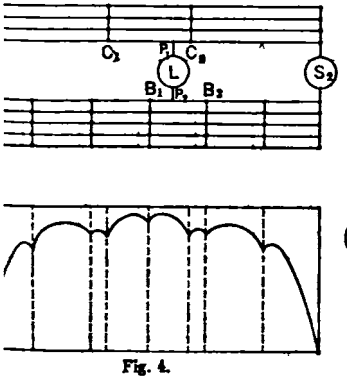


Fig. 4.

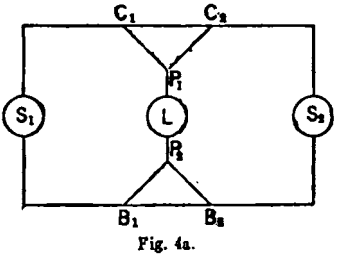


Fig. 4a.

2. In Fig. 4 is shown a 4-track road with 4 trolleys, both track and trolley oss-bonded. Fig. 4a is a simplified diagram of Fig. 4, corresponding points ing designated by identical letters.

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S_1 and S_2 are substations; L is a load placed arbitrarily between points P_1 on the positive system and P_2 on the negative system; C_1 and C_2 are ties between positive conductors and B_1 and B_2 ties between negative conductors.

Let

a = resistance of loop $S_1C_1P_1LP_2B_1S_1$,
b = resistance of loop $C_1P_1C_2C_1$,
c = resistance of contact conductor C_1P_1,
d = resistance of contact conductor C_2P_1,
e = resistance of loop $B_1P_1B_2B_1$,
f = resistance of track B_1P_1,
g = resistance of track B_2P_1,
h = resistance $\frac{d^2}{b} + \frac{g^2}{e}$,
i = resistance $\frac{c^2}{b} + \frac{f^2}{e}$,
j = resistance $S_2C_1P_1LP_2B_2S_2$.

These resistances are the resistances of the transmitting conductors and do not include the internal resistances of the substations and load. The equivalent resistance is

$$R = \frac{aj - ah - ji - 2\left(\frac{fg}{e} \times \frac{cd}{b}\right) + \frac{f^2d^2 + c^2g^2}{eb}}{a + j - h - i - 2\left(\frac{fg}{e} + \frac{cd}{b}\right)}.$$

Concentrated Load, Section Fed by Feeders from Both Ends. — Fig. 5 shows a simple case with feeders for the positive conductors only. The general formula is available for such a circuit. Any such network can, however, be calculated by Kirchhoff's Laws (q.v.), using the numerical values of the resistances for the various resistances. The equivalent resistance from the substations to the load is then the drop in voltage for a load of one ampere.

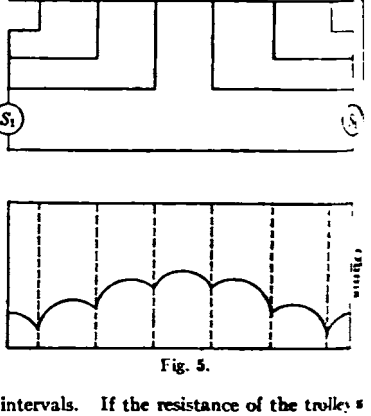


Fig. 5.

Ways of Reducing Total Drop. — Three methods are employed for reducing the total drop in the trolley and rails, viz:

1. **Plain or "Non-boosted" Feeders.** — Copper feeders, usually bare, may be connected to the trolley wire, third rail or track rails at frequent intervals. If the resistance of the trolley is high compared with that of the rails, which is usually the case, the feeders should be used to reënforce the trolley wire and not the track. In general, the most economical use of additional copper is to connect it in parallel with that side of the circuit having initially the higher resistance.

2. **Boosted Feeders.** — An insulated feeder may be tapped into the trolley wire or third rail at one point, and connected to a booster at the substa-

The principle of this method is to increase the activity of the feeder, i.e., ke it carry more current and thereby reduce the current in the trolley wire. is necessary only where the resistance of the line is so low that a moderate- feeder does not take its full share of current. It is not much used because line resistance is already low and the load is small, the drop will usually be enough naturally, and if the load is great, the booster and feeder will ly have to be so large in order to produce any effect, as to be prohibitive it cost and cost of operation.

3. **Floating Battery**, i.e., a battery connected across the line so as to e when the line potential is high and discharge when it is low. This scheme cy little used on account of the high cost of operating and maintaining a ry. It is difficult to imagine under what conditions such a system would mmercially practicable, but if anywhere, it would be on a long line with load and small feeders. Typical calculations for floating batteries are given ndon's *Storage Battery Engineering*, Chap. XLIV.

ays of Reducing Drop in the Negative Side of Circuit. — Owing to ecessity of preventing the leakage of current from track rails into the earth, y be necessary to reduce, not the total drop in the negative system, but the in the grounded portion of the negative. This may be accomplished by se of insulated feeders connected to the track rails so as to drain the current the latter and thus reduce the drop in the rails, regardless of the drop in eeders themselves. Such feeders may be used with or without a booster. with boosters, this method is probably the most economical way of reduc- he drop in return rails where a large reduction is necessary to prevent rolysis.

Negative Feeder with Booster. — In the case where the load is uni- ly distributed over the line, the size of booster which must be installed in ubstation may be determined as follows:

t a = amperes entering negative feeder system per foot of line,
r = resistance of negative feeder system per foot,
R = total resistance of the feeder connecting the booster to the negative feeder system,
I = total amperes entering negative feeder system from the motors,
I_0 = amperes to be taken off by booster,
$\frac{I - I_0}{a}$ = distance from substation to the point at which the current in the negative feeders is to be zero,
l_1 = distance from booster tap to point in negative feeders where current is zero,
l_2 = the distance from the booster to the end of the line.

n the booster voltage is

$$RI_0 - \tfrac{1}{2}\, ar(l^2 - l_1^2).$$

he output of the booster is, of course, the product of the current and voltage. he total drop is

$$\tfrac{1}{2}\, ar(l^2 - l_1^2 + l_2^2).$$

Del Mar's *Electric Power Conductors*, Chap. V, for a more complete treatment.

'ormulas and Constants for Alternating Current Trolley Circuits. — tle information is available on the effective or a-c. resistance (*see Alternating rents*) and reactance of steel rails. As a rough approximation the a-c. re- tance of a rail at 25 cycles per second may be taken as 4 to 5 times its d-c. istance and the reactance of the rail as approximately the same as that of one re of a pair of No. 0000 wires at a distance apart equal to the height of the

trolley wire above the track i.e., roughly as 0.4 ohm per mile. As a m of fact the a-c. resistance depends upon the shape of the rail, its mag quality, the value of the current and the frequency; to a lesser extent inductance, and therefore the reactance, depends upon these same items.

Data from Tests on N. Y., N. H. & H. R.R. — The following were obtained by A. W. Copley from tests on the New York New Haven Hartford Railroad and reported in the Trans. A.I.E.E., 1908, Vol. 27, (2) p. 1 An analysis of these tests is also given by H. Pender in the Elec. World, Vol. 53, p. 1457. Copley's results showed that a considerable portion of current entering the track from the load leaked to the earth. The comb resistance r of any number of trolley wires, and track rails and earth, as d mined by Copley, can be represented by the following formula

$$r = \frac{p_1 r_1 + p_2 r_2}{100},$$

where r_1 = the resistance of each trolley wire separately, p_1 = the per cen the total current in this wire, r_2 = the a-c. resistance of each rail separa and p_2 = the per cent of the total current in this rail. Similarly, the comb reactance x of any number of trolley wires and track rails and earth return be represented approximately by the formula

$$x = \frac{p_1 x_1 + p_2 x_2}{100},$$

where x_1 = the reactance of a given trolley wire, x_2 = the reactance of a rail and p_1 and p_2 as above.

Pender gives the following values for trolley wire and rail separately, upon Copley's tests:

Item	Resistance, ohms per mile		Reactance,* ohms per mile	
	25 cycles	15 cycles	25 cycles	15 cycles
Single trolley wire, No. 0000 B. & S....	0.26	0.26	0.38	0.33
000 B. & S....	0.33	0.33	0.36	0.33
00 B. & S....	0.42	0.42	0.39	0.33
Single rail, 100 pounds to the yard.....	0.16	0.13	0.44	0.36

* For the trolley wire 25 ft. above the track, changing the height of the trolley 5 ft. up or down changes these values by less than 5 per cent.

The combined resistance and reactance respectively of the trolley wires and earth are given in the following table:

For any other weight of rail the a-c. resistance of the rail itself may be ta as roughly inversely proportional to the weight per yard. The reactan of the rail, however, is practically independent of its cross-section, for the m netic flux within the rail is relatively small compared with the total flux rounding the rail (*see Inductance*).

Formulas for Single-phase Calculations. — The calculation of power lost and drop in voltage between a load and the power house are c lated in the same manner as in the case of an ordinary single-phase a-c. ta

RESISTANCE AND REACTANCE PER MILE OF ROAD

100-pound Rails

mber of tracks.....	.....		1		2		4	
mber of trolley wires.....	1		1		2		4	
mber of rails.....	1		2		4		8	
cent of total current return-ng through rails†.....	25		40°		58°		75°	
cles per second.....	25	15	25	15	25	15	25	15
mbined resistance of trolley ires, track and earth per mile f road								
No. 0000 B. & S. trolley.....	0.30	0.29	0.29°	0.28°	0.16°	0.15°	0.086°	0.082°
000 B. & S. trolley.....	0.37	0.36	0.36	0.35	0.20	0.19	0.11	0.10
00 B. & S. trolley.....	0.46	0.45	0.45	0.44	0.24	0.23	0.13	0.12
mbined reactance of trolley ires, track and earth per mile f road, all three sizes of trolley ire.....	0.49	0.30	0.47°	0.28°	0.27°	0.18°	0.17°	0.10°

The figures marked thus ° are taken directly from the paper by Copley, whose tests confined to No. 0000 trolley wires; the other values are calculated by Pender.

The percentages of total current returning through the rails are test results on the ., N. H. & H. R.R., and refer to relatively long sections (over 5 miles); a greater ortion of current flows in the rails in the immediate vicinity of the load and power e. The proportion of the total current which will return through the earth will nd upon the nature of the soil and ballast; for any other division of current the ance and reactance can be obtained from the approximate formulas given above. proportion of current returning through the earth on the N. Y., N. H. & H. R.R. has greatly reduced since the above data were obtained, by the use of the three-wire m shown in Fig. 6.

ion line (*see Transmission Lines*). For a concentrated load (e.g., a single) the calculation is as follows: Let

V = volts between trolley wire and track;
P = kilowatts at the locomotive delivered to locomotive;
s ϕ = power factor of load taken by locomotive;
l = distance in miles, between power house and locomotive;
r = combined resistance in ohms, per mile of trolley wire, rails and earth return;
x = combined reactance, in ohms, per mile of trolley wire, rails and earth returns;
$R = rl$;
$X = xl$.

n the current taken by the locomotive is

$$I = \frac{1000\,P}{V\cos\phi} \quad \text{amperes,}$$

power lost is

$$p = \frac{R\,I^2}{1000} \quad \text{kilowatts,}$$

drop in voltage between the power house and locomotive is

$$v = \sqrt{(V\cos\phi + RI)^2 + (V\sin\phi + XI)^2} - V \quad \text{volts,}$$

the power factor at the power house is

$$\cos\phi_0 = \frac{1000\,(P+p)}{V+v}.$$

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Example. — 2000 kw. at 25 cycles per second are to be supplied t locomotive at 90 per cent power factor and 10,000 volts at a distance of miles from the power house. The circuit consists of a No. 0000 trolley wire two 100-lb. track rails. Then $V = 10{,}000$, $P = 2000$, $\cos\phi = 0.9$, $\sin\phi = 0.4$ $l = 20$, $r = 0.29$ (assuming only 40 per cent of the current returning through rails), $x = 0.47$ (same assumption), $R = 0.29 \times 20 = 5.8$, $X = 0.47 \times 20 =$ Whence

$$I = \frac{1000 \times 2000}{10{,}000 \times 0.9} = 222 \text{ amperes},$$

$$p = \frac{5.8 \times (222)^2}{1000} = 286 \text{ kilowatts},$$

$$v = \sqrt{(10{,}000 \times 0.9 + 5.8 \times 222)^2 + (10{,}000 \times 0.435 + 9.4 \times 222)^2} - 10{,}000 =$$
2130 volts,

$$\cos\phi_0 = \frac{1000\,(2000 + 286)}{222\,(10{,}000 + 2130)} = 0.848.$$

Scheme of Connections Used by N.Y., N.H. & H.R.R. — The tribution system is shown diagrammatically in Fig. 6 where A is the tro

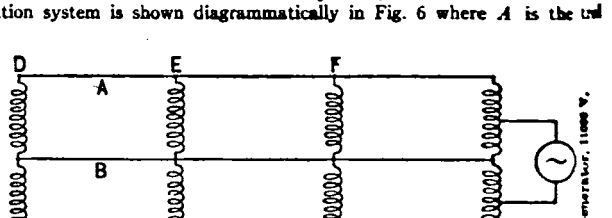


Fig. 6.

wires, B the track rails and C a feeder. These three sets of conductors connected at intervals of about two miles through auto-transformers D, E and The difference of potential between A and B, and between B and C is 11 volts and between A and C is 22,000 volts. The effect of this arrangement to practically give a transmission voltage of 22,000 with 11,000 volts at trolley, and to greatly reduce the current in the grounded conductors with a sequent reduction of disturbances to telephone lines.

MECHANICAL DESIGN OF OVERHEAD SYSTEM. — The va parts of the overhead system will first be described, and then the various of construction, span wire, catenary, etc. The American Electric Rail Engineering Association has adopted specifications for overhead line mater which cover most of the mechanical details pertaining to ordinary trolley li

Parts of Overhead Trolley Construction. — The trolley wire is secu to an "ear" by soldering, clamps or other means; the ear is bolted to a "s pension" which may or may not be provided with an insulating portion. Th suspensions are carried by span wires which in turn are fastened to the po or brackets, or may be fastened directly to the bracket. If the "ear" is n insulated, "strain" insulators are inserted in the span wire between the ear its point of attachment to the poles or brackets. A slightly different kind suspension, called a "pull-off," is used on curves. At turnouts "trolley

: be used to guide the trolley wheel. These various parts are illustrated in accompanying cuts.

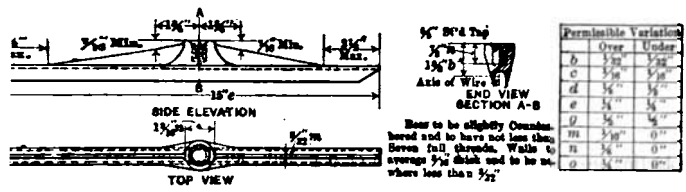


Fig. 7

Trolley Ears. — Figs. 7 to 10 are for round wire. Fig. 7 shows the dard straight-line ear of the A.E.R.E.A. It is made of cast bronze of approx-tely the following composition:

Copper	84 per cent
Zinc	10
Tin	3
Lead	3
	100 per cent

The ear shown in Fig. 8, which has a deep groove into which the wire is soldered type in common use. These ears may be provided with rings as in Fig. 9



Fig. 8. Fig. 9.

Fig. 10. Fig. 11.

Types of Trolley Ears for Round Wire

which guy wires are attached to relieve the strain at curves and for steadying line at intervals. Fig. 10 shows the type of ear used at points where the

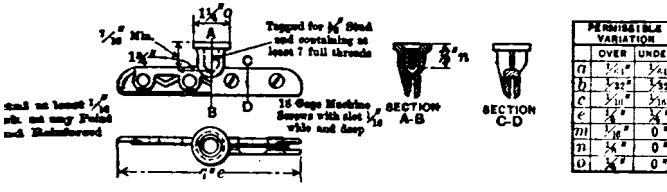


Fig. 12

olley is spliced, which should always be at an ear. Fig. 11 shows an ear with terminal for a feeder connection.

Figs. 12 to 14 are designed for grooved or figure "8" trolley wire. Special ooved or figure-8 wire affords a smoother running surface for the trolley heel or bow as the ear only grips the upper part, leaving the lower part solutely even. This construction is practically essential for bow trolleys. he design shown in Fig. 12 is the standard of the A.E.R.A. It is made of [illegible] which must conform with A.S.T.M. standards.

Soldering Trolley Wire to Ears. — The strain should be taken off the wire by a U-shaped clamp catching hold of it on each side of the ear. The



Fig. 13.



Fig. 14.

Types of Trolley Ears for Figure "8" Wires

soldering iron should weigh about 8 or 9 pounds, and should have a groove fitting half way round the wire. Special precautions should be taken not to have the iron unnecessarily hot.

Suspensions for Straight Line Work. — Fig. 15 shows an uninsulated suspension with ear attached for straight line work. Fig. 16 shows a suspension with strain insulators at each end; this is also used on curves for double-track



Fig. 15.



Fig. 16.



Fig. 17.



Fig. 18.



Fig. 19.



Fig. 20.

Types of Suspensions

work. Figs. 17 and 18 show solid insulated suspensions for span wire and side bracket construction, respectively. These types are frequently used, and are quite satisfactory if the insulating material used in their construction is properly made. Fig. 19 shows a section of an assembled cap and cone suspension. Fig. 20 shows a cap and cone suspension with ear attached. The cap and cone are made separate. This type is preferred by some engineers on account of the possibility of replacing injured bolts and insulation without removing the whole suspension. This advantage is partly offset by the greater liability to trouble due to multiplicity of parts, and this type of suspension is now little used.

Strain Insulators. — Fig. 21 shows a "globe" strain insulator, the type most commonly used. Fig. 22 shows a "Brooklyn" strain insulator. This type is used on wooden pole and light iron pole construction to draw span wires taut. It is also required even for heavy iron pole construction if spans are long and temperature variation great. Bolts may be provided at both ends if an extra amount of adjustment is required. A globe strain and a Brooklyn strain may be used in series where extra insulation is required.



Fig. 21.



Fig. 22.

Strain Insulators



Fig. 23.



Fig. 24.

Pull-offs

Pull-offs. — Fig. 23 shows a cap and cone pull-off for single-curve construction and Fig. 24 a cap and cone pull-off for double-track curve construc-

ll-offs of the same type as the uninsulated and solid insulated suspen- n in Figs. 15, 17 and 18 are also used.

olley Frogs. — A trolley frog is a malleable iron casting used at or crossovers where trolley wires from different tracks unite. Its func- hold the diverging wires together and afford a smooth running path to r wheel when a car passes or enters a switch. A common type is illus- Fig. 25. Frogs are made for various divergence, and both right and left The usual angles are 8, 15 and 20 de-

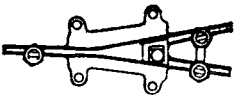
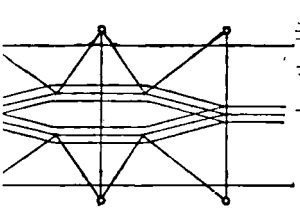


Fig. 25. Trolley Frog

d Tension in Overhead System. — attention must be paid to designing ead structure in such a manner that it stand the extra tension due to the contraction of the wires at low res and the extra loads due to wind and sleet, and a sufficient allow- d be made in the height of the trolley wire to take care of the extra sag xperiences at high temperatures. With a simple trolley construction ons in tension and sag may be calculated by a direct application of iven in the article on *Transmission Lines;* in the case of catenary n, the additional load due to trolley wire, clips, etc., is treated in vay as a sleet or wind load.

Suspension. — The following discussion applies primarily to span- de-bracket construction; catenary construction is treated in a sepa- n below. Details of standard parts are given in the A.E.R.A. Engi- nual.

ght of Trolley Wire Above Rail. — The height of wire varies ninimum of 16 feet and a maximum of 22 feet, the usual height being et. It is usual to raise the wire at railroad crossings to a height of nore above the top of rails. Catenary construction should be used ceeding 150 feet.



6. Simple Pull-off Arrangement

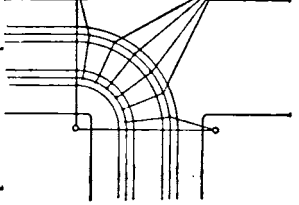


Fig. 27. Simple Pull-off Arrangement

e of Poles. — Bracket-arm poles on tangent construction should e backwards not exceeding 3 inches, and span-wire poles in hard ke of from 4 to 5 inches. In soft ground a rake of 12 inches is not

Center poles should be set vertically except at curves, where they away from the curve along the perpendicular to the tangent at that curve.

norage. — At both ends of every grade and curve, there should be t anchorage. If there are not many grades and curves, anchorages rovided at intervals of from ¼ to ½ of a mile. An anchorage is made

by means of a steel cable running from the trolley wire to one or more anch poles through an anchor ear and strain insulators.

Curves. — At curves in the track the trolley wire should be made t follow the curve by means of pull-offs or wires pulling the trolley wire outwa as shown in Figs. 26 and 27.

Wherever possible the pull-off wires should be radial to the trolley wire. Th however, requires a large number of poles, and is therefore impracticable i cities. In such cases, the bridle, bow-string or backbone construction shown Figs. 28, 29, and 30 is resorted to. In this construction the pull-off wir

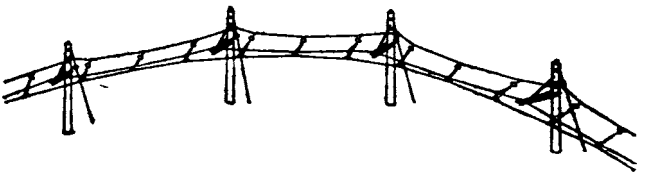


Fig. 28. Bridle Construction at Curve

instead of being anchored to individual poles are fastened to a wire which i stretched between poles. While this construction is almost universally used i cities, it is more expensive to maintain than single pull-offs, and is therefore no favored for interurban lines.

A combination of the two types of construction is shown in Fig. 31. Figs. 2 to 31 are from G. E. Co. publications.

Spacing of Pull-offs at Curves. — The number of pull-offs should b sufficient to keep the wire within about 2½ inches from the theoretical curv This may be accomplished by spacing the successive ears in accordance with th following relations:

Let L = distance between pull-offs in feet,
R = radius of curve in feet,
a = offset of wire in inches from theoretical curve, midway between pull-offs, the ears being assumed to lie on the theoretical curve.

Then,

$$L = \sqrt{\frac{2aR}{3} - \left(\frac{a}{6}\right)^2},$$

or

$$L = 0.815\sqrt{aR},$$

with an error less than ⅛ per cent for all radii greater than 40 feet.

If a is to be 2½ inches, then

$$L = 1.29\sqrt{R} \text{ approximately.}$$

If the ears are set exactly on the theoretical curve, the wire will depart 2½ inches from the correct position half way between the two ears; if the ears are set 1¼ inches from the curve, the mid-point of the wire will be only 1¼ inches when L is taken equal to $1.29\sqrt{R}$.

Offset of Trolley Wire at Curves. — It is usual, at curves, to offset the trolley wire from the center of the track (a) because the trolley wheel is tilted inward due to the elevation of the outer rail, and (b) because in order to keep the wheel on the wire, the latter must be so placed that the projection of the pole on the plane of the track is always tangential to the wire.

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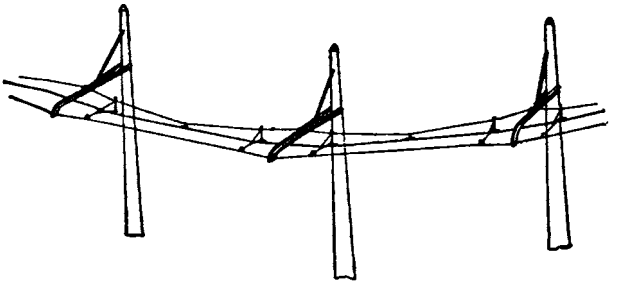


Fig. 29. Bow-string Construction at Curve

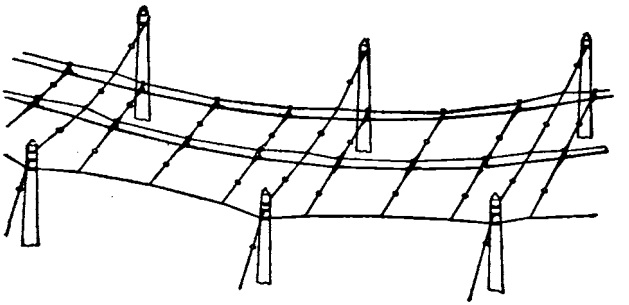


Fig. 30. Backbone Construction at Curve

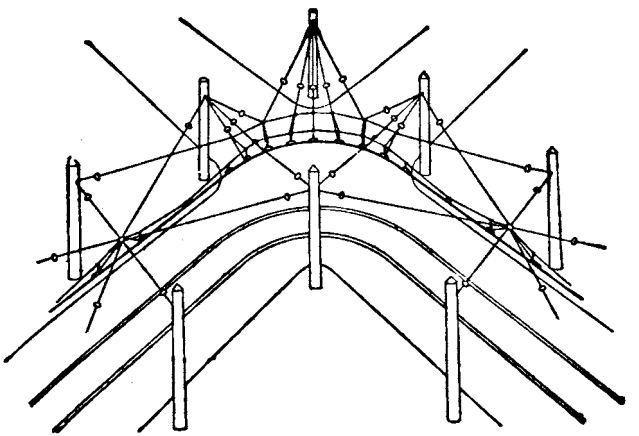


Fig. 31. Combination Construction at Curve

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(*a*). The former offset, measured horizontally toward the inside of the curve, equals $h \tan \theta$, where h is the normal height of the wire above the top of rail and θ is the angle of elevation between the plane of the track and the horizontal. For standard gauge and wire 18 feet above the top of rail this offset is about $\frac{1}{2}$ inches for every inch of elevation.

(*b*). The latter offset, also measured horizontally toward the center of the curve, is calculated as follows, assuming the curve to be longer than the rail itself; for shorter curves the offset will be less. Let

R = radius of curve,

L = horizontal distance of center of trolley wheel to center of trolley base, usually about 11 feet,

G = distance from center of car to center of truck.

In the case where the trolley base is located over the truck center, as on cars with two trolleys, the offset is

$$R - \sqrt{R^2 - L^2}.$$

If the trolley base is located over the car center as on cars with one trolley, the offset equals

$$R - \sqrt{R^2 - G^2 - L^2}.$$

The total offset is the sum of the offsets (*a*) and (*b*).

Curves of Small Curvature. — If the curvature* is less than 1°, the poles are frequently spaced closer together and no pull-offs used. The following table gives the practice of the Denver and Interurban R.R. Co., which may be considered typical, the divergence of the wire from the theoretical curve being kept within 3½ inches.

SPACING OF POLES ON CURVES, INTERURBAN ROAD

Degree of curvature of track	Pole spacing, feet	Divergence of trolley wire from track center, inches	Degree of curvature of track	Pole spacing, feet	Divergence of trolley wire from track center, inches
Tangent	120	0	6	60	2.87
1	120	1.87	7	50	2.34
2	110	3.37	8	50	2.64
3	90	3.06	9	50	2.94
4	80	3.37	10	50	3.24
5	70	3.06			

Turnouts. — (*See also Railways, Location and Permanent Way for*) The location of the trolley frog at turnouts may be determined as follows. Referring to Fig. 32, from switch point A draw a line to center point D of track frog distance BC and from switch point B draw a line to center point E of arc AEC. The intersection of these two lines at F will be the proper location of the frog. While certain variables, such as super-elevation of the outer rail on the curve, length of wheel base and projection of trolley pole

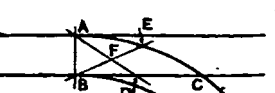


Fig. 32.

* The degree of curvature of a track is the angle which subtends a chord 100 feet long, between points on the center line of the track.

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from center of car, may necessitate slight variation of setting, this ill be found so nearly correct that a very small alteration, which letermined by experiment, will compensate for the variable con-

ompanying table gives the istance from track switch ack frog with which each ley frogs may be most ily used:

imum frog distance given : with which the 15° frogs rl to best advantage cor- › a turnout radius of 40 hen suburban cars, using trolley wheels, run over it is advisable to use 15° rather than 20° frogs throughout the city a even where the minimum frog distance is less than 20 feet.

Track-frog distance	Divergence angle of trolley frog
Up to 22 feet	20°
From 20 to 30 feet	15°
Above 28 feet	8°

OF TRUNK & INTERURBAN RAILWAY CONSTRUCTION.
CATENARY SUSPENSION

Railway	Voltage	Type of support	Tangent spacing of poles	Size of trolley wire, A. W. G. or B. & S.	Size of messenger wire, in.	Suspensions per span
, Westchester and y. Co.	11,000	Bridges	300	0000	5/8	30
aconda & Pacific	2,400	Span wire	110	0000	..	11
Milwaukee & St.	3,000	Bracket	150	0000	1/4	10
nterurban Ry.	11,000	Bracket	120	0000	7/16	12
ction System	.....	Bracket	140	.....	...	3
s & Cincinnati Co.	3,300	Bracket	120	.....	...	...
El. Ry. & Lgt. Co.		Center pole	110	0000	9/16	3
I. & H. R.R.	11,000	Bridges	300	0000	5/8‡	30
Western	11,000	Span wire	300	000*	1/2	10
t. (Philadelphia–	11,000	Span wire	300	000†	9/16	10
Inland Empire	.....	Span wire	100	000	5/16	...
Lake Shore &	6,600	Bridges	300	0000	7/16	10
ion Co.	600	Bracket	150	000	3/8	3
, Baltimore & An- Co.	6,000	Bracket	150	0000	1/4	9

- o copper or steel supporting wire above the copper contact wire.
). 00 supporting wire above the N–000 phono-electric contact wire.
ıd catenary with D inch messenger cable supporting the smaller one.

Messenger cables composed of 7 strands in all cases.)

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Catenary Construction. — Modern practice regarding catenary construction is illustrated in the preceding table. The constructions on the N. Y., N. H. & H. R.R., and Pennsylvania R.R. are described in greater detail below.

Simple and Compound Catenary Construction. — Catenary construction may be divided into simple and compound. In the former the trolley wire or wires are carried by one or two messenger cables which are supported only at the poles, bents or span wires; in the latter, the horizontal wire or wires are carried by a messenger cable, which is itself suspended by another messenger cable which is supported at the poles, bents or span wires. The advantages of the compound catenary are greater flexibility, reduced stresses in the supporting wires, shorter hangers, better lightning protection and superior curve construction. (*See description of N. Y., N. H. & H. R.R., construction below.*) The simple catenary is sometimes made with two messenger cables from which the horizontal wire or wires are suspended by triangular frames.

To obtain a line which will not require frequent readjustment, the messenger cable must be installed with practically uniform tension throughout its length, making it necessary to have less sag in the shorter spans. For this reason certain definite pole spacings and corresponding hanger lengths have been standardized (*see next section below*).

TANGENT CONSTRUCTION

Number of Hangers per Span. Pantagraph or Bow Trolleys

Length pole spacing, feet	Number of points of suspension	Length of hangers, inches										
		6	6¾	8½	11	12	13½	14¾	16	17½	19¼	20
150	11	1	2	2	2	..	..	2	..	..	2	
125	9	..	..	..	1	2	2	..	2	..	2	
110	8	..	..	..	..	..	2	2	..	2	..	
95	7	..	..	..	..	..	..	..	3	2	..	
80	6	..	..	..	..	..	..	..	..	2	2	
70	5	..	..	..	..	..	..	..	..	..	3	
55	4	..	..	..	..	..	..	..	..	..	..	

Number of hangers per span. Wheel trolleys

Length pole spacing, feet	Number of points of suspension	Length of hangers, inches							
		6	11	13½	14¾	16	17½	19¼	20
150	3	1	..	..	2	..	..	..	..
125	3	..	1	..	..	..	2	..	..
110	3	..	..	1	..	..	2	..	..
95	3	..	..	..	..	1	..	2	..
80	3	..	..	..	..	..	1	2	..
70	2	..	..	..	..	..	..	..	2
55	2	..	..	..	..	..	..	..	2

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spensions. — (*See also p.* 1841.) The number of suspensions depends speed at which the cars are to be run and upon whether a bow or wheel used. The three-point suspension in which, with 150 feet spacing, s are 50 feet apart has been found ample for wheel collectors at speeds m.p.h. With the sliding pantagraph or bow trolley an eleven-point has been found sufficient, with 150 feet pole spacing.

ngers. — (*See also p.* 1842.) Where only one horizontal wire is sus- om the messenger cable, the hangers should hang loosely from the should be screwed fast to the trolley wire. This permits the trolley e slightly as the trolley passes under it, thereby making the wire rible along its entire length. Where a steel contact wire is clipped to ntal conductor, the hangers are usually rigidly attached at both ends, lication of horizontal wires assures uniform flexibility, regardless of s.

nd Equipment or Erection. — Work should be done, as far as prac- h the aid of a construction train at least five cars long and equipped le scaffolds. With such a train the following daily results are attain-

	Men	Number erected
Erecting poles	26	117
Erecting brackets	18	150
Stringing catenary	17*	7 miles
Stringing and splicing trolley wire	12*	7 miles
Clipping messenger and trolley	13*	3½ miles

* Exclusive of train crews.

L EXAMPLES OF CATENARY CONSTRUCTION. — The amples are given to illustrate in greater detail the methods employed construction.

rk, New Haven & Hartford R.R. — The various types of con- ccessively adopted by this company are all for high-speed traffic. l construction consisted of a simple catenary system made rigid by

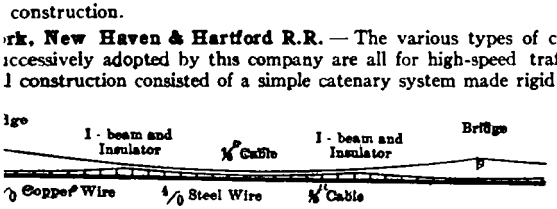


Fig. 33

two steel messenger cables with equilateral triangular steel pipe fferent lengths, joining them to the copper trolley wire. This having to be too rigid was modified by the addition of a steel contact wire rom the copper wire by clips midway between hangers. Considera- nomy and the desirability of securing better lightning protection doption of a compound catenary, that is one in which one messenger ported from another by suspension insulators, the upper cable being The copper wire is supported horizontally by suspensions of suit- s from the lower steel cable and a steel contact wire clipped to the

copper wire midway between hangers as shown in Fig. 33. Both of the ab types of construction involve the use of heavy lattice steel bents spaced 300 apart.

Pennsylvania R.R. — While both types remain in successful operation the N. Y., N. H. & H. R.R., a less expensive one was developed for the N York Connecting Railroad and the Philadelphia & Paoli Branch of the Pe sylvania Railroad. This construction is especially suitable where there opportunity to use guy poles instead of lattice bents. In this construct pairs of guyed steel poles, one on each side of the track, are spaced 300 f apart. The two poles of a pair are joined by two messenger cables as shown Fig. 34, making a small catenary system across the tracks with a vertical s

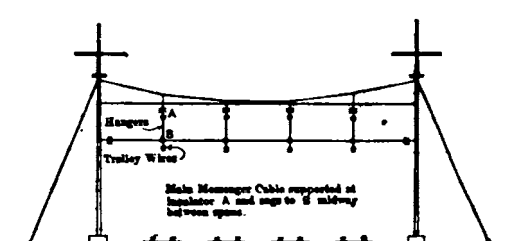


Fig. 34

pension rod over the center of each track. The upper of these cables has diameter of 5/16 inch and the lower of 1/2 inch. The vertical rods are 3/8 in in diameter and terminate in malleable iron clamps. An insulator consisting of three 10-inch porcelain disks is attached to each of these clamps and the main messenger cables suspended therefrom over the center of each track. These messenger cables consist of 1/4-inch double galvanized extra strong steel. The usual No. 2–0 grooved copper wire is suspended from this messenger cable by hangers 30 feet apart and a No. 3–0 phonoelectric contact wire is clipped 1 3/4 inches below the copper wire.

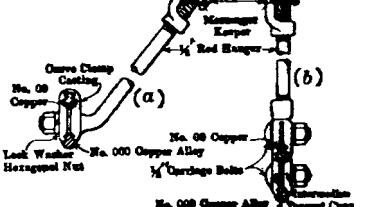


Fig. 35

The hangers used for supporting the copper wire are shown in Fig. 35. They are made of hot-galvanized steel.

To prevent side swaying of the lower wires in heavy winds a steady-brace is installed between poles and wires. These consist of steel wires insulated from the structure by strings of three porcelain insulators similar to those used to support the messenger cable. The contact wires themselves are insulated from it by single wooden strain insulators 6 inches long.

On the curves, steadies or pull-offs are used, but the hangers between the main messenger cables and the copper wires are spaced 15 feet instead of 30 feet as on tangents and the suspension rods are differently bolted as shown in Fig. 35.

e guys are 1 ½-inch rods attached to the poles through collars provided buckles. They are anchored in reinforced concrete blocks 8 feet or w ground and protected from the ground by 3-inch boiler tubes.

», Milwaukee & St. Paul R.R. — The 3000-volt trolley system of & St. P. R.R., comprising 660 miles of electrified trunk line, has two ntact conductors suspended by alternate hangers from the same This enables 2000 amperes to be collected by a copper-shod panto- ector at a speed of 60 m.p.h. The return circuit has an aerial con- ich is connected to the track rails every 8000 feet, preventing the : of dangerous voltages at rail joints in case of broken bonds.

onstruction. — In yards, wire cross-spans between poles, are used the messenger cables the insulators being suspended from the by ⅛-inch soft-steel cable. A horizontal steady-wire insulated slightly above the level of the contact wire supports the steady- which the contact wire is clipped. On curves, an additional insulated : is attached to the messenger wire at the poles. The messenger n reduced from ⅝ inch to ⅜ inch and the hangers are spaced 15 feet s and 10 feet on curves. A copper contact wire is not required.

d Sections. — Main-line conductors are usually divided into m cross-over to cross-over. Wherever conditions permit, sections are y staggering the contact wires laterally and running the two wires out 18 inches apart, each to a separate insulator. The ends are o avoid catching the pantograph.

s. — Turnouts are made by means of steel deflectors or frames the diverging wires at a fixed angle apart.

in Spans. — The stresses in the ⅛-inch cable of the original onstruction of the N. Y., N. H. & H. R.R. are as follows on a tangent an:

Condition	Tempera- ture, ° F.	Sag, ft.	Stress, lb.
Normal	60	6.42	7,550
Normal	−10	5.71	8,550
Sleet and wind	−10	6.46	14,750

s in the ⅛-inch cable of the original triangular construction of the [. & H. R.R. are as follows on a tangent 140-foot span:

Condition	Tempera- ture, ° F.	Stress, lb.
Normal	60	4930
Normal	−10	7100
Sleet and wind	−10	8400

in the copper wire and contact wire are negligible. Sleet is assumed : wire to a depth of one-half inch and the wind is assumed to exert of ⅜ of 8 pounds per square foot.

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Hangers. — The longest hangers of the original triangular construct of the N. Y., N. H. & H. R.R. (140 feet apart) have a length of 15½ inc measured between centers of wires. The shortest hangers are 4½ inches l For main-line construction they are made of ¼-inch rods, for yards, of ⅜-i rods.

SPECIFICATIONS. — (*See also article on Specifications.*) Specificat for trolley wire are given under *Wires and Cables, Bare*, and for insulators *Insulators for Overhead Lines*. The specifications of the American Ele Railway Engineering Association, which refer to overhead trolley systems, as follows:

Specifications for Overhead Line Material (for 750 Volt Direct-Cur Direct Suspension).

Railroad Specifications for Electric Light, Power Supply and Trolley Li Crossing Steam and Electric Railways.

These two specifications aggregating 87 pages contain a great deal of valua data, including drawings of various detail parts and general layouts.

OPERATION. — The operation of overhead lines for low-speed cars pres few difficulties owing to the adaptability of the trolley pole and wheel at s speeds. With high-speed cars the case is different as the collector wheel rapidly and the line must be kept uniformly level, smooth and elastic throu out and all special work must be maintained in first-class condition. If the c lector vibrates in resonance with the loops in the contact wire, an increase in number of supports will usually cure the trouble.

Prevention of Formation of Sleet. — Sleet may be prevented from for ing on the wires by greasing the latter with petroleum jelly and if it does fo it may be easily removed by any of the numerous commercial forms of sl cutters.

Wear of Trolley Wheel, Bow and Trolley Wire. — The wear of t trolley wires is not serious either with wheel or bow collectors. On the lines the Indianapolis & Cincinnati Traction Co., a copper trolley wire lost less tha 1 per cent in weight after it had experienced 39,000 car movements, each c taking an average of about 40 amperes by an aluminum slider.

The vertical wear of the steel contact wire on the N. Y., N. H. & H. R.R. was 0.028 inch in thirty months, which is practically 4.5 per cent per year of the ful diameter of the wire (one-half taken to permit wire to be held in clips) which even on this vertical diameter basis, indicates a life of over 20 years; but as a matter of fact it will be much more than this, for the reason that as the vertical diameter lessens the breadth of contact increases throughout, thus diminishing the rate of vertical wear. There is practically no corrosion on the under side of the wire where there is much traffic, for the wire is covered with a film of grap deposited by the pantograph shoe (*W. S. Murray*). The upper part, however rusts and rain water washes the rust on to the roofs of the cars (*Amberg*).

Change in Length of Trolley Wire. — The change in length of copper due to changes in temperature is one of the greatest difficulties in the maintenance of overhead work. A drop of 100° F. in temperature will cause a copper bar to contract approximately 1 inch for every 100 feet of length. If it be restrained, at the ends this will cause an additional stress of 2500 pounds in a No. 0000 trolley. (*See Transmission Lines.*)

European catenary lines are usually maintained at constant tension by means of weights pulling on the free ends of the trolley wire at the end of every section.

Flashing. — Considerable trouble has been experienced with flashing on high-voltage d-c. lines. This has been largely overcome by placing a resistance shunt across the station buses to shunt out the harmonics set up by the shun

of the machine armatures. In addition to the above, flash suppressors consisting of electrically operated switches that kill the field of the excited d-c. generators, thereby killing the d-c. voltage instantly. riers are also used on the high-voltage commutators.

NG OF TROLLEY CIRCUITS. — Trolley lines have to be tested, sistance, and (2) for insulation from ground. The resistance may ed by grounding one end of the wire to the track rails and circulat- it at reduced voltage. The drop in the overhead lines may be using another trolley wire, a telephone wire or the earth as a ead. If the earth is used, the connections to ground should be suffi- from the track rails to be outside the zone of potential disturbance *olysis of Underground Structures*).

RS OF TROLLEY CIRCUITS. — The repair methods of four lways are given below.

lphia Rapid Transit Co. — The overhead line organization is in he Superintendent of Overhead Lines and is divided into maintenance uction crews, emergency crews, a pole crew and one special crew on and electric switch and signal maintenance.

ntenance and construction crews and the pole crew are under separate The emergency crews and the electric switch and signal crew report ie Superintendent of Overhead Lines.

ntenance and construction foreman has four crews, each consisting men, one helper and a driver. The pole gang consists of the foreman, oreman, five helpers and two drivers. There are also two men who rs to sidewalks and metal awnings in connection with the pole work. ni.e emergency stations, seven of which are manned for 24 hours id two for twelve hours per day. These stations care for approxi- miles of line each, taking care of line troubles, traffic blockades and t of the line repairs in the district. They, however, when needed, calls in other districts. The movements of these emergency crews led by telephone by an emergency operator at headquarters to whom is reported and who keeps a log sheet showing all movements of these ey do not leave their stations except on his orders.

these emergency stations are equipped with two-ton auto trucks elescopic towers. Four stations are each equipped with two-horse ower wagon and four horses. One of these wagon stations has also truck equipped for handling wrecks but not line troubles.

ion to the above there are tower trolley cars for heavy work located these stations.

United Railway Company. — The maintenance and construction consists of three gasoline power line wagons, one three-ton horse idlass truck, one single truck line car, and one double truck line car, vith hoist and windlass. The gasoline power wagons and line cars manned by one foreman, two line men, a driver or trolley man.

rgency station is located in the center of the city and serves twenty- of city line. Its equipment includes three gasoline power line wagons asoline wrecking and hose jumper wagon. These men are on duty ncy work during the day time and four at night.

rgency station is the headquarters for all equipment.

Traction System. — The line is divided, for overhead maintenance into districts averaging 90 miles in length. A line foreman and s are assigned to each district and are given a tower line car with rew.

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Light maintenance work is handled from gasoline motor car equipped w
ht collapsible tower, the regular line car being used only for the heavier w
N. Y., Westchester & Boston Ry. — This line has 54 miles of 11,000-v
ntact wire. The general foreman has one day foreman, one night foreman
e linemen and one assistant lineman. They use a work train consisting
gasoline-electric locomotive and work car, the former carrying the work
ıtform. (Zogbaum.)

COST PER MILE OF SPAN-WIRE TROLLEY CONSTRUCTION
(600 VOLTS)

(Exclusive of Track Work and Bonding—Before the War Prices)

Item	Unit price	Single track		Double track	
		Quantity	Total cost	Quantity	Total cost
Material (incl. 2 double curves):					
Yellow-pine poles, octagon	$6.00	88	$528	.....	
Iron poles, No. 2	19.00	.....	....	88	$1672
Iron poles, No. 4	36.00	.....	....	4	144
Cement	2.35 & 2.15	22 bbl.	52	33 bbl.	71
Broken stone	0.95	14 cu. yd.	13	14 cu. yd.	13
Black paint	0.90	20 gal.	18	11 gal.	10
Span wire	0.012	1250 ft.	15	2500 ft.	30
Pull-off wire	0.006	1250 ft.	8	2500 ft.	15
No. 000 copper wire, per lb.	0.18	1 mi.	483	2 mi.	966
Straight-line suspensions	0.285	36	10	72	21
Side-feed suspensions	0.57	8	5	16	9
Deep groove ears	0.235	56	13	112	26
Frogs	3.25	2	7	4	13
Diagonals	3.60	.....	....	2	7
Brooklyn strains	0.71	.....	....	110	78
Frog pull-offs	0.36	6	2	12	4
Pole clamps	0.12	9	1	18	2
Globe strains	0.31	15	5	30	9
Side-feed wire (No. 0, inches)	0.102	120 ft.	12	240 ft.	24
Double bodies	0.93	6	6	12	11
Single bodies	0.53	6	3	12	6
Miscellaneous	.....	.....	1	.....	1
Total material	.....	.....	$1182	.....	$2938
Labor (incl. 2 double curves):					
Setting poles	.....	.....	$156	.....	$312
Trucking	.....	.....	25	.....	50
Painting, one coat	.....	.....	9	.....	17
Running trolley wire	.....	.....	50	.....	100
Building 2 double curves	.....	.....	34	.....	34
Putting up span wire	.....	.....	20	.....	20
Total labor	.....	.....	$ 294	.....	$ 573
Grand total per mile	.....	.....	$1476	.....	$3511

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OF TROLLEY CONSTRUCTION. — The costs given in the ables will serve as a rough guide in making preliminary estimates. pre-war prices, as but little work of this character has been done ar.

for Curves. — Under ordinary conditions curves add about 10 per cost of direct-suspension construction and about 15 per cent to the nary construction.

for 1200-volt Construction. — The following amounts should be ive proper values for 1200-volt construction.

spension:

ket construction..... $40.00
n construction..... 40.00

suspension:

ket construction..... $10.00
n construction..... 10.00

RATIVE COST PER MILE OF SINGLE-TRACK DIRECT SUSPENSION AND CATENARY CONSTRUCTION

600-volt Line, Tangent Track

Item	Direct suspension		Catenary, three-point	
	Bracket	Span	Bracket	Span
nches by 30 feet	$265	$530	$180	$360
uy and span cable	45	150	21	100
r cable	....	....	92	92
trolley wire	540	540	540	540
e material	145	99	144	101
naterial	995	1319	977	1193
poles	185	371	126	252
brackets	13	....	9	....
span wire and guys	....	212	....	144
and clamping wire	75	75	200	200
anchors	100	100	50	60
abor	373	758	385	656
us extras	150	150	150	150
l	$1518	$2227	$1512	$1999

lt trolley system on the Portland Division of the Southern Pacific ving wooden poles, bracket suspension and simple catenary, cost ile for material and $600 for labor, a total of $2100 for tangent . Due to curves, etc., the average cost was about 20 per cent

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COST OF COMPOUND CATENARY ON TANGENT, N. Y. N. H. & H. R.R. PER MILE OF SINGLE TRACK

(E. J. Amberg, 1915)

Item	2-track	4-track	6-track
Catenary Material	$2800	$2800	$2800
Catenary labor and work train	600	600	600
Steel work erected	2300	2200	3300
Foundations installed	800	800	800
Total	$6500	$6400	$7500

The cost per mile of 2400-volt, single-track distribution system (including feeders and bonding), on the Butte, Anaconda & Pacific Ry Co. was given by J. B. Cox as $5514 per mile of single track (1915).

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EY SYSTEMS, UNDERGROUND.— (*See also Trolley Systems,*
This system is little used on account of its cost, the installations at , New York, Washington and London being the only notable ones. ial feature of all these systems is the underground conductor which from the car by a "Plough" extending through a continuous slot the tracks.

'ORK SYSTEM. — The most successful construction is the latest type, a brief description of which is given below.

l Description. — The street is excavated and cleared of obstructions ı of about 5 feet 6 inches and a depth of about 3 feet and cast-iron . 1) set in the excavation about 5 feet apart. The track and slot pported on these yokes and the whole system made solid with con- ı fills the excavation from the foundation to near the top of the rails / a tunnel under the slot free from masonry. The conductors are sus- his tunnel, by special strain insulators, no part of the electrical system ıded. The use of two insulated conductors avoids trouble in case ıl grounding.

The yoke shown in Fig. 1 is made in three parts. The lowest ı rests on the floor of the excavation is a 6-inch steel I-beam, 4 feet g. Two castings 6½ : are riveted to this, rving to support one ıd one slot rail. Fig. th slot rails in place ne track rail. The carried on a timber ch extends from yoke g the whole line. The e held to the yokes unk iron plates the ends of which project beyond the stringer and have accommodate bolts running through the yoke. These bolts serve ıal purpose of fastening the rails to the stringers as they also pass s which bear upon the foot of the rail. The rails are further secured s running to the center of the yoke. The slot rails are bolted direct and are connected to the track rails by long bolts every 30 inches.

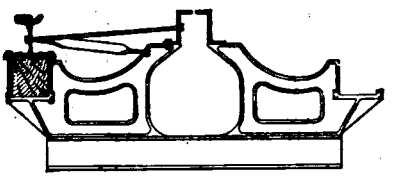


Fig. 1.

· Boxes. — A pair of cast-iron boxes are laid across from the slot track rails and bolted to them every 15 feet as shown in Fig. 2. ain the insulators ort the contact con- nside each box is a ves running normal k; resting on these bolted to them is a idge which holds the The top of the box l with a cast-iron ı is flush with the :e.

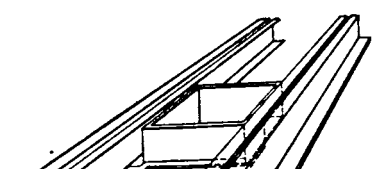


Fig. 2.

Work. — When the laid the tunnel which the conductors and ıing is formed with collapsible sheet iron, fitting closely to the center he yokes and run from yoke to yoke. The space from the bottom

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of the insulator boxes to the road foundation is formed with boards. Con is then poured into the excavation completely filling every part but the and its offsets at the insulator boxes. The concrete is poured to wit height of a paving block of the rail tops. When the concrete is hard sheet-iron form is collapsed and pulled along to the next section. The at the bottom of the insulator boxes being collapsible are drawn out th

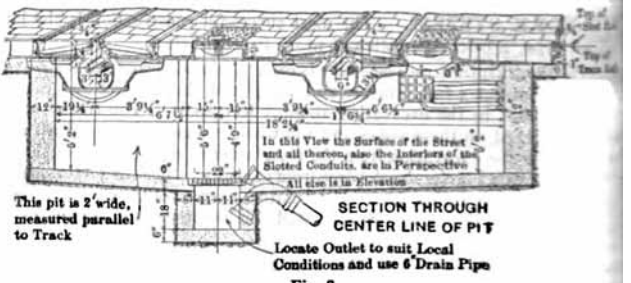


Fig. 3.

the handholes and are used again elsewhere. The depth of the comple tunnel is 18 inches from the base of the slot rails. A view of an older York City construction is shown in Fig. 3, which is taken from an artic the *Street Railway Journal*.

THE LONDON SYSTEM has alternate long and short yokes, the long fulfilling the same function as the New York ones, the short ones serving to give additional support to the slot rails. No stringers are used, the resting on hard-wood blocks at the yokes only.

THE BUDA-PEST CONSTRUCTION has the slot in the track rail saving considerable iron, but necessitating an excessively wide slot to acco date the wheel flanges.

COSTS. — The type of construction in New York City cost from $ to $100,000 per mile of track, exclusive of feeders, depending upon the cond under which it was installed. Due to the high cost of this system, its us not extended.

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AND CONVERSION FACTORS. — In this article are given rical interrelations, or "conversion factors" for all the commonly English and metric units. For the definitions of the various quan- *Mechanics, Principles of; Heat and Thermal Properties; Temperature; and Magnetism, Principles of; Alternating Currents; Units, Practical* and *Photometric Quantities*. For a list of the abbreviations and sym- ted by the American Institute of Electrical Engineers see *Abbrev- d Symbols.*

lowing is a list of the tables of conversion factors given in this

echanical Quantities

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ity and Speed..... 1864
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'eight..... 1866
Specific Gravity..... 1866
..... 1867
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Quantity of Electricity; Dielectric Flux..... p. 1870
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Electric Current..... 1871
Current Density..... 1871
Electric Potential Difference; Electromotive Force..... 1871
Electric Potential Gradient; Electrostatic Field Intensity..... 1872
Electric Resistance..... 1872
Electric Resistivity..... 1873
Electric Conductivity..... 1873
Capacity..... 1874
Inductance..... 1874
Magnetic Flux..... 1874
Magnetic Flux Density..... 1874
Magnetic Potential Difference; Magnetomotive Force..... 1875
Magnetic Potential Gradient; Magnetizing Force..... 1875

IS OF UNITS. — By the magnitude of any quantity is meant magnitude of this quantity as compared with some other quantity *ature;* e.g., a length of 10 inches means a length which is ten times of one inch. To measure a quantity, then, it is necessary either t first some fixed magnitude of the same nature which may be used rd of reference, or unit, or (2) to define the quantity in such a way it of measurement may be derived from the arbitrarily selected quantities involved in the definition.

ntal and Derived Units. — Units which are chosen arbitrarily fundamental" units; those which are derived from a set of fun- its are called "derived" units. All mechanical units can be de- set of three fundamental units; the three units ordinarily chosen ntal are those of length, mass and time. In relations involving changes, an arbitrary unit of temperature is also chosen; to ex- ical and magnetic quantities at least one electrical or magnetic arily chosen; to express photometric quantities the unit of luminous arbitrarily chosen. These arbitrarily chosen non-mechanical units uxiliary fundamental" units.

and Metric Systems of Units. — There are two systems of units in use in English speaking countries, the English and the metric, systems. The latter system is used universally by physicists ed countries and also forms the basis of the electrostatic and elec-

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tromagnetic systems of electric units used by engineers as well as physici The English system of mechanical units, however, is used almost univers by English speaking peoples, in engineering, in commerce and in the arts; is also the basis of the system of thermal units used largely by engineers. gineers, however, are coming to use the metric system to a greater and gr extent for all purposes.

In both the English and the metric systems length, mass and time are ch as the fundamental quantities. In the English system the fundamental u for these three quantities are respectively the foot, the pound (avoirdu and the second; this system is therefore also called the foot-pound-sec system. In the metric system the corresponding units are the centim gram and the second; this system is therefore also called the centim gram-second, or c.g.s., system. The magnitudes of these fundamental u have been fixed arbitrarily by law; see below.

Absolute and Gravitational Units. — Two different units of force units derived therefrom) are used in both systems, viz.: (1) the unit of forc defined as that force which will give unit acceleration to unit mass, and the unit of force is defined as that force which will give to unit mass an acc ation equal to the acceleration of a freely falling body under the influenc "gravity" or the pull of the earth alone (*see Mechanics, Principles of*). The unit is called the "absolute" unit of force and the second the "gravitati unit of force, and derived units based on these two units are called abs and gravitational units respectively. The gravitational units are not def unless the latitude and elevation of the point at which the acceleration due gravity, usually represented by the symbol "g," is specified. By internati agreement (*Troisème Conf. Gen. des Poids et Mes., 1901, p. 66*) the v $g_0 = 980.665$ cm. per sec. per sec. ($= 32.1739$ feet per sec. per sec.) has chosen as the standard value for the acceleration due to gravity; this valu g may be called the "gravitational acceleration constant." The value 98 was chosen to represent the value of g at 45° latitude and sea level, but measurements give a slightly different value of g at this latitude and elevati the value 980.665, however, is retained as the *standard* value of g_0.

The gravitational unit of force in the English system is called the po and in the metric system the gram, the same names being used for the of force as for the unit of mass. This arises from the fact that unit mas a force exerted upon it by the earth, i.e., has a *weight*, numerically equal t mass, when the force is expressed in terms of this gravitational unit. (Th exactly true only at the latitude and elevation for which $g = g_0$, but the varia with both latitude and elevation is usually negligible in engineering work.*) absolute unit of force in the English system is called the poundal, but is pra cally never used; the absolute unit of force in the metric system is called dyne, and is the unit of force commonly used by scientists. In engineeri work the common units of force are the gravitational units, pound or gr and their multiples and submultiples.

The relation between the absolute and gravitational units of force are:

1 pound = 32.1739 poundals,
1 gram = 980.665 dynes.

Weight and Mass. — The word weight is used in two different sense viz.: (1) to mean the force with which the earth attracts a piece of matte

* The force acting on a mass of 1 pound at sea level at the equator is 0.997 pound, and at sea level at either pole of the earth is 1.002651 pound. An increase elevation of 10,000 feet diminishes the force acting on a mass of 1 pound by o 0.00096. See Landolt, Börnstein and Roth, *Physikalish-Chemische Tabellen*.

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› designate a given mass or quantity of matter; in other words, weight › designate both force and mass. As commonly employed the term /ariably has its second meaning; that is, by a "weight of 10 pounds" a piece of matter which has a mass of 10 pounds. A weight (2nd 10 pounds has a weight (1st sense) of 10 pounds at 45 degrees latitude :vel (practically), but at any other latitude and elevation it has a it sense) slightly different from 10 pounds, and on the sun, for exam- have a weight (1st sense) many times 10 pounds.

connection it should be noted that a beam-balance when used in the /ay to compare two pieces of matter measures weight in the second it would "read" the same whether the measurement were made on or on the sun), that is, a beam-balance as ordinarily used compares l not forces. A beam-balance, however, is frequently used in testing nnection with a Prony brake, see *Index*) to compare a force produced hine with the pull on a standard mass (*or "weight"*) due to f great precision is desired the reading of the balance should then d for the value of "g" at the place of observation, but in ordinary nts the inaccuracy of the balance is likely to be much greater than orrection factor. For values of "g" at various places see reference bottom of preceding page.

ARDS OF THE FUNDAMENTAL UNITS. — The physical ıpon which the c.g.s. system of units is based, and the legalized f the foot and pound used in Great Britain and the United States ed below.

l of Length. — The standard meter (100 centimeters) is the dis- een two lines on a platinum-iridium bar carefully preserved at the Weights and Measures, at Sevres, France, when the bar is kept at emperature of zero degrees centigrade throughout. In the United ard (3 feet) was defined by Act of Congress, July 28, 1866, as

$$1 \text{ U.S. yard} = \frac{3600}{3937} \text{ meter},$$

y the British imperial yard is defined by law as

$$1 \text{ British imperial yard} = \frac{3600}{3937.079} \text{ meter}.$$

ring purposes the U. S. and British yards may be considered as

of Mass and Force. — The standard kilogram (1000 grams) as a is a cylinder of platinum preserved at the Bureau of Weights and t Sevres, France. The U. S. pound avoirdupois is defined by law *ress, 1866*) as $\frac{1}{2.2046}$ kilogram, but in 1893, the Superintendent of l Measures, with the approval of the Secretary of the Treasury, e pound to be

$$1 \text{ U. S. pound} = \frac{1}{2.204622} \text{ kilogram}.$$

imperial pound has the same value.

relations between pound and kilogram hold whether these units units of mass or as units of force, the unit of force being defined in

* Bull. Bureau Standards, 1904, Vol. 1, p. 380.

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both cases as the pull of the earth on unit mass at 45 degrees latitude and level.

Standard of Time.—**The standard second universally adopted** is the $\frac{1}{86,400}$ th part of a mean solar day. The solar day is the interva time between two successive transits of the sun across a meridian of the e at the point of observation; this interval varies in length at different ti during the year, but the average length of the interval for one year is cons as far as can be determined by any known methods of observation.

STANDARDS OF THE AUXILIARY FUNDAMENTAL UNITS. The standards of temperature, dielectric coefficient, magnetic permeabili luminous intensity ordinarily used are defined below.

Standard of Temperature. — Two units of temperature, or tempera scales, are commonly employed, viz., the centigrade and the Fahrenheit s The relation between these two units results solely from the manner in w they are defined.

$$1 \text{ degree centigrade} = \frac{9}{5} \text{ degrees Fahrenheit.}$$

Due to the difference in the zeros of the two scales, a temperature of t_f deg Fahrenheit corresponds to a temperature of

$$t_c = \frac{5}{9}(t_f - 32) \text{ degrees centigrade,}$$

and vice versa,

$$t_f = \frac{9}{5} t_c + 32 \text{ degrees Fahrenheit.}$$

Standards of the Auxiliary Fundamental Electrical Units. — Three tems of electrical and magnetic units are in use, viz., (1) the c.g.s. elec static system, (2) the c.g.s. electromagnetic system, and (3) the practical sys In the c.g.s. electrostatic system the dielectric coefficient k of air at 0° C 760 mm. mercury pressure is arbitrarily chosen as unity. In the c.g.s. elect magnetic system the magnetic permeability of air under the same stand conditions is arbitrarily chosen as unity. In the practical system a con standard of the unit of resistance (called the ohm) is arbitrarily chosen *Units, Practical Electrical*); this unit resistance was originally designed t equal to 10^9 times the unit of resistance in the c.g.s. electromagnetic syst and within the limits of ordinary experimental error this relation may st considered exact.

Use of the Prefixes "Stat" and "Ab."— To designate the electri and electromagnetic units in the electrostatic and electromagnetic systems units respectively the prefixes "stat" and "ab" may be used with the name of t corresponding practical unit. For example, the c.g.s. electrostatic unit of qu tity may be called the statcoulomb and the c.g.s. electromagnetic unit of quant may be called the abcoulomb. For the names and definitions of the vari electrical and magnetic units see the article on *Electricity and Magnet Principles of*.

Standards of Luminous Intensity. — Two standards are in use, the int national candle and the hefner, the latter being used chiefly in Germany. S article on *Photometric Quantities* for the specifications for these units.

EXPERIMENTALLY DETERMINED CONVERSION FACTORS.— By conversion factor is meant the numerical factor which gives the magnitude one unit for any given quantity in terms of any other unit for the same quantity

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e, in the expression 1 yd. = 3600/3937 meter, the factor 3600/3937 is
ion factor between the yard and the meter.
se of two units for the same quantity based on two different sets of
chosen units which are defined independently, the conversion factor
ained only by experiment. The more important experimentally
conversion factors are given in the paragraphs immediately following.

- and Water-column Pressure. — To convert pressure per unit
eight of mercury column the density of mercury must be known.
l Scheel (*Zeitsch. f. Instrk. de., 1898, Vol. 18, p. 138*) give the density
at 0° C. as 13.59545 grams per (cm.)³. Using the standard value
tational acceleration constant, $g_0 = 980.665$, the relation between the
. cm. and 1 cm. of mercury column at 0° C. is then

1. mercury column at 0° C. = 13332.6 dynes per sq. cm.

lensity of water as 1 gram per (cm.)³ at 4° C.,

m. water column at 4° C. = 980.665 dynes per sq. cm.

cal Equivalent of Heat. — Very useful units of energy are those
the mass of a standard substance and temperature, viz., the heat
ergy) required to raise the temperature of a specified mass of water
umber of degrees; see *Heat and Thermal Properties*. The experi-
ermined relation between the mean small calorie (i.e., the one-hun-
f the heat required to raise the temperature of 1 gram of water
o 100 C. at 760 mm. mercury pressure) and the erg is

1 mean small calorie = 4.1834×10^7 ergs.

nd Davis, *Steam Tables and Diagrams*, N. Y., 1912. From this
the relations (fixed by definition) given above between the yard
er, the pound and the kilogram, the value of the gravitational
constant g_0, and the two temperature scales, Marks and Davis,
relation

1 British thermal unit = 777.52 foot-pounds.

hermal unit as here used is defined as the $\frac{1}{180}$ th part of the heat
aise the temperature of 1 pound of water from 32° F. to 212° F. at
cury pressure. See also *Heat and Thermal Properties*.
imentally determined conversion factor between the energy unit
units of temperature and mass, and the energy unit based on the
h, mass and time, i.e., the unit of mechanical work, is called the
equivalent of heat."

between the Three Systems of Electrical Units. — The
relation, experimentally determined, between the c.g.s. electrostatic
electromagnetic system is that

1 abfarad = 9×10^{20} statfarads,

nsequence of the definitions of the various terms is equivalent to
mb = 3×10^{10} statcoulombs, the erg being the unit of
th systems.
nental relations between the c.g.s. electromagnetic system and the
em are

1 abcoulomb = 10 coulombs,
1 erg = 10^{-7} watt-seconds, or joules,

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the erg being the unit of energy in the c.g.s. electromagnetic system as watt-second or joule the unit of energy in the practical system.

Relation between the International Candle and the Hefner. — experimentally determined relation is

1 hefner = 0.9 international candle.

MULTIPLES AND SUBMULTIPLES OF UNITS. — Multiples submultiples of the metric units are designated by the following prefixes; relations are *definitions* and are therefore absolutely exact.

micro = $\frac{1}{1{,}000{,}000}$	or	10^{-6}
milli = $\frac{1}{1{,}000}$	or	10^{-3}
centi = $\frac{1}{100}$	or	10^{-2}
deci = $\frac{1}{10}$	or	10^{-1}
deka = 10	or	10
hecto = 100	or	10^{2}
kilo = 1,000	or	10^{3}
myria = 10,000	or	10^{4}
mega = 1,000,000	or	10^{6}

The multiples and submultiples of the English units are given in bold type in the tables below.

CALCULATION OF CONVERSION FACTORS. — The conve factors noted above, which are either definitions or results of experiment, the basis for the calculation of the conversion factors for the various de units. The method of procedure is first to express one of the pair of units *A*, in terms of its component units (length, mass, time, temperature, cap or resistance, and luminous intensity), then express the magnitude of ea these units in terms of the corresponding component units of *B*; the va the resultant numerical factor is the conversion factor. For example, let i required to find the conversion factor between pressure in pounds per sq foot and pressure in dynes per square centimeter.

$$1 \text{ lb. per sq. ft.} = \frac{(1 \text{ lb. force})}{(1 \text{ ft.})^2}.$$

$$1 \text{ lb. force} = \frac{1}{2.204622} \times (1 \text{ kilogram force}).$$

$$1 \text{ kilogram force} = 1000 \times (1 \text{ gram force}).$$

$$1 \text{ gram force} = 980.665 \times (1 \text{ dyne}).$$

Therefore

$$1 \text{ lb. force} = \frac{1000 \times 980.665}{2.204622} \times (1 \text{ dyne}).$$

Also

$$1 \text{ ft.} = \frac{1}{3} \times (1 \text{ yd}).$$

$$1 \text{ yd.} = \frac{3600}{3937} \times (1 \text{ meter}).$$

$$1 \text{ meter} = 100 \times (1 \text{ cm.}).$$

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$$1 \text{ ft.} = \frac{1}{3}\left(\frac{3600}{3937}\right) \times (100) \times (1 \text{ cm.}).$$

$$\frac{1 \text{ lb. force}}{(1 \text{ ft.})^2} = \frac{1000 \times 980.665 \times (3 \times 3937)^2}{2.204622 \times (3600 \times 100)^2} \times \frac{(1 \text{ dyne})}{(1 \text{ cm.})^2}$$

$$= 478.799 \times \frac{(1 \text{ dyne})}{(1 \text{ cm.})^2}.$$

$$\frac{(1 \text{ dyne})}{(1 \text{ cm.})^2} = 1 \text{ dyne per sq. cm.}$$

1 pound per sq. ft. = 478.799 dynes per sq. cm.

SIONAL FORMULAS. — Instead of writing the expression for a : in words, it is frequently convenient to express it in algebraic sym- . specific symbol for each of the fundamental or auxiliary fundamental example, let L stand for a length of 1 centimeter, M for a mass of T for a time interval of 1 second; then the unit of force in the c.g.s. tem (the dyne) may be written

$$F = MLT^{-2},$$

: same as 1 dyne = (1 gram) $\times \frac{(1 \text{ cm.})}{(1 \text{ sec.})^2}$.

, such as $F = MLT^{-2}$, where each letter represents the magnitude nit of the quantity for which it stands, is called a "dimensional for-)ure number, or a quantity which is the ratio of two units of the sions, such as an angle, has zero dimensions and does not appear onal formula.

nal formulas are useful for two purposes, viz., (1) as a systematic calculating conversion factors and (2) as a check of algebraic for- sing various relations. Unless one has a large number of conversion lculate it is probably simpler to use the direct method given in the ction. Certain quantities, for example, work and torque, may me dimensions although they are physically entirely different. ch quantities are physically different their conversion factors are The second use of dimensional formulas is based on the fact that n any set of terms connected either by equal signs, plus signs or must have the same dimensions.

plete list of the dimensional formulas for the various mechanical, ermal, and photometric quantities see Hering, C., *Conversion Tables*, . In the tables below are given, in the parentheses after the mensional formulas of the mechanical quantities in terms of length, ne, designated by L, M and T respectively. For the electrical and antities the dimensions are expressed in terms of electric potential quantity of electricity Q and time T. In the *c.g.s. electromagnetic* its Q may be expressed in terms of L, M, and T by the formula

$$Q = L^{\frac{1}{2}}M^{\frac{1}{2}}\mu^{-\frac{1}{2}};$$

lectrostatic system by the formula

$$Q = L^{\frac{3}{2}}M^{\frac{1}{2}}T^{-1}k^{\frac{1}{2}}.$$

ms $VQ = L^2MT^{-2}$ = energy.

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TABLES OF CONVERSION FACTORS.* — The following tables the most commonly required conversion factors for mechanical, electrical magnetic quantities. See *Heat and Thermal Properties* for special heat (other than energy) and *Photometric Quantities* for the special photometric

LENGTH (*L*)

cm. = *centimeter.* *m.* = *meter.*
ft. = *foot.* *mi.* = *mile.*
in. = *inch.* *mm.* = *millimeter.*
km. = *kilometer.* *yd.* = *yard.*

1 centimeter	1 foot	1 inch	1 kilometer	1 kn
0.3937 in.	30.48 cm.	2.540 cm.	10^5 cm.	6080 ft.
0.01 m.	12 in.	0.02540 m.	3281 ft.	1.853 km.
393.7 mil	0.3048 m.	10^3 mil	1000 m.	1853 m.
10 mm.	304.8 mm.	25.40 mm.	0.6214 mi.	1.152 mi.
.....	0.3333 yd.	.....	1094 yd.	2027 yd.

1 meter	1 mil	1 mile	1 millimeter	1 yard
100 cm.	0.002540 cm.	1.609×10^5 cm.	0.1 cm.	91.44 cm.
3.281 ft.	0.001 in.	5280 ft.	0.03937 in.	3 ft.
39.37 in.	0.02540 mm.	1.609 km.	0.001 meter	36 in.
0.001 km.	.....	1609 m.	39.37 mil.	0.9144 m.
1000 mm.	.....	1760 yd.	.....	.....
1.094 yd.	.....	.....	.....	.....

* Example. — 7 yards equals how many meters? *Answer*, 1 yard = 0.9144 m. therefore 7 yards = $7 \times 0.9144 = 6.4008$ meters.

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AREA (L^2)

C.M. = *circular mil.*
hect. = *hectare.*
sq. cm. = *square centimeter.*
sq. ft. = *square foot.*
sq. in. = *square inch.*
sq. km. = *square kilometer.*
sq. m. = *square meter.*
sq. mil. = *square mil.*
sq. mi. = *square mile.*
sq. mm. = *square millimeter.*
sq. yd. = *square yard.*

cre	1 are	1 circular mil *	1 hectare
f ares	0.02471 acre	5.067×10^{-6} sq. cm.	2.471 acres
f hect.	0.01 hect.	7.854×10^{-7} sq. in.	100 ares
sq. ft.	1076 sq. ft.	0.7854 sq. mil.	1.076×10^{5} sq. ft.
sq. km.	10^{-4} sq. km.	5.067×10^{-4} sq. mm.	0.01 sq. km.
sq. m.	100 sq. m.	.....	10^{4} sq. m.
sq. mi.	3.861×10^{-3} sq. mi.	.....	3.861×10^{-3} sq. mi.
sq. yd.	119.6 sq. yd.	.....	1.196×10^{4} sq. yd.

dimeter	1 square foot		1 square inch
C.M.	2.296×10^{-5} acre	9.290×10^{-6} sq. km.	1.273×10^{6} C. M.
sq. ft.	9.290×10^{-4} are	0.09290 sq. m.	6.452 sq. cm.
sq. in.	1.833×10^{6} C. M.	1.44×10^{6} sq. mil.	6.944×10^{-3} sq. ft.
sq. mil.	9.290×10^{-6} hect.	3.587×10^{-8} sq. mi.	10^{6} sq. mil.
sq. m.	929.0 sq. cm.	9.890×10^{4} sq. mm.	645.2 sq. mm.
sq. mm.	144 sq. in.	0.1111 sq. yd.	.....

e kilometer	1 square meter	1 square mil †
7.1 acres	2.471×10^{-4} acre	1.273 C. M.
10^{4} ares	0.01 are	6.452×10^{-4} sq. cm.
100 hect.	10^{-4} hect.	10^{-6} sq. in.
10^{6} sq. ft.	10.76 sq. ft.	6.452×10^{-6} sq. mm.
10^{6} sq. m.	10^{-6} sq. km.	.....
861 sq. mi.	3.861×10^{-7} sq. mi.	.....
10^{6} sq. yd.	1.196 sq. yd.	.....

are mile	1 square millimeter	1 square yard
40 acres	1.973×10^{3} C. M.	2.066×10^{-4} acre
10^{4} ares	0.01 sq. cm.	8.361×10^{-3} are
10^{2} hect.	1.076×10^{-5} sq. ft.	8.361×10^{-4} hect.
10^{6} sq. ft.	1.550×10^{-3} sq. in.	9 sq. ft.
590 sq. km.	1.550×10^{9} sq. mil.	8.361×10^{-7} sq. km.
10^{6} sq. m.	.....	0.8361 sq. m.
10^{6} sq. yd.	.....	3.228×10^{-7} sq. mi.

mil is the area of a circle 1 mil, or 0.001 in., in diameter.
ail is the area of a square 1 mil, or 0.001 in., on each side.

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VOLUME (L^3)

bu. = *bushel.*
cu. cm. = *cubic centimeter.*
cu. ft. = *cubic foot.*
cu. in. = *cubic inch.*
cu. m. = *cubic meter.*
cu. yd. = *cubic yard.*
gal. = *gallon.*
lit. = *liter.*
pt. = *pint.*
qt. = *quart.*

1 bushel (dry*)	1 cu. centimeter	1 cubic foot	1 cubic inch
1.244 cu. ft.	3.531×10^{-5} cu. ft.	2.832×10^{4} cu. cm.	16.39 cu. cm.
2150 cu. in.	6.102×10^{-2} cu. in.	1728 cu. in.	5.787×10^{-4} cu. ft.
0.03524 cu. m.	10^{-6} cu. m.	0.02832 cu. m.	1.639×10^{-5} cu. m.
4 pk. (dry)	1.308×10^{-6} cu. yd.	0.03704 cu. yd.	2.143×10^{-5} cu. yd.
64 pt. (dry)	2.642×10^{-4} gal.	7.481 gal.	4.329×10^{-3} gal.
32 qt. (dry)	10^{-3} lit.	28.32* lit.	1.639×10^{-2} lit.
.....	2.113×10^{-3} pt.	59.84 pt.	0.03463 pt.
.....	1.057×10^{-3} qt.	29.92 qt.	0.01732 qt.

1 cubic meter	1 cubic yard	1 gallon (liq. *)
10^{6} cu. cm.	7.646×10^{5} cu. cm.	3785 cu. cm.
35.31 cu. ft.	27 cu. ft.	0.1337 cu. ft.
61,023 cu. in.	46,656 cu. in.	231 cu. in.
1.308 cu. yd.	0.7646 cu. m.	3.785×10^{-3} cu. m.
264.2 gal.	202.0 gal.	4.951×10^{-3} cu. yd.
10^{3} lit.	764.6 lit.	3.785 lit.
2113 pt.	1616 pt.	8 pt.
1057 qt.	807.9 qt.	4 qt.

1 liter	1 pint (liq.*)	1 quart (liq. *)
10^{3} cu. cm.	473.2 cu. cm.	946.4 cu. cm.
0.03531 cu. ft.	0.01671 cu. ft.	0.03342 cu. ft.
61.02 cu. in.	28.87 cu. in.	57.75 cu. in.
10^{-3} cu. m.	4.732×10^{-4} cu. m.	9.464×10^{-4} cu. m.
1.308×10^{-3} cu. yd.	6.189×10^{-4} cu. yd.	1.238×10^{-3} cu. yd.
0.2642 gal.	0.125 gal.	0.25 gal.
2.113 pt.	0.4732 lit.	0.9464 lit.
1.057 qt.	0.5 qt.	2 pt.

* Dry measure units = 1.164 × (liquid measure units). Quarts, pints, bushels and pecks as here used are United States measures; see Hering's *Conversion Tables* for English measures.

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PLANE ANGLE (*Zero Dimensions*)

deg. or ° = *degree.* *rad.* = *radian.*
min. or ' = *minute.* *rev.* = *revolution.*
quad. = *quadrant.* *sec. or "* = *second.*

1 degree	1 minute	1 quadrant
60 min.	2.909×10^{-4} rad.	90 deg.
0.01745 rad.	60 sec.	5400 min.
3600 sec.	.....	1.571 rad.
.....	.....	324,000 sec.

1 radian *	1 revolution	1 second
57.30 deg.	360 deg.	4.848×10^{-6} rad.
3438 min.	21,600 min.	.....
0.637 quad.	4 quad.	.....
206,265 sec.	6.283 rad.	.....
.....	1.296×10^{6} sec.	.....

* radians = 360 degrees by definition.

SOLID ANGLE (*Zero dimensions*)

hemisphere	1 sphere *	1 sph. right angle	1 steradian †
.5 sphere	2 hem. sp.	0.25 hem. sph.	0.1592 hem. sph.
4 sph. rt. ang.	8 sph. rt. ang.	0.125 sphere	0.07958 sphere
13 steradians	12.57 steradians	1.571 steradians	0.6366 sph. rt. ang.

* sphere is the total solid angle about a point.
† steradians = 1 sphere, by definition.

TIME (*T*)

hr. = *hour.* *mo.* = *month.* *wk.* = *week.*
min. = *minute.* *sec.* = *second.* *yr.* = *year.*

1 day	1 hour	1 week	1 aver. month	1 common year	1 leap year
24 hr.	60 min.	7 days	1/12 civil yr.	365 days	366 days
1440 min.	3600 sec.	168 hr.	30.42 days	8,760 hr.	8,784 hr.
86,400 sec.	.....	10,080 min.	730 hr.	525,600 min.	527,040 min
.....	.....	604,800 sec.	43,800 min.	12 mo.	31,622,400 sec.
.....	.....	.....	2,628,000 sec.	31,536,000 sec.	52.27 wk.
.....	.....	.....	.....	52.14 wk.	

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LINEAR VELOCITY AND SPEED (LT^{-1})

1 centimeter per sec.	1 foot per minute	1 foot per second
1.969 ft. per min.	0.5080 cm. per sec.	30.48 cm. per sec.
0.03281 ft. per sec.	0.01667 ft. per sec.	1.097 km. per hr.
0.036 km. per hr.	0.01829 km. per hr.	0.5921 knot per hr.
0.6 m. per min.	0.3048 m. per min.	18.29 m. per min.
0.02237 mile per hr.	0.01136 mile per hr.	0.6818 mile per hr.
3.728×10^{-4} mile per min.	.....	0.01136 mile per min.

1 kilometer per hour	1 kilometer per minute	1 knot per hour
27.78 cm. per sec.	54.68 ft. per sec.	51.48 cm. per sec.
54.68 ft. per min.	32.38 knots per hr.	1.689 ft. per sec.
0.9113 ft. per sec.	16.67 m. per hr.	1.853 km. per hr.
0.5396 knot per hr.	37.28 miles per hr.	1.152 miles per hr.
16.67 m. per min.	0.6214 mile per min.	.....
0.6214 mile per hr.	.....	.....

1 meter per minute	1 meter per second
1.667 cm. per sec.	196.8 ft. per min.
3.281 ft. per min.	3.281 ft. per sec.
0.05468 ft. per sec.	3.6 km. per hr.
0.06 km. per hr.	0.06 km. per min.
0.03728 mile per hr.	2.237 miles per hr.
.....	0.03728 mile per min.

1 mile per hour	1 mile per minute
44.70 cm. per sec.	2682 cm. per sec.
88 ft. per min.	88 ft. per sec.
1.467 ft. per sec.	1.609 km. per min.
1.609 km. per hr.	0.8684 knot per min.
0.8684 knot per hr.	60 miles per hr.
26.82 m. per min.	.....

ANGULAR SPEED (T^{-1})

1 deg. per sec.	1 rad. per sec.	1 rev. per min.	1 rev. per sec.
0.01745 rad. per sec.	57.30 deg. per sec.	6 deg. per sec.	360 deg. per sec.
0.1667 rev. per min.	0.1592 rev. per sec.	0.1047 rad. per sec.	6.283 rad. per sec.
0.002778 rev. per sec.	9.549 rev. per min.	0.01667 rev. per sec.	60 rev. per min.

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LINEAR ACCELERATION (LT^{-2})

m. per sec. per sec.	1 foot per sec. per sec.	Gravity-g_0
181 ft. per sec. per sec.	30.48 cm. per sec. per sec.	980.7 cm. per sec. per sec
120 gravity	0.03108 gravity	32.17 ft. per sec. per sec.
236 km. per hr. per sec.	1.097 km. per hr. per sec.	35.30 km. per hr. per sec
.01 m. per sec. per sec.	0.3048 m. per sec. per sec.	9.807 m. per sec. per sec.
237 mile per hr. per sec.	0.6818 mile per hr. per sec.	21.94 miles per hr. per se

lometer per hour per sec.	1 meter per sec. per sec.	1 mile per hour per sec.
.78 cm. per sec. per sec.	100 cm. per sec. per sec.	44.70 cm. per sec. per se
113 ft. per sec. per sec.	3.281 ft. per sec. per sec.	1.467 ft. per sec. per se
833 gravity	0.1020 gravity	0.04559 gravity
78 m. per sec. per sec.	3.6 km. per hr. per sec.	1.609 km. per hr. per se
214 mile per hr. per sec.	2.237 miles per hr. per sec.	0.4470 m. per sec. per se

ANGULAR ACCELERATION (T^{-2})

rad. = *radian* *rev.* = *revolution*

1 rad. per sec. per sec.	1 rev. per min. per min.
573.0 rev. per min. per min.	1.745×10^{-3} rad. per sec.per sec.
9.549 rev. per min. per sec.	0.01667 rev. per min. per sec.
0.1592 rev. per sec. per sec.	2.778×10^{-4} rev. per sec. per sec.

1 rev. per min. per sec.	1 rev. per sec. per sec.
0.1047 rad. per sec. per sec.	6.283 rad. per sec. per sec.
60 rev. per min. per min.	3600 rev. per min. per mi
0.01667 rev. per sec. per sec.	60 rev. per min. per sec.

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MASS (M) AND WEIGHT *

kg. = *kilogram.* *oz.* = *ounce.*
mg. = *milligram* *lb.* = *pound* †

1 grain †	1 gram	1 kilogram	
0.06480 gram	15.43 grains	15,432 grains	2.205 lb.
64.80 mg.	10^{-3} kg.	10^{3} grams	9.842×10^{-4} long ton
2.286×10^{-3} oz.	10^{3} mg.	10^{6} mg.	10^{-3} metric ton
.....	0.03527 oz.	35.27 oz.	1.102×10^{-3} short ton
.....	2.205×10^{-3} lb.	.....	.....

1 milligram	1 ounce †	1 pound †
0.01543 grain	437.5 grains	7000 grains
10^{-3} gram	28.35 grams	453.6 grams
10^{-6} kg.	0.02835 kg.	0.4536 kg.
.....	28,350 mg.	4.536×10^{5} mg.
.....	0.06250 lb.	16 oz.

1 long ton	1 metric ton	1 ton (short)
1016 kg.	10^{3} kg.	907.2 kg.
2240 lb.	2205 lb.	2000 lb.
1.016 metric tons	0.9842 long ton	0.8929 long ton
1.120 short tons	1.102 short tons	0.9072 metric ton

* These same conversion factors apply to the *gravitational* units of force having the corresponding names. The dimensions of these units when used as gravitational units of force are MLT^{-2}; see table for *Force* on next page.

† Avoirdupois pound and its subdivisions used throughout.

DENSITY OR MASS PER UNIT VOLUME (ML^{-3})

1 gram per cu. cm.	1 kg. per cu. meter
10^{3} kg. per cu. m.	10^{-3} g. per cu. cm.
62.43 lb. per cu. ft.	0.06243 lb. per cu. ft.
0.03613 lb. per cu. in.	3.613×10^{-5} lb. per cu. in.
3.405×10^{7} lb. per mil ft.	3.405×10^{-10} lb. per mil ft.

1 pound per cu. ft.	1 pound per cu. in.
0.01602 g. per cu. cm.	27.68 g. per cu. cm.
16.02 kg. per cu. m.	2.768×10^{4} kg. per cu. m.
5.787×10^{-4} lb. per cu. in.	1728 lb. per cu. ft.
5.456×10^{-9} lb. per mil ft.	9.425×10^{-6} lb. per mil ft.

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FORCE (MLT^{-2})

kg. = *kilogram.* *lb.* = *pound.*

1 dyne *	1 gram	1 kilogram
1.020×10^{-6} gram	980.7 dynes	980,665 dynes
1.020×10^{-6} kg.	10^{-3} kg.	10^{3} grams
2.248×10^{-6} lb.	2.205×10^{-3} lb.	2.205 lb.
7.233×10^{-5} poundal	0.07093 poundal	70.93 poundals

1 pound	1 poundal†
444,823 dynes	13,826 dynes
453.6 grams	14.10 grams
0.4536 kg.	0.01410 kg.
32.1739 poundals	0.03108 lb.

*Force required to give a mass of 1 gram an acceleration of 1 cm. per sec. per sec.
†Force required to give a mass of 1 pound an acceleration of 1 ft. per sec. per sec.

TORQUE OR MOMENT OF FORCE (L^2MT^{-2}) *

cm-dyne = *centimeter-dyne.* *m-kg.* = *meter-kilogram.*
cm-gram = *centimeter-gram.* *lb-ft.* = *pound-foot.*

1 centimeter-dyne	1 centimeter-gram
1.020×10^{-8} cm-gram	980.7 cm-dynes
1.020×10^{-8} m-kg.	10^{-3} m-kg.
7.376×10^{-8} lb-ft.	7.233×10^{-5} lb-ft.

1 meter-kilogram	1 pound-foot
9.807×10^{7} cm-dynes	1.356×10^{7} cm-dynes
10^{3} cm-grams	13,825 cm-grams
7.233 lb-ft.	0.1383 m-kg.

* Same dimensions as energy; see below.

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PRESSURE OR FORCE PER UNIT AREA ($L^{-1}MT^{-2}$)

barie = *dyne per sq. cm.*
mercury = *column of mercury.*
ton = *2000 lb.*
water = *column of water.*

1 atmosphere	1 barie or dyne per sq. cm.	1 cm. of mercury
76.0 cm. mercury	9.870×10^{-7} atmosphere	0.01316 atmosphere
29.92 in. mercury	0.01020 kg. per sq. m.	0.4461 ft. water
33.90 ft. water	2.089×10^{-3} lb. per sq. ft.	136.0 kg. per sq. m.
10,333 kg. per sq. m.	1.450×10^{-5} lb. per sq. in.	27.85 lb. per sq. ft.
14.70 lb. per sq. in.	.....	0.1934 lb. per sq. in.
1.058 tons per sq. ft.	.....	.....

1 inch of mercury	1 inch of water	1 foot of water
0.03342 atmosphere	0.002458 atmosphere	0.02950 atmosphere
1.133 ft. water	0.07355 in. mercury	0.8826 in. mercury
345.3 kg. per sq. m.	25.40 kg. per sq. m.	304.8 kg. per sq. m.
70.73 lb. per sq. ft.	5.204 lb. per sq. ft.	62.43 lb. per sq. ft.
0.4912 lb. per sq. in.	0.03613 lb. per sq. in.	0.4335 lb. per sq. in.

1 kilogram per square meter	1 kilogram per sq. mm.	1 pound per square foot
9.678×10^{-5} atmosphere	96.78 atmospheres	4.725×10^{-4} atmosphere
98.07 baries	98.07×10^{6} baries	478.8 baries
3.281×10^{-3} ft. water	3.281×10^{3} ft. water	0.01602 ft. water
2.896×10^{-3} in. mercury	2.048×10^{3} lb. per sq. ft.	0.01414 in. mercury
0.2048 lb. per sq. ft.	1.422×10^{3} lb. per sq. in.	4.882 kg. per sq. m.
1.422×10^{-3} lb. per sq. in.	.....	6.944×10^{-3} lb. per sq. in.

1 pound per sq. inch	1 short ton per sq. ft.	1 short ton per sq. in.
0.06804 atmosphere	0.9450 atmosphere	136.1 atmospheres
2.307 ft. water	32.04 ft. water	4613 ft. water
2.036 in. mercury	28.28 in. mercury	1.406×10^{6} kg. per sq. m.
703.1 kg. per sq. m.	9765 kg. per sq. m.	2.88×10^{2} lb. per sq. ft.
144 lb. per sq. ft.	2000 lb. per sq. ft.	2000 lb. per sq. in.
.....	13.89 lb. per sq. in.	.....

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ENERGY AND WORK (L^2MT^{-2})*

B.t.u. = *British thermal unit.*
ft-lb. = *foot-pound.*
kg-cal. = *kilogram-calorie.*
gram-cal. = *gram-calorie.*
gram-cm. = *gram-centimeter.*
hp-hr. = *horse-power-hour.*
kg-m. = *kilogram-meter.*
kw-hr. = *kilowatt-hour.*
watt-hr. = *watt-hour.*

British thermal unit	1 erg or dyne-centimeter	1 foot-pound
0.2520 kg-cal.	9.486×10^{-11} B.t.u.	1.286×10^{-3} B.t.u.
777.5 ft-lb.	2.390×10^{-11} kg-cal.	3.241×10^{-4} kg-cal.
3.927×10^{-4} hp-hr.	7.376×10^{-8} ft-lb.	1.356×10^{7} ergs
1054 joules	1.020×10^{-8} gram-cm.	5.050×10^{-7} hp-hr.
107.5 kg-m.	10^{-7} joule	1.356 joules
2.928×10^{-4} kw-hr.	1.020×10^{-8} kg-m.	0.1383 kg-m.
.....	.....	3.766×10^{-7} kw-hr.

kilogram-calorie †	1 gram-centimeter	1 horse-power-hour
3.968 B.t.u.	9.302×10^{-8} B.t.u.	2547 B.t.u.
3086 ft-lb.	2.344×10^{-8} kg-cal.	641.7 kg-cal.
1.558×10^{-3} hp-hr.	980.7 ergs	1.98×10^{6} ft-lb.
4183 joules	7.233×10^{-5} ft-lb.	2.684×10^{6} joules
426.6 kg-m.	9.807×10^{-5} joule	2.737×10^{5} kg-m.
1.162×10^{-3} kw-hr.	10^{-5} kg-m.	0.7457 kw-hr.

1 joule or watt-second	1 kilogram-meter
9.486×10^{-4} B.t.u.	9.302×10^{-3} B.t.u.
2.390×10^{-4} kg-cal.	2.344×10^{-3} kg-cal.
10^{7} ergs	9.807×10^{7} ergs
0.7376 ft-lb.	7.233 ft-lb.
0.1020 kg-m.	9.807 joules
2.778×10^{-4} watt-hr.	2.724×10^{-6} kw-hr.

1 kilowatt-hour	1 watt-hour
3415 B.t.u.	3.415 B.t.u.
860.5 kg-cal.	0.8605 kg-cal.
2.655×10^{6} ft-lb.	2655 ft-lb.
1.341 hp-hr.	1.341×10^{-3} hp-hr.
3.6×10^{6} joules	367.1 kg-m.
3.671×10^{5} kg-m.	10^{-3} kw-hr.

* See note at bottom of next table.

† 1 gram-calorie = 10^{-3} kilogram-calorie; 1 Ostwald calorie = 10^{-2} kilogram-calorie.

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POWER OR RATE OF DOING WORK (L^2MT^{-3})*

B.t.u. = British thermal unit; met. h.p. = metric horse-power.

1 B.t.u. per minute	1 erg per second	1 foot-pound per minu
777.5 ft-lb. per min.	5.692×10^{-9} B.t.u. per min.	1.286×10^{-3} B.t.u. per mi
12.96 ft-lb. per sec.	1.434×10^{-9} kg-cal. per min.	3.241×10^{-4} kg-cal. per m
0.02356 h.p.	4.426×10^{-9} ft-lb. per min.	0.01667 ft-lb. per sec.
0.01757 kw.	7.376×10^{-8} ft-lb. per sec.	3.030×10^{-5} h.p.
0.02389 met. h.p.	1.341×10^{-10} h.p.	2.260×10^{-5} kw.
17.57 watts	10^{-10} kw.	3.072×10^{-5} met. h.p.
.....	1.360×10^{-10} met. h.p.	.....

1 foot-pound per second	1 horse-power	1 kg-cal. per minut
7.717×10^{-3} B.t.u. per min.	42.44 B.t.u. per min.	3086 ft-lb. per m
1.945×10^{-3} kg-cal. per min.	10.70 kg-cal. per min.	51.43 ft-lb. per sec.
1.818×10^{-3} h.p.	33,000 ft-lb. per min.	0.09351 h.p.
1.356×10^{-3} kw.	550 ft-lb. per sec.	0.06972 kw.
1.843×10^{-3} met. h.p.	0.7457 kw.	0.09481 met. h.p.
1.356 watts	1.014 met. h.p.	69.72 watts
.....	*745.7 watts	.....

1 kilowatt	1 metric horse-power	1 watt
56.92 B.t.u. per min.	41.86 B.t.u. per min.	0.05692 B.t.u. per mi
14.34 kg-cal. per min.	10.55 kg-cal. per min.	0.01434 kg-cal. per m
4.425×10^4 ft-lb. per min.	3.255×10^4 ft-lb. per min.	10^7 erg per sec.
737.6 ft-lb. per sec.	542.5 ft-lb. per sec.	44.26 ft-lb. per se
1.341 h.p.	0.9863 h.p.	0.7376 ft-lb. per sec.
1.360 met. h.p.	0.7354 kw.	1.341×10^{-3} h.p.
10^3 watts	735.4 watts	10^{-3} kw.
.....	.....	1.360×10^{-3} met. h.p.

* The value 746 watts, has been adopted by the Bureau of Standards as the ex equivalent of one horse-power; this, however, is not consistent with the use of 980 cm. per sec. per sec. as the standard value of g, which latter is used throughout th tables.

QUANTITY OF ELECTRICITY; DIELECTRIC FLUX (Q)

Abcoul. = abcoulomb; coul. = coulomb; statcoul. = statcoulomb.

1 abcoulomb	1 coulomb	1 statcoulomb
10 coul.	$\frac{1}{10}$ abcoul.	$\frac{1}{3}\times10^{-10}$ abcoul.
3×10^{10} statcoul.	3×10^9 statcoul.	$\frac{1}{3}\times10^{-9}$ coul.

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CHARGE PER UNIT AREA; DIELECTRIC FLUX DENSITY (QL^{-2})

1 coulomb per square centimeter	1 coulomb per square centimeter
10 coul. per sq. cm.	$\frac{1}{10}$ abcoul. per sq. cm.
64.52 coul. per sq. in.	6.452 coul. per sq. in.
3×10^{10} statcoul. per sq. cm.	3×10^{9} statcoul. per sq. cm.
1 coulomb per square inch	**1 statcoulomb per square centimeter**
0.01550 abcoul. per sq. cm.	$\frac{1}{3}\times10^{-10}$ abcoul. per sq. cm.
0.1550 coul. per sq. cm.	$\frac{1}{3}\times10^{-9}$ coul. per sq. cm.
550×10^{8} statcoul. per sq. cm.	2.150×10^{-8} coul. per sq. in.

ELECTRIC CURRENT (QT^{-1})

1 abampere	1 ampere	1 statampere
10 amperes	$\frac{1}{10}$ abamp.	$\frac{1}{3}\times10^{-10}$ abamp.
3×10^{10} statamp.	3×10^{9} statamp.	$\frac{1}{3}\times10^{-9}$ ampere

CURRENT DENSITY ($QT^{-1}L^{-2}$)

abampere per square centimeter	1 ampere per square centimeter
10 amperes per sq. cm.	$\frac{1}{10}$ abampere per sq. cm.
64.52 amperes per sq. in.	6.452 amperes per sq. in.
3×10^{10} statamp. per sq. cm.	3×10^{9} statamp. per sq. cm.
1 ampere per square inch	**1 statamp. per square centimeter**
0.01550 abamp. per sq. cm.	$\frac{1}{3}\times10^{-10}$ abamp. per sq. cm.
0.1550 ampere per sq. cm.	$\frac{1}{3}\times10^{-9}$ ampere per sq. cm.
4.650×10^{8} statamp. per sq. cm.	2.150×10^{-8} ampere per sq. in.

ELECTRIC POTENTIAL DIFFERENCE; ELECTROMOTIVE FORCE (V)

1 abvolt	1 statvolt	1 volt
$\frac{1}{3}\times10^{-10}$ statvolt	3×10^{10} abvolts	10^{8} abvolts
10^{-8} volt	300 volts	$\frac{1}{300}$ statvolt

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ELECTRIC POTENTIAL GRADIENT; ELECTROSTATIC FIELD INTENSITY (VL^{-1})

1 abvolt per centimeter	1 statvolt per centimeter
$\frac{1}{3}\times10^{-20}$ statvolt per cm.	3×10^{10} abvolts per cm.
10^{-8} volt per cm.	300 volts per cm.
2.540×10^{-8} volt per in.	762.0 volts per in.

1 volt per centimeter	1 volt per inch
10^{8} abvolts per cm.	3.937×10^{7} abvolts per cm.
$\frac{1}{300}$ statvolt per cm.	1.312×10^{-6} statvolt per cm.
2.540 volts per in.	0.3937 volt per cm.

ELECTRIC RESISTANCE ($Q^{-1}VT$)

1 abohm	1 megohm	1 microhm
10^{-15} megohm	10^{15} abohms	10^{9} abohms
10^{-6} microhm	10^{12} microhms	10^{-12} megohm
10^{-9} ohm	10^{9} ohms	10^{-6} ohm
$\frac{1}{9}\times10^{-20}$ statohm	$\frac{1}{9}\times10^{-5}$ statohm	$\frac{1}{9}\times10^{-17}$ statohm

1 ohm	1 statohm
10^{9} abohms	9×10^{20} abohms
10^{-6} megohms	9×10^{5} megohms
10^{6} microhms	9×10^{17} microhms
$\frac{1}{9}\times10^{-11}$ statohm	9×10^{11} ohms

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ELECTRIC RESISTIVITY † ($Q^{-1}VTL$)

See also *Resistance and Conductance*

1 abohm per cm. cube	1 microhm per cm. cube	1 microhm per in. cube
10⁻⁹ microhm per cm. cube	10^{3} abohms per cm. cube	2.540×10^{3} abohms per cm. cube
7×10^{-4} microhm per in. cube	0.3937 microhm per in. cube	2.540 microhms per cm. cube
5×10^{-8} ohm per mil-ft.	6.015 ohms per mil-ft.	15.28 ohms per mil-ft.
$10^{-9}\,\delta$ ohm per meter-gram	$10^{-3}\,\delta$ ohm per meter-gram	$2.540\times10^{-3}\,\delta$ ohm per meter-gram

1 ohm per mil-foot	1 ohm per meter-gram *
1.662×10^{3} abohms per cm. cube	$\frac{10^{6}}{\delta}$ abohms per cm. cube
0.1662 microhm per cm. cube	$\frac{10^{6}}{\delta}$ microhms per cm. cube
0.06524 microhm per in. cube	$\frac{39.37}{\delta}$ microhms per in. cube
$1.662\times10^{-3}\,\delta$ ohm per meter-gram	$\frac{6.015\times10^{3}}{\delta}$ ohms per mil-ft.

* See p. 1858 for multiples and submultiples.

† In this table δ is density expressed as a decimal fraction.

ELECTRIC CONDUCTIVITY † ($QV^{-1}T^{-1}L^{-1}$)

1 abmho per cm. cube	1 mho per meter-gram	1 mho per mil-foot
$\frac{10^{9}}{\delta}$ mhos per meter-gram	$10^{-6}\,\delta$ abmho per cm. cube	6.015×10^{-3} abmho per cm. cube
1.662×10^{3} mhos per mil-ft.	$1.662\times10^{-3}\,\delta$ mho per mil-foot	$\frac{6015}{\delta}$ mhos per meter-gram
$10^{3}\,\delta$ megmhos per cm. cube	$10^{-3}\,\delta$ megmho per cm. cube	6.015 megmhos per cm. cube
2.540×10^{3} megmhos per in. cube	$2.540\times10^{-3}\,\delta$ megmho per in. cube	15.28 megmhos per in. cube

1 megmho per cm. cube	1 megmho per in. cube
10^{-3} abmho per cm. cube	3.937×10^{-4} abmho per cm. cube
$\frac{10^{3}}{\delta}$ mhos per meter-gram	$\frac{39.37}{\delta}$ mhos per meter-gram
0.1662 mho per mil-foot	0.06524 mho per mil-foot
2.540 megmhos per in. cube	0.3937 megmho per cm. cube

† In this table δ is density expressed as a decimal fraction

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CAPACITY (QV^{-1})

Abf. = abfarad; mf. = microfarad; statf. = statfarad

1 abfarad	1 farad	1 microfarad	1 statfarad
10^{9} farads 10^{15} mf. 9×10^{20} statf.	10^{-9} abf. 10^{6} mf. 9×10^{11} statf.	10^{-15} abf. 10^{-6} farad 9×10^{5} statf.	$\frac{1}{9}\times10^{-20}$ abf. $\frac{1}{9}\times10^{-11}$ farad. $\frac{1}{9}\times10^{-5}$ mf.

INDUCTANCE ($VQ^{-1}T^{2}$)

Abh. = abhenry; mh. = millihenry; stath. = stathenry

1 abhenry	1 henry	1 millihenry	1 stathenry
10^{-9} henry 10^{-6} mh. $\frac{1}{9}\times10^{-20}$ stath.	10^{9} abh. 10^{3} mh. $\frac{1}{9}\times10^{-11}$ stath.	10^{6} abh. 10^{-3} henry $\frac{1}{9}\times10^{-14}$ stath.	9×10^{20} abh. 9×10^{11} henries 9×10^{14} mh.

MAGNETIC FLUX (VT)

1 maxwell or "line"	1 kiloline	1 volt-second*
10^{-3} kiloline 10^{-8} volt-sec.*	10^{3} maxwells 10^{-5} volt-sec.*	10^{8} maxwells 10^{5} kilolines

MAGNETIC FLUX DENSITY (VTL^{-2})

1 gauss, or line per square centimeter	1 line per square inch
6.452 lines per sq. in. 10^{-8} volt-sec.* per sq. cm. 6.452×10^{-8} volt-sec.* per sq. in.	0.1550 gauss 1.55×10^{-8} volt-sec.* per sq. cm. 10^{-8} volt-sec.* per sq. in.
1 volt-sec. per square centimeter	**1 volt-sec. per square inch**
10^{8} gausses 6.452×10^{8} lines per sq. in. 6.452 volt-sec.* per sq. in.	1.550×10^{7} gausses 10^{8} lines per sq. in. 0.1550 volt-sec.* per sq. cm.

* By volt-second is meant the unit of flux which must be used in the equation $e=\frac{d\phi}{dt}$ in order to obtain e in volts when t is in seconds; this unit is sometimes called a "weber."

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GNETIC POTENTIAL DIFFERENCE; MAGNETOMOTIVE FORCE (QT^{-1})

A bamp-turns = abampere-turns; amp-turns = ampere-turns; stalamp-turns = statampere-turns

abampere-turn	1 ampere-turn	1 gilbert
10 amp-turns 2.57 gilberts	$\frac{1}{10}$ abamp-turn 1.257 gilberts	0.07958 abamp-turn 0.7958 amp-turn

NETIC POTENTIAL GRADIENT; MAGNETIZING FORCE ($QL^{-1}T^{-1}$)

1 abamp-turn per cm.	1 ampere-turn per cm.
10 amp-turns per cm. 25.40 amp-turns per inch 12.57 gilberts per cm.	$\frac{1}{10}$ abamp-turn per cm. 2.540 amp-turns per inch 1.257 gilberts per cm.

1 amp-turn per inch	1 gilbert per cm.
0.03937 abamp-turn per cm. 0.3937 amp-turn per cm. 0.4950 gilbert per cm.	0.07958 abamp-turn per cm. 0.7958 amp-turn per cm. 2.021 amp-turns per inch

IBLIOGRAPHY. — A more complete set of conversion factors is given book by Hering called *Conversion Tables*. See also circular of the Bureau tandards entitled *Tables of Equivalents*, 1913.

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UNITS, PRACTICAL ELECTRIC. — (*See also Electricity and Magnetism, Principles of; Units and Conversion Factors.*) Following the recommendation of the Chicago International Electrical Congress of 1893, the following Act was passed by Congress. (Act approved July 12, 1894.) *Be it enacted, etc.* That from and after the passage of this act the legal units of electrical measure in the United States shall be as follows:

First. The unit of resistance shall be what is known as the international ohm, which is substantially equal to one thousand million units of resistance of the centimeter-gram-second system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice fourteen and four thousand five hundred and twenty-one ten-thousandths (14.4521) grams in mass, of a constant cross-sectional area, and of the length of one hundred and six and three-tenths (106.3) centimeters.

Second. The unit of current shall be what is known as the international ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electromagnetic units, and is the practical equivalent of the unvarying current, which, when passed through a solution of nitrate of silver in water in accordance with standard specifications, deposits silver at the rate of one thousand one hundred and eighteen millionths (0.001118) of a gram per second.

Third. The unit of electromotive force shall be what is known as the international volt, which is the electromotive force that, steadily applied to a conductor whose resistance is one international ohm, will produce a current of one international ampere, and is practically equivalent to $\frac{1000^*}{1434}$ of the electromotive force between the poles or electrodes of the voltaic cell known as Clark cell, at a temperature of fifteen degrees centigrade (15° C.), and prepared in the manner described in the standard specifications.

Fourth. The unit of quantity shall be what is known as the international coulomb, which is the quantity of electricity transferred by a current of one international ampere in one second.

Fifth. The unit of capacity shall be what is known as the international farad, which is the capacity of a condenser charged to a potential of one international volt by one international coulomb of electricity.

Sixth. The unit of work shall be the joule, which is equal to ten million units of work in the centimeter-gram-second system, and which is practically equivalent to the energy expended in one second by an international ampere in an international ohm.

Seventh. The unit of power shall be the watt, which is equal to ten million units of power in the centimeter-gram-second system, and which is practically equivalent to the work done at the rate of one joule per second.

Eighth. The unit of induction shall be the henry, which is the induction in a circuit when the electromotive force induced in this circuit is one international volt while the inducing current varies at the rate of one ampere per second.

SECTION 2. That it shall be the duty of the National Academy of Sciences to prescribe and publish, as soon as possible after the passage of this act, such specifications of detail as shall be necessary for the practical application of the definitions of the ampere and volt hereinbefore given, and such specifications shall be the standard specifications herein mentioned.

NOTES ON THE ABOVE DEFINITIONS. — The specifications mentioned above were prepared by a committee, and their report, based on the best

* Later experiments give an e.m.f. of 1.4328 volts at 15° C.

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t had been done up to that time, was accepted and adopted by the Academy of Sciences on February 9, 1895.
on is called to the wording of the definitions of the three fundamental :

international ohm is based upon, but *not stated to be equal* to, 10^9 s of resistance; it is, however, *definitely defined* in terms of a column of

international ampere *is* one-tenth of the c.g.s. unit of current, and is be represented *sufficiently well for practical purposes* by the current osits a definite mass of silver per second under specified conditions.
international volt is the e.m.f. which will cause an international ampere rough an international ohm, and is stated to be represented *sufficiently actical purposes* by a definite fractional part of the e.m.f. of the Clark

ient investigation has shown that the figures for the silver voltameter 'lark cell are not equivalent. The e.m.f. of the Clark cell is really ernational volts at 15°.

'ICAL STANDARDS. — The Act of July 12, 1894, is still in force tage has been taken of the manner of stating how the international e practically realized to use as a standard of e.m.f. the Weston normal l of the Clark cell (*see Cells, Standard*).
l resistance coils (*see Resistors, Standard*) are used as secondary of resistance. These are usually accurately adjusted by the makers. .t accuracy is required these standard resistances should be sent to 1 of Standards for calibration. Much more accurate results can be n an ordinary laboratory by using properly calibrated secondary than by attempting to construct primary standards in accordance efinitions in the above Act.
of a voltameter for the calibration of current-measuring instruments r seldom employed. A more accurate method for ordinary laboratory determine, by means of a properly calibrated potentiometer (q.v.), drop produced by the current through a standard resistance.

GRAPHY. — *The so-called International Electric Units*, Bull. Bur. 4, Vol. 1, p. 30; *Selection and Definition of the Fundamental Elec-*, Bull. Bur. Stand., 1908, Vol. 5, p. 243; *Announcement of Change in e International Volt*, Circ. No. 29, Bureau of Standards.

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UNLOADERS, COAL AND ORE. — (*See also Cranes; Motors, Industrial Applications of; Power Stations.*) Coal and ore unloaders may be divided into two distinct classes, namely, the stiff-leg type and the bridge type. Both are adapted to electric drive and each possesses certain advantages under certain conditions for which it is designed. Unloaders range in capacity from three to fifteen tons per bucket load. The capacity in tons per hour varies within wide limits, but records have been established where under normal operating conditions four 15-ton equipments unloaded 10,000 tons in five hours. The power required naturally also varies under different conditions, but an average of from 0.4 to 0.5 kilowatt hour per ton is not uncommon.

STIFF-LEG UNLOADERS (Fig. 1) are mainly used at receiving docks for unloading ore from the boat to railway cars or to a large concrete trough from which it is in turn transferred to the storage yards by means of ore bridges. The machine, as seen from Fig. 1, consists essentially of a massive pantograph the short leg of which forms an integral part of the carriage *C*. This leg is rigidly vertical, hence the stiff leg *L* which carries the bucket *B* must always be vertical. The weight of the moving parts of the link motion is nearly counterbalanced at *W* by the main hoist, rotation and bucket motors and their respective drums. The motor house on the carriage *C* contains the trolley motor and the magnetic control panels for all the above motors. The carriage is mounted on trucks and moves back and forth on the girder runway *G*. The girder structure supports a hopper with rotating gates which receives the ore from the bucket *B* and distributes it slowly to the weighing larry which in turn deposits it in the ore car underneath or in the concrete trough *I*. Cables from the main hoist drum at *W* are attached to the rear of the carriage. The operator rides in the bucket leg and has absolute control of lowering, opening, closing, bucket rotation, hoisting and trolleying movements. The entire girder structure is mounted on trucks and can be run along the dock at will by means of the bridge movement motor. Magnetic control is employed throughout and all motors except leg-rotation and bridge-movement motors are arranged for dynamic braking.

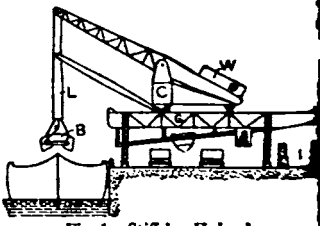


Fig. 1. Stiff-leg Unloader

Cycles of Motor Movements. — The service of the main hoist and opening and closing motor is intermittent with continuous repetition of cycle often at the rate of one round trip per minute for several consecutive hours. The leg rotation motor is used chiefly in cleaning up the bottom of the boat between hatches and involves rapid and frequent reversals at irregular intervals. The trolley-motor cycle includes acceleration, free running, retardation, reversal and repeat with every bucket load hoisted. The ore-gate motor operates intermittently wherever ore is distributed to the weighing larry. The larry travel and hopper-gate motors both operate on a continuously repeated cycle of short duration. The bridge-movement motor is used only at irregular intervals for locating the bucket over the hatches.

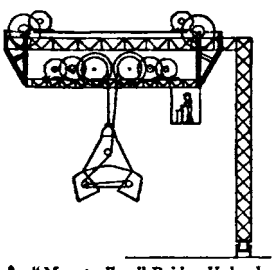
Motor Equipment. — The following table shows the motor equipment of a modern unloader of the stiff-leg type. The main-hoist motor has a continuous rating, but all the others are rated on an intermittent basis.

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MOTOR EQUIPMENT, 15-TON STIFF-LEG UNLOADER

of rs	H.P.	R.p.m.	Volts, d-c.	Application	Type of motor
	135	350	230	Main hoist	Compound wound
	75	500	230	Trolley	Compound wound
	75	500	230	Bucket { Opening / Closing	Compound wound
	100	450	230	Ore gates	Compound wound
	100	450	230	Larry	Compound wound
	100	450	230	Bridge movement	Compound wound
	20	750	230	Leg rotation	Series wound
	30	750	230	Larry hopper	Series wound

IDGE-TYPE UNLOADERS (Figs. 2 and 3) can be divided into two al classes, viz., the "man-trolley" and the "rope-trolley." In the former isting and conveying motors together with a cab containing the control ment and operator are mounted on a carriage which runs the length of the e, as shown in Fig. 2. In the rope-trolley unloader the motors are located stationary motor house and power is transmitted to the hoisting drum and age by means of cables, as shown in Fig. 3. The operator is also located in tionary cab as seen.



2. "Man-trolley" Bridge Unloader

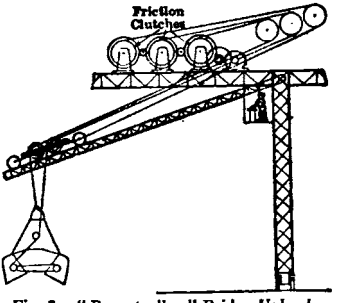


Fig. 3. "Rope-trolley" Bridge Unloader

MOTOR EQUIPMENT, 625-FOOT "MAN-TROLLEY" BRIDGE UNLOADER

lo. of otors	H.P.	R.p.m	Volts	Application	Type of motor
4	125	450	230	Main hoist	Series wound
4	50	500	230	Main trolley	Series wound
4	40	460	230	Bridge movement	Series wound

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MOTOR EQUIPMENT, 7-TON ROPE-OPERATED BRIDGE-TYPE UNLOADER

No. of motors	H.P.	R.p.m.	Volts	Application	Type of mot
2	55	430	250	Opening lines	Series wound
3	55	430	250	Closing and hoisting	Series wound
1	25	430	250	Travel	Series wound
1	11	...	250	Bucket twist	Series wound
1	15	...	250	Car-loading drums	Shunt wound

TYPE OF MOTOR. — The selection of the most suitable type of motor f coal and ore bridge work must be determined for each specific installation b local considerations. In general the requirements are not quite as severe a those commonly included under the term "steel mill service," and standard indu trial motors in a few instances have been used for high-speed bridges with suc success. As a rule, however, especially for ore bridges, the mill-type motor i recommended, since even under the best conditions the short cycle, rapid an frequent acceleration, severe vibration, dirt and moisture, all demand the mo rugged construction.

The question of alternating- or direct-current motors is usually one of comparat tive first costs, costs of maintenance and operation. Where adjustable speed under variable load are required the induction motor with its constant-sp characteristics is somewhat at a disadvantage if compared with the direct-curre motor equipped with interpoles and best available control. For dynamic brak the direct-current motor also offers fewer complications in the control. Furth more, for the rack movement or trolley travel the acceleration losses are l for the series direct-current motor. On the other hand, the efficiency of tra formation and distribution of power is considerably higher for alternating- th for direct-current systems so that the apparent gain due to the characteristic o the series motor may be more than offset by the simplicity and ruggedness o the induction motor, the elimination of motor-generator sets, equalizer sets an in some cases even of static transformers.

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S. — (*See also Boilers; Gas Engines; Pipes; Power Stations; Steam Steam Turbines.*) The following types of valves are used to control of fluids in pipes.

Valve. — The opening in this valve is perpendicular to the axis of the l is closed by a disk which moves across the opening. A gate valve t little resistance to the flow of the fluid, since when fully opened les a straight passage the full diameter of the pipe (*see Pipe and*

Valve. — In this valve the opening is in a partition parallel to and hrough the axis of the pipe. The opening is closed by a mushroom-isk which is screwed down against the partition. The name "globe" es from the globular form of the casing. The passage through a globe the general shape of the letter S, and consequently offers considerable to the flow (*see Pipe and Piping*). It is simpler in construction per than a gate valve, and the contact surfaces are more easily

Valve. — This valve has the inlet and outlet at right angles to each may therefore be installed in place of an elbow. The opening is at les to the inlet. The closing mechanism may be either of the gate or be type.

— This type of valve consists of a conical plug with a hole through licular to its axis, mounted in a suitable casing. The valve is opened g the plug so that the hole is in line with the pipe and is closed by plug a quarter turn. Cocks are frequently used on blow-off piping.

alves. — A stop valve is any valve that is controlled by hand or other ieans, and used to stop the flow of fluid in a pipe.

Valves. — A check valve is any valve which opens automatically pressure in the normal direction reaches a predetermined value, but losed when the pressure is less than this amount or is in the opposite Ordinary forms of check valves resemble a globe valve without a idle. The closing device may be a disk, ball or cup. When the disk l to swing about an axis like a hinge the valve is called a "swing check," alve," or "butterfly valve." When the disk or other device is lifted the valve is called a "lift-check valve." A check valve placed at f the suction pipe of a pump is called a "foot valve."

Valves. — Lift check valves provided either with a helical spring or l and lever mechanism to hold the valve closed under normal pressure as safety valves; the former type is called a pop safety valve, the ever safety valve. The pop safety valve has practically supplanted type, since it closes more promptly and is less liable to leak.

Valves. — Check valves used to relieve excessive back pressure in ric exhaust pipes are called "back-pressure valves," and when used ing to condensers to relieve excessive pressure are called "atmospheric es."

ng Valves are used when it is desired to obtain steam at a pressure hat of the boiler. In this type of valve the opening is relatively small, eam in expanding through this small opening has its pressure reduced. r size of opening for various rates of flow is maintained automatically ing the force produced on the closing mechanism by the pressure on essure side of the valve against the force produced on this mechanism al spring. The size of the opening then adjusts itself automatically in this balance irrespective of the rate of flow.

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SELECTION OF TYPE OF VALVE. — For low-pressure work standard cast-iron valves with bronze seats have been more than satisfactory They are now made of a great many types, all of which give very good res The solid wedge gate is perhaps the earliest and the best known. The sp wedge type and the parallel two-gate type are also well known and larg sold. Globe valves are not usually used for steam work on account of t resistance offered to the passage of the steam, but for throttle valves and stop valves are still the standard. For high-pressure work and especially w superheated steam the use of the steel body valve with steel seats and di has becoms standard and many varieties of valves are now on the mark some of which are doing excellent work. Nickel-bronze and nickel are also u for seats and stems with good results. In choosing a valve for high-press and high-temperature work, great stress should be laid on the absence of cha for unequal expansion in the body and gates. The metal should be so pla that what expansion occurs will be equable in all directions and the gates designed that they cannot spring out of true under different degrees of h Such mechanism as may be used between the gates in a double-gate valve press them up against the seats should be as carefully designed as the body the valve, as small deflections in this part of the mechanism will prevent tig ness. The most satisfactory valves for this work have been of the doub wedge type, although there are good parallel seat and solid-wedge valves the market which have stood severe tests.

ELECTRICAL OPERATION OF VALVES. — (*See also Motors, Indu trial Applications of.*) The advantages of electrical motor operation for la valves is emphasized not only by the fact that such valves must be closed i very short time, which would be impossible with hand control, but also by t fact that remote control is very often essential, as, for example, in hydroelec power developments where it becomes desirable to control the gate valves fr the control switchboard. The service of valve motors is exceedingly intermitte and may vary from comparatively short intervals, such as once every hour, weeks or even months. Due to the intermittent nature of the service, efficien or power factor need not be considered in this kind of motor application, t main consideration being the most reliable system of operation.

Size of Motor. — The proper size of a motor for driving a valve will va with the duty and conditions under which the valve operates. A small val may only require a one-horse-power motor, whereas very large valves, su as the Stoney-Gate valves at Panama, require 40-horse-power motors. The r quired motor capacity also depends to a large extent on the pressure on t valve. When opening the valve, the torque is a maximum shortly after th time of unseating, that is, after the wedges have been released and the acti motion begins. The torque then drops some until the valve has opened abo one-fourth, after which it takes comparatively little power to complete the ope ing. When closing the valve, friction only needs to be overcome in starting i there is no pressure on the valve until it has begun to close. After the valve about three-fourths closed the pressure causes the torque to increase rapidl At the end of the closing cycle the torque does not, however, reach the valu did during the period of starting.

Type of Motor. — Either direct- or alternating-current motors may be use With the former the series- or compound-wound type is generally used as it giv a high starting torque. With the latter the squirrel-cage induction motor i most widely used for small- and medium-size valves, principally on account o its simplicity. To overcome the sticking when opening, the drive is sometimes provided with a "lost motion" so as to give a hammer blow. For alternating-

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otors this is furthermore of value in that it permits the motor to speed nd gain in torque before the load comes on.

Equipment. — Where the size of the motor permits, the simplest control is to throw the motor directly on the line without the use of esistances. The automatic overload circuit breaker which should tection under normal operating conditions, must be prevented from ring the rush of starting current. This is readily accomplished either ircuiting the overload coil of the circuit breaker or by opening the s to the coil. The former is the preferable method as this will leave oad protection even though the coil is short-circuited. A push button provided for this purpose.

itches which will open the circuit when the gate has reached its limit hould always be provided. As a further precaution against over- o high closing torque the motors should preferably be geared to the s through efficient and reliable friction clutches.

e motors are too large to be thrown directly on the line, starting re- ust be provided. With direct-current series motors a permanent nd a running resistance are often provided. The permanent resist- ns fixed in the circuit and should be so dimensioned as to give the torque required. The running resistance is short-circuited at start- ie motor current drops to any desired value, at which time a current opens the shunt circuit of the contactor used for short-circuiting ice. This running resistance should be such as to prevent excessive ht load and to limit the torque should the valve seat itself before the sconnected. The same general scheme may be used with alternating- tors, but with these there is no danger of exceeding the synchronous

for Indicating Valve Positions. — When it is desired to indicate chboard the position of the gate throughout its range of travel, this be done by placing a number of sliding contacts on the inside of witch housing. These contacts are then connected with a row of nt lamps installed on the switchboard, and as the limit switch travels lamps on the board will light successively.

system, much more comprehensive, is used in connection with the rs at the Panama Canal. In connection with each limit switch there a "synchronizing transmitting device." This consists merely of a ator which is mechanically connected to and revolves with the limit is electrically connected to a small motor which is mounted on the tchboard and there mechanically connected to some sort of indicating as a pointer. When the generator at the valve revolves, the motor ird will follow in synchronism thus indicating the exact position of

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VECTORS. — (*See also Complex Quantities.*) Any quantity which requ for its complete specification a magnitude and a direction is called a vec quantity. Such a quantity may be represented graphically by a line havi length equal to the magnitude of the quantity and a direction parallel to direction of the quantity. Such a line is called a vector. Its direction is general, specified by the angles which it makes with three arbitrarily ch lines or axes of reference. Vectors which lie in the same or in parallel pl are called co-planar vectors; the direction of a vector in the plane in which lies (or parallel planes) may be specified by the angle which it makes wit single line of reference in this plane.

Quantities which are completely specified by magnitude and "sense" (i whether positive or negative) are called scalar quantities. Forces, velociti displacements, etc., are vector quantities, while time, work, mass, etc., scalar quantities.

Vector Addition and Subtraction. — Since vector quantities cannot completely specified by ordinary numbers, the various operations of arithme such as addition, subtraction, multiplication and division have no mean when applied to such quantities. Analogous processes, however, are of gr value in dealing with them. For example, the resultant of two forces wh make an angle with each other is, by the ordinary parallelogram of forces, equal to the diagonal of the parallelogram formed by drawing from the free ends of the two lines representing the forces, lines parallel to these forces. That is, the resultant of OA and OB in Fig. 1 is the diagonal OC. Both the length OC and direction (the angle AOC) of the resultant is fixed by this construction. The resultant OC is called the vector sum of OA and OB. Similarly, the vector sum of OA and AB is equal to OB, or vice versa, AB may be called the vector difference of OB and OA. The angle XAB gives direction of this vector difference when OA is subtracted vectorially from O When OB is subtracted vectorially from OA the vector difference also has same length or magnitude, but is in the opposite direction, i.e., makes angle $180° - \angle XAB$ with OA.

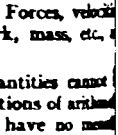


Fig. 1

Components of a Vector. — Any vector may be considered as made up any number of vectors which when added vectorially, as described above, gi a resultant vector equal to the given vector. It is frequently convenient analyzing problems involving vectors to resolve each vector into two comp nents, one parallel to and the other perpendicular to the axis of refere The first component is usually referred to as the horizontal component and second as the vertical component. It is readily proved that the horizontal com ponent H of the resultant (or vector sum) of any number of vectors is equ to the algebraic sum of the horizontal components h_1, h_2, etc., of the individu vectors, i.e.,

$$H = h_1 + h_2 + \text{etc.}$$

and the vertical component V of the resultant is equal to the algebraic sum the vertical components v_1, v_2, etc., of the individual vectors, i.e.,

$$V = v_1 + v_2 + \text{etc.}$$

The length of the resultant is then

$$S = \sqrt{H^2 + V^2}$$

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akes with the axis of reference the angle σ where

$$\tan \sigma = \frac{V}{H}.$$

ical Representation of a Vector. — The geometrical representation plex quantity (*see Complex Quantities*) is a vector, i.e., the line repre- complex quantity has both magnitude and direction. Any vector may, therefore, be represented by a complex quantity, and the opera- ector addition and subtraction may be carried out by the ordinary of algebraic addition and subtraction of complex quantities. For ex- o vectors A and B may be represented by the algebraic expressions

$$\dot{A} = h_1 + jv_1,$$
$$\dot{B} = h_2 + jv_2,$$

nd h_1 and h_2 and v_1 and v_2 are the horizontal and vertical components re- , and the dots under A and B signify that $\dot{A}$ and $\dot{B}$ are vector quan- ie vector sum of $\dot{A}$ and $\dot{B}$ is then

$$\dot{S} = \dot{A} + \dot{B} = (h_1 + h_2) + j(v_1 + v_2),$$

the magnitude

$$S = \sqrt{(h_1 + h_2)^2 + (v_1 + v_2)^2},$$

igle

$$\sigma = \tan^{-1} \frac{v_1 + v_2}{h_1 + h_2}.$$

ication and Division of a Vector by a Number. — Multiplying a a real number n means taking a vector n times as long; dividing / n means taking a vector $\frac{1}{n}$ of the length of the original vector. The ultiplying a vector by an imaginary number jn is defined as a vector e length of the original vector and making a positive angle of 90° riginal vector. The result of dividing a vector by an imaginary is defined as equivalent to multiplying the vector by $\frac{1}{jn} = -j\frac{1}{n}$ equivalent to a vector $\frac{1}{n}$ of the length of the original vector and egative angle of 90° with the given vector. Hence the multiplication of a vector $h + jv$ by a complex number $n + jn$ is equivalent to lgebraic multiplication or division of two complex numbers (*see uantities*).

Product of Two Vectors. — Multiplication, in the ordinary sense, ctor by another has no meaning, since a vector is not a number but oth magnitude and direction. In the analysis of the more com- oblems of mechanics and electricity, certain expressions arise, how- are analogous to ordinary multiplication. One of these expressions quantity equal to the product of the magnitude of the two the cosine of the angle between them. This product is called the luct of the two vectors. The scalar product of the two vectors A $B \cos \theta$ where θ is the angle between them. If the vectors are as complex quantities

$$\dot{A} = h_1 + jv_1,$$
$$\dot{B} = h_2 + jv_2,$$

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the scalar product is

$$h_1h_2 + v_1v_2.$$

Note that this has no relation to the algebraic product of the two expressi $h_1 + jv_1$ and $h_2 + jv_2$.

Vector Product of Two Vectors. — Another expression which arises a vector quantity at right angles to the plane of the two vectors and equal magnitude to the product of the magnitudes of the two vectors by the sin the angle between them. This product is called the vector product of the t vectors.

Example. — The vector product of the vector A by the vector B (Fig is $AB \sin \theta$, and is in the direction in which a right-handed screw, to the be of which A is conceived to be fixed, is advanced when A is turned through angle of less than 180° into coincidence with B. From this definition it fo lows that the vector product of B times A is equal but *opposite* to the vect product of A times B. When A and B are expressed as complex quantities t vector product of A times B is

$$h_1v_2 - h_2v_1.$$

Note that the algebraic product of the expressions

$$h_1 + jv_1 \quad \text{and} \quad h_2 + jv_2 \quad \text{is} \quad h_1h_2 - v_1v_2 + j\,(h_1v_2 + h_2v_1).$$

The real and imaginary parts of this expression are *not* equal to the scalar a vector products.

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ON, LAWS OF. — (*See also Illumination, Laws of; Photometric ities; Photometry.*) Light enters the eye through the *cornea*, a thin, trans-, curved wall, and passes successively through the *aqueous humor*, the the *biconvex lens*, and the *vitreous humor* to an image on the rear wall *na*. The cornea and lens possess the image-forming function, and accom-ion to distance is given by the varying curvature of the lens. The humors ptical contact and preserve the size and form of the eye. The contraction ilation of the pupil gives automatic accommodation to the intensity and ity of light in the field of view. The retina adapts itself automatically sibility to the flux density of the light falling upon it; while comfortable covers a range of brightness of ten billion to one, the sensibility of the varies in the ratio of one hundred million to one.

retina comprises an elaborate structure of microscopic nerve terminals as rods and cones. In its periphery rods predominate, but the ratio of to rods increases steadily toward the axial region of *fovea*, where the cones y predominate. The directly visualized image falls on the fovea and the ness of perception diminishes markedly in passing to the periphery. At ow intensities rod vision predominates. At moderate and high intensi-one vision predominates. In the former state the relative sensibility to ue end of the spectrum is emphasized, in the latter state the relative sensi-to the red. As an optical system the eye has a chromatic aberration of imately two diopters.

EMENTS OF VISION. — Visual sensations in general are characterized tensity, extensity, quality and duration. Intensity refers to the aspects ion measurable photometrically, such as brightness and contrast, determin-ux density at the retina. Extensity involves the perception of contour, ective, relief, detail and distance. Quality discriminates between sensa-of color and non-color. Duration relates to the growth, fatigue, persist-nd intermittency of visual sensations.

ensity Relations. — For a given quantity of radiant energy, the luminous tion (light) varies with the wave frequency of the radiation, with its ity and with the time of exposure eye to it. The eye is most sen-and the ratio of light to energy maximum at a wave length of 0.000558 mm. in the green part e spectrum. Here the ratio of to radiation is about 0.0015 lu-per watt of radiation. From ave length the luminous equiv-of radiation decreases rapidly rd both shorter and longer wave lengths. It is about 0.0000006 lumen watt at wave lengths 0.00040 and 0.00073 mm. The data on the complete for ratio of light to radiation are given in the following table and in 1. These data are the means for about 200 subjects collected by Ives, ing, Coblentz and Hyde in four different laboratories. These data are cable to all moderate and high intensities. At very low intensities a ar curve displaced toward shorter waves obtains.

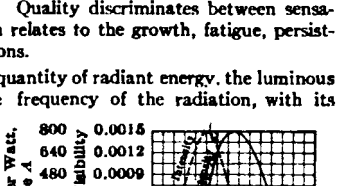


Fig. 1

Purkinje Effect. — Transition from vision at low intensity to high lves relative loss of sensibility to blue and gain of sensibility to red, so that lights of reddish and bluish hue respectively show a ratio of intensities h varies with the brightness of the field of view. This is known as the kinje effect. In fields above a brightness of one lumen per square foot the

VISIBILITY OF RADIATION AVERAGE NORMAL EYE

Wave length ($\mu\mu$)	Relative to that at 556 $\mu\mu$	Absolute (Lumens per watt)	Wave length ($\mu\mu$)	Relative to that at 556 $\mu\mu$	Absolute (Lumens per watt)
400	0.0004	0.0000006	600	0.631	0.00095
10	.0012	.0000018	10	.503	.00075
20	.0040	.0000060	20	.380	.00057
30	.0116	.000017	30	.262	.00039
40	.023	.000034	40	.170	.00025
450	0.038	0.000057	650	0.103	0.000154
60	.060	.000090	60	.059	.000089
70	.091	.000136	70	.030	.000045
80	.139	.000208	80	.016	.000024
90	.208	.000312	90	.0081	.000012
500	0.323	0.00048	700	0.0041	0.00
10	.484	.00073	10	.0021	.00
20	.670	.00100	20	.0010	.000001
30	.836	.00125	30	.00052	.000008
40	.942	.00142	40	.00025	.000004
550	0.993	0.00149	750	0.00012	0.000002
60	.996	.00149	60	.00006	.000001
70	.952	.00143			
80	.870	.00130			
90	.757	.00114			

shift is slight. Photometric comparisons involving color differences should be made only in bright fields.

Intensity Sensibility. — For an eye viewing a field of a given brightness there exists for each brightness to which the eye is adapted (1) a minimum brightness just perceptible, (2) a ratio of brightness (contrast) just perceptible, (3) a maximum brightness just tolerable.

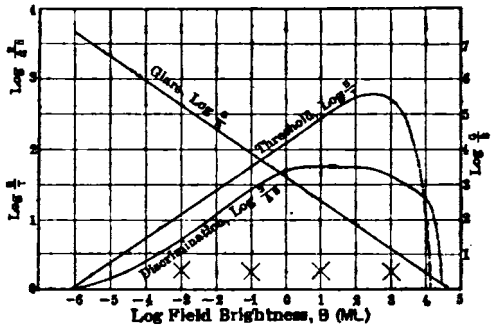
Field brightness		Difference fraction	Discrimination factor	Threshold limit	Glare limit
0.000001 m.l.		(1.00)	1.0	0.00000093 m.l.	20.1 m.l.
0.00001		(0.66)	1.5	0.0000042	40.7
0.0001		0.395	2.5	0.000019	89.
0.001	(E.N.)	0.204	4.5	0.000087	86.
0.01		0.078	12.8	0.00039	400.
0.1	(I.N.)	0.037	27.0	0.00174	810. m.l.
1.0		0.0208	48.2	0.0081	1.66 l.
10.	(I.D.)	0.0174	57.5	0.036	3.47
100.		0.0172	58.1	0.28	7.25
1,000.	(E.D.)	0.0240	41.7	2.15	14.45
10,000.		(0.048)	(20.9)	(232.)	30.90

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ief summary of the data on threshold limit, discrimination and glare given in the table at bottom of page 1888.

example, an average eye adapted to a field brightness of 0.1 m.l. can just ontrast of 1.037 : 1—the discrimination is about half (27/57) its maximum

The deepest shadow in which it can see anything is 0.0017 m.l. in ness and the brightest tolerable high light is 800 m.l.



l. Threshold, Discriminating Power and Glare Sensibility at Various Levels.

illuminating engineer is chiefly concerned with four quite distinct brightvels, namely:

0.001 m.l. (E.N.) Exteriors at night, street lighting.
0.01 m.l. (I.N.) Interiors at night, interior artificial lighting
1.0 m.l. (I.D.) Interior daylight lighting.
1.0 l. (E.D.) Exterior full daylight lighting.

glare sensibility (G) is a linear function of log field brightness (B) such that

$$\text{Log } G = 3.23 + 0.32 \log B,$$
$$G = 1700B^{0.32}.$$

reshold sensibility (T) is also a linear function of log field brightness at the highest intensities (over 0.1 lambert) such that

$$\text{Log } T = 0.66 \log B - 2.10,$$
$$T = 125B^{0.66}.$$

ility to **contrast** is nearly constant (about 2 per cent) over the wide of intermediate intensities with which vision is chiefly concerned.

RATE OF INCREASE AND DECREASE OF THRESHOLD SENSIBILITY

Time	$B_0 = 0$, $B = 25$m.l. Sensibility decrease	$B_0 = 25$m.l., $B = 0$ Sensibility increase
1 second	2.1 times	1.6 times
2 seconds	4.2 times	2.6 times
5 seconds	16.2 times	7.6 times
10 seconds	58 times	14.4 times
10 minutes	120 times	20.9 times

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Effect of Alternate Exposures. — If an eye is fully adapted to a [illegible] of a given brightness, then suddenly exposed to a dark field it gains rapid sensibility as shown in the table on page 1889, while if adapted to dark and then exposed to a bright field it loses sensibility but at a lower ratio.

Since the loss of sensibility in a given interval is greater than the re[illegible] the net result of a succession of exposures to alternate light and darkness is a considerable *depression* of mean sensibility.

Color of Various Sources. — In monochromatic analysis white [illegible] is mixed with light of a pure spectral hue to match the color to be analyz[illegible] L. A. Jones gives the following color analyses of common light sources.

Source	Color	
	White	Hue
1. Sunlight	100	472
2. Average clear sky	60	472
3. Standard candle	13	593
4. Hefner lamp	14	593
5. Pentane lamp	15	592
6. Tungsten glow lamp at 1.25 w.p.c.	35	585
7. Carbon glow lamp at 3.8 w.p.c.	25	591
8. Nernst glower at 150 w.p.c.	31	586
9. Nitrogen filled tungsten:		
at 1.00 w.p.c.	34	586
at 0.50 w.p.c.	45	584
at 0.35 w.p.c.	53	584
10. Mercury-vapor arc	70	496
11. Helium tube	32	598
12. Neon tube	6	605
13. Crater of carbon arc:		
at 1.8 amperes	59	584
at 3.2 amperes	62	584
at 5.0 amperes	67	583
14. Acetylene flame (flat)	36	585

Extensity Relations. — Extensity is perceived largely through differen[ces] in brightness and color, by varying visual angles and by acuity, or the po[wer] of resolving detail. Acuity follows a logarithmic relation to brightness simi[lar] to the strength of sensation. The same practical lower limit, say from one to two lumens per square foot, affords a fair normal basis of acuity. Above this the gain in acuity is relatively much less than the increase in illumination. Acuity, however, is not independent of color, due to the chromatic aberration of the eye. Retinal images formed by approximately monochromatic light are sharper than those due to a rich spectrum. Luckeish (*see Elec. W., Vol. [illegible] p. 1252*) gives the data in Fig. 3 for the relative acuity with various colo[rs]. For near vision blue light is more readily focussed, whereas for distant visi[on] red light is more readily focussed.

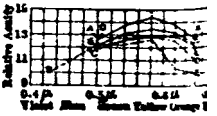


Fig. 3

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lare. — The effectiveness of illumination is depressed to a marked
/ disturbing influences grouped under the term glare, which may be
ately defined as the relative overbrightness of part of the field of view.
glare, caused by the slowly changing adaptation of the eye when
from a dim region into a brilliantly lighted one, causes only temporary
t. Persistent glare, in addition to the depression of visual functions,
ighly injurious. No complete quantitative analysis of glare has yet
e. The following qualitative relations have been well established:

re effect, or reduction of visual effectiveness, increases as the glaring
proaches the eye. Glare increases as the ratio of the distance of the
urce to that of the visualized object from the eye diminishes. The
t which a light source ceases to be glaring depends on its intensity,
and position in the field of view.

e increases with the quantity of light received from the source.

e increases with the brilliancy of the glaring source and with its de-
ntrast to objects visualized. An automobile headlight is exceedingly
night, but not glaring by day. Any light source giving an after-
cessive in brilliancy. Glare due to this cause is accentuated by the
ency of the eye to wander from the object of vision and fix on the
urce, causing a fatigue of attention.

e increases as the retinal image of the glaring source approaches the
ie field of view. Depression of vision from side light is due in part
and in part to the dilution of the central image by light scattered
Glare due to bright walls and backgrounds is largely of the latter
glare from bright sources situated at an angle from the line of vision
6 degrees is generally negligible.

f practical cases of glare are due to directly visible light sources of
and brilliancy, to scattered light from side sources and backgrounds
ect reflection of bright images by glazed surfaces in the immediate
r. Prevention should be sought by the proper location and shading
irces, by creating suitable constrasts between the field and its
s and by avoiding the use of glazed surfaces, especially highly-sized

. — Below certain frequencies intermittent sensations retain a
distinctness and produce a flicker effect. If a critical frequency is
e sensations blend into a continuous effect equal in intensity to the
ity over the complete cycle. Examples are the rotating sectored
e electric lamp operated by alternating current. The vanishing
f flicker increases with the degree of variation from maximum to
nith the solid angle subtended by the object viewed and with the
its brightness. The vanishing frequency of flicker is higher for
or colored light. Within the common limits of practice the vanish-
y is between 30 and 45 cycles per second. Electric lamps display
le flicker in themselves or in illuminated objects at frequencies
cycles.

r Color Relations. — Non-colored sensations are white gray, and
r sensations differ in brightness in hue and in tone. The hue of
termined by the spectral position of its predominant component.
int depends on the degree of dilution with white or black. Thus
pink and claret may agree in hue, but differ essentially in tone.
ions are equal in brightness when they may be rapidly alternated
f view without the appearance of flicker.

thesis and Analysis of Colors may be accomplished by mixing red,
ue in proper proportions, or by diluting the predominant hue with

necessary to reproduce it. Tri-chromatic specification gives the mixing p portions of red, green and blue. Mono-chromatic specification gives the spe hue and the degree of dilution. The tri-chromatic analysis as determined the colorimeter (*see Photometry*) is of greatest practical utility. In this sy the proportions of red, green and blue found in average daylight, though equal, are taken as 33.3 per cent each to fix three color scales. The n proportions of these colors on the scales so established which reproduce given light serve to specify it and to compare its color composition with day

Relation of Color of Light to Appearance of Objects. — Ob appear in the colors which they reflect or transmit to the eye. To pro true color effects light must possess all the components necessary to re objects and possess them in proper proportions. If the spectrum is defici parts or its components differ greatly from the proportions in daylight it in general produce distorted color effects.

Artificial White Light. — With the exception of the carbon fi vacuum tube no artificial illuminant approaches closely the color value of light. White light may be approximated by synthesis by combining the of two sources, one excessive in red and the other excessive in blue, as the in descent electric lamp and the mercury arc. A closer realization may be obta from any incandescent lamp by means of a selective absorption screen w removes the excess of red and green light. The latter method involves a sacrifice of efficiency.

SUMMARY OF CONDITIONS FOR BEST VISION. — The su brightness of objects viewed should not be less than 0.0015 candle per s inch nor more than 1.5 candles. In terms of the illumination of ordinary paper these values correspond roughly to limits of 1 to 1000 foot-candles. value best adapted to any condition varies with the individual, the closen application the nature of the surroundings and the general degree of diff For reading by daylight 100 foot-candles is approximately the best cond

ILLUMINATION IN FOOT-CANDLES

Nature of illuminated surface	Foot-candles at floor le	
	Minimum required	Good practice
Roadways and yard thoroughfares	0.02	0.05- 0.1
Storage spaces, stairways, passageways, aisles, exits and elevator entrances	0.25	0.50- 2.0
	Foot-candles at the wo	
Work not requiring discrimination of detail	0.50	1.00- 2.0
Rough manufacturing and assembling	1.00	2.00- 4.0
Machining and bench work	2.00	3.00- 6.0
Fine manufacturing and office work	3.00	4.00- 8.0
Special fine work, drafting, engraving, sewing	5.00	7.00-25.0

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cial light approximately from 4 to 10. The degree of illumination is strongly influenced by the contrast between objects visualized and roundings. The high diffusion of daylight and the flatness of the con- ich it gives account in large measure for the higher illumination desired. seeing the objects viewed should be brighter than the surroundings, ontrast should not exceed 10 : 1. The illumination provided for work close application should be in inverse ratio to the reflecting power of minant surfaces. Directly visible light sources may generally be shaded a brightness of 2.5 candles per square inch with advantage to vision. ns outlined under *Glare* should be observed.

ccompanying table indicates the range of artificial illumination in lles which has been found satisfactory under practical conditions.

ion. — Vision is aided by the sharp definition of details down to an inge of 1 in 10,000. Reading is easiest with type subtending an angle r in 100. For comfort it should not be larger than 1 : 20 nor less than

sts in intensity are best at about 1 : 10, but should not be less than Contrasts as slight as 98 : 100 are readily perceivable in good light.

nity of light on the working area is important. Excessively bright titute an annoying glare and interfere with the fixation of vision.

ess of light is essential, as flicker causes rapid fatigue.

– A well-balanced spectrum is required for the true revelation of ors. Fatigue is most rapid in the extreme blue end of the spectrum violet radiations may cause injury if present in unusual quantity. ing a strongly dominant yellow-green hue gives the highest visual

n. — Complete diffusion tends to eliminate shadows, with the re- s of relief. The value of moderate shadows varies greatly with the ces, but is greatest where color distinctions are lacking.

EFFICIENCY. — The resultant of all conditions affecting vision is the somewhat loose term visual efficiency. This concept must take the fundamental discriminations of brightness, detail and color and ntenance of these faculties in use. Tests of visual acuity have been l as a working criterion of visual efficiency. As applied to the momen- of vision this criterion is unsatisfactory as it invites a semi-conscious r to offset fatigue. An ideal criterion must take account of the e of acuity in work, of the ease with which fixation of vision and re sustained, and of the general requirements of ocular hygiene. *Ill. Eng. Soc., Vol. 8, p. 40.*)

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VOLTMETERS. — (*See also Ammeters; Wattmeters.*) A voltmeter is an instrument for measuring the potential difference, or voltage, between the two points to which its two terminals are connected. Any type of ammeter (q.v.) may be used as a voltmeter, but when designed for this purpose the coil which carries the current is made of a number of turns of fine wire, so that the moving element will be deflected by a very small current (from 10 to 200 milliamperes for full-scale deflection, depending upon the type) and to limit the current to this value a high resistance, contained within the case of the instrument, is usually inserted in series with the coil. The high resistance may be provided with taps brought out to additional binding posts, so that the same instrument will give full-scale deflection for say 75, 150 and 300 volts, depending upon which binding post is used in conjunction with the terminal marked "0" or "+." The range of a voltmeter may also be indefinitely extended by the use of multipliers (*see below*) or potential transformers (*see Transformer, Instrument*).

Current Taken by, and Resistance of, Voltmeters. — The current taken by voltmeters of various types for full-scale deflection, and the resistance per volt of full-scale deflection are usually as follows:

Type of voltmeter	Milliamperes for full-scale deflection	Ohms per volt of full-scale deflection *
Iron-vane type	83 to 60	12 to 17
Moving-coil type	20 to 10	50 to 100
Electrodynamic type	83 to 40	12 to 25
Hot-wire type	250 to 187	4 to 5.3

* For example, a moving-iron type voltmeter having a 150-volt scale would have a resistance of from $12 \times 150 = 1800$ to $17 \times 150 = 2550$ ohms. The current taken by the instrument would be from 83 to 60 milliamperes. Lower ranges in moving-iron and in electrodynamic voltmeters require larger currents for full-scale deflection, in order to keep down errors due to frequency.

When a d-c. voltmeter is connected to any two points on a network, its reading is in general lower than the previous potential difference between the points, because the voltmeter draws some current from the network. Let the voltmeter reading be V_1. If the voltmeter be now shunted by a resistance equal to its own, a second reading V_2, lower than V_1, will be obtained. The potential difference V can then be found from the formula,

$$V = V_1 V_2 / (2V_2 - V_1).$$

The above method gives correct results not only when the voltmeter is connected directly to the points but also when it is connected through "pressure wires" of appreciable resistance.

Temperature and Inductance Errors. — In order that a voltmeter calibrated at one temperature shall read correctly at all other ordinary temperatures, it is necessary that its total resistance shall change with temperature by only the small amount necessary to offset the resultant effect of temperature change in the springs, magnets, or other operative parts. To secure this condition, the resistance included in series with the active winding (which latter is usually made of copper wire) must have a very low temperature coefficient

in, constantan, and various other alloys may be used for this purpose; :s, *Resistance*. The total resistance of a permanent-magnet moving-coil :r, or of a voltmeter of the electrodynamic type should increase about cent per degree C. if its readings are to be independent of temperature. dded resistance in an a-c. voltmeter is wound non-inductively, either as coil or on a card. The total impedance is then only slightly greater total resistance for well-designed voltmeters used at ordinary lighting er frequencies. At higher frequencies the voltmeter will read lower of its higher impedance. If the reading is correct at the calibration y f_1, the reading at frequency f_2 may be corrected by multiplying by or $1+2\pi^2L^2(f_2^2-f_1^2)/R^2$, where R is the resistance, L the inductance. $f_1^2L^2/R^2$ and $2\pi^2f_2^2L^2/R^2$ are each small in comparison with unity. cases the term f_1^2 may be neglected.

pliers and Potential Transformers. — A voltmeter multiplier is n external resistor placed in series with the voltmeter. These resistors e of high-resistance alloys having a low temperature coefficient, and id non-inductively. If r and R are the resistance of the voltmeter e multiplier respectively, v and V the value of one scale division in volts ınd with multiplier respectively, then

$$V=v(R+r)/r.$$

$(R+r)/r$ is frequently called the "multiplying power" of the multiplier ıltmeter in question.

ltages above 750 volts potential transformers are to be preferred to s for a-c. circuits; see *Transformers, Instrument*.

ıstatic Voltmeters. — When the current taken by the ordinary form ter is an appreciable fraction of the load current or when the frequency igh, as in radio work, an electrometer (*see article on Electrometers*) static voltmeter may be used. The ordinary electrostatic voltmeter ciple the same as an electrometer, but is provided with a pointer and is so constructed as to be more readily portable than the ordinary ter which is read by means of a telescope and scale. Repulsion elec- oltmeters are also used, the principle of operation being the repulsion nductors charged with electricity of the same sign, as in a gold-leaf pe.

ser multipliers are sometimes used with electrostatic voltmeters; see *ers*.

ng of Voltmeters. — A voltmeter may be checked by comparing it andard voltmeter whose correction curve is known, or it may be irectly by means of a potentiometer and standard cell; see *Potentio-* lot-wire and electrodynamic voltmeters for alternating-current work ed on direct or alternating current; a moving-iron voltmeter should l by comparing it, on alternating current, with one of the other types been previously checked on direct current. Electrostatic voltmeters y employed commercially only for high voltages, and therefore must l on alternating current.

tions in Use and Installation, Costs, Bibliography, etc. — See on *Ammeters*.

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WATER WHEELS AND THEIR SETTINGS. — (*See also Hydraulic Principles of; Power Stations, Hydroelectric; Water Wheels, Speed Regulation of*) —A water wheel is a machine for converting the energy of falling water into mechanical work. The old-fashioned undershot and over-shot wheels are now seldom used. In modern water wheels, usually called hydraulic turbines, the energy of the water is gradually transformed into kinetic energy as the water passes through a set of guides and vanes.

Work is the product of force times distance, and power is the rate of doing work. Let f be the total force in pounds exerted by the water on the runner of a turbine, let L be the distance in feet travelled by a point on the runner located at the center of pressure, and let t be the time in seconds for this point to travel this distance. The power developed by the water is then

$$P = \frac{f}{550} \cdot \frac{L}{t} \qquad \text{horsepower} \qquad (1)$$

The power developed by falling water may also be expressed in terms of the rate of flow in cubic-feet per second, Q, and the *net* effective head h, in feet. The potential energy of Q cubic-feet of water at an elevation of h feet is $62.4Qh$ foot-pounds. Hence for a rate of flow of Q cubic feet per second the *theoretical* power developed is:

$$P = \frac{62.4Qh}{550} = \frac{Qh}{8.814} \qquad \text{horsepower} \qquad (2)$$

It is important to note that in this equation h is not the difference in elevation between the intake and discharge levels, but is equal to this gross head H less the sum of the heads corresponding to the friction losses in the conduit system and the residual velocity where the water is returned to the stream.

All the energy developed by the water as it passes through the turbine is not converted into useful work. The ratio, e, of the power output of the turbine measured on the turbine shaft, to the theoretical power of the water, is the efficiency of the turbine. The output of the turbine may then be expressed by the equation:

$$P_0 = \frac{Qhe}{8.814}. \qquad (3)$$

Speed of Rotation. — In the conversion of energy by an hydraulic turbine the factor $\frac{L}{t}$ in equation (1) is the *linear speed* of the runner at the center of pressure.

If the linear speed is zero, it is evident that the power must be zero. If the linear speed is too great, approximately equal to the spouting velocity of the water corresponding to the head on the turbine, the pressure of the water on the runner is zero and again no power is produced. It is evident, therefore, that at some linear speed between these limits the power and the efficiency will be the greatest. In other words, the linear speed of the runner must be a fixed percentage (theoretically about 50 per cent) of the spouting velocity of the water, in order to obtain the best efficiency. Therefore, since the *speed of rotation* or revolutions per minute (commonly termed "speed" of the runner) varies directly as the linear speed, it increases with the head (and spouting velocity), if the diameter is constant. It also decreases as the diameter (and capacity) increases.

Consequently, for a given type of runner, low heads and large capacities require a low speed and, conversely, high heads and small capacities require high speeds. It is the object of turbine builders to keep the speed within

onable limits to suit the characteristics of the generators and other machin- and for this purpose many types of runners have been developed.

LASSIFICATION OF TURBINES. — Modern hydraulic turbines of two types: reaction turbines and impulse turbines. The basic difference reen the two types is in the runner.

eaction Turbines. — A typical low-head reaction turbine and runner are cated in Figs. 1 and 2. The water enters the runner through the guide

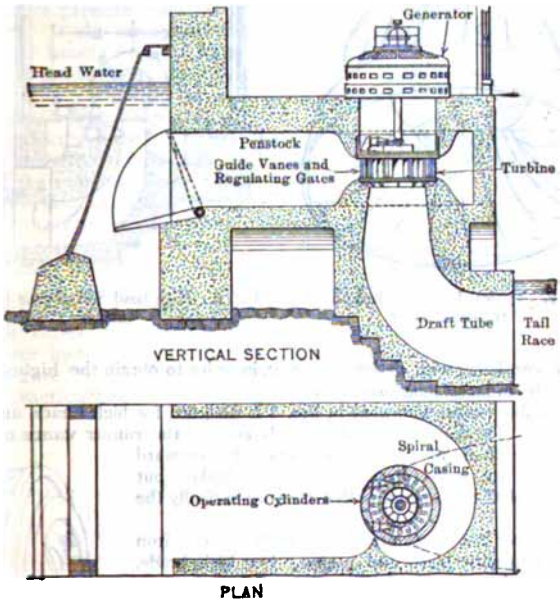


Fig. 1. Low-head Spiral-case Reaction Turbine

es and regulating gates. It passes inwards and downwards through the ner vanes to the draft tube.

Power is developed by the pressure and reaction of the water on the runner es, the runner being completely filled. Modern reaction turbines are adapt- e to all heads up to about 800 feet where the units are large.

mpulse Turbines. — A typical impulse turbine and runner are indicated ig. 8. The pressure head is first converted into velocity through the nozzle he end of the penstock, and power is developed by the impulse of the water acting upon the buckets on the rim of the runner.

The impulse turbine must never be submerged, it being necessary to allow water to fall away freely from the buckets. Small impulse turbines are uptable to all heads. For all capacities they are used exclusively for heads ater than about 800 feet.

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CHARACTERISTICS OF REACTION TURBINES — The Runner.— Reaction runners vary in shape and design depending upon the conditions under which they are to be used. The runner indicated in Fig. 2 is designed for a low-head, large-capacity turbine. The diameter is made as small as

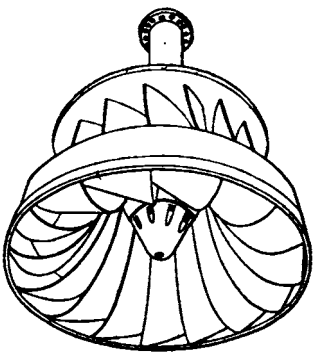


Fig. 2. Typical Low-head Reaction-turbine Runner

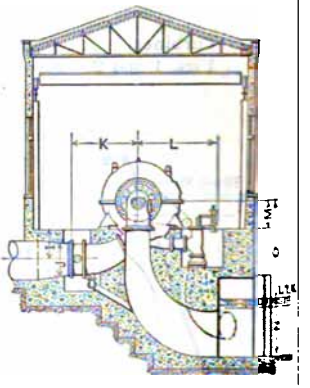


Fig. 3. High-head Spiral-case Reaction turbine

possible, consistent with desired capacity, in order to obtain the highest speed. This results in large, long runner vanes.

The double runner indicated in Fig. 4 is designed for high heads and small discharges. The diameter is relatively larger and the runner vanes narrower and smaller than in the former type. In outward appearance the two types are quite dissimilar; but the action of the water and pathof flow are basically the same.



Fig. 4. Typical High-head Double-discharge Reaction turbine Runner

Runners for low heads are usually made of cast iron or cast iron with plate-steel blades. For high heads, cast steel or bronze are often used to reduce the wear of the metal resulting from the high velocities.

No uniformity exists among turbine manufacturers in the methods of measuring the diameters of reaction runners. For this reason it is never possible to compare the diameter of a runner with that of another make; or even with a runner of another type of the same manufacturer. Diameters are therefore employed only for comparison of runners of the same type and, as relative diameters only are used, it is never necessary to know the actual points to which the diameter is measured when selecting the type and size of runner for a given installation.

The capacity of a runner is specified as a certain full gate capacity at a given head and speed.

The Gates. — In modern installation, wicket-gates are used because they present the least resistance to flow when in a part open position. Cylinder gates, consisting of a steel cylinder, moving axially over the opening to the

inner, are sometimes adopted for small installations and those designed to erate normally at full gate. Cylinder gates are not efficient when operated rt open, owing to the sharp contraction at the bottom of the cylinder.

Wicket gates are actuated by the governor or hand control through rods and vers. The gates of the turbine indicated in Fig. 1 are controlled by two erating cylinders located in the turbine pit. Oil is admitted by the gov-nor to the cylinders and the resulting movement of the piston rods revolves ghtly a shifting ring to which are connected the individual gate-links for oving the gates.

The Draft Tube. — The function of the draft tube is to utilize, by suction negative pressure below the turbine, the head between the turbine and the il race. It also serves to reclaim as much as possible of the velocity head of e water issuing from the runner, which is sometimes very great. They are creased gradually in area towards the outlet where the average velocity is ually from 3 to 10 feet per second, the higher velocities being for the higher ad installations.

The velocity of the water, when leaving the runner, is not strictly axial but, e to imperfect reaction and skin friction, has a swirling motion in the direc-n of the rotating runner. It is only the component of this velocity in the ial direction which can be reclaimed by the ordinary form of draft tube. It is for the purpose of reclaiming more of the residual velocity that a spiral pe of draft tube has recently been developed. It is, however, adaptable onomically only to special cases because of its relatively larger size.

Because of the draft tube, turbines can be set well above tail water in order be convenient at all times for inspection.

Draft tubes are sometimes constructed of steel plate; but more often, for e larger installations, they are shaped in the concrete of the power house bstructure.

The practical limit of the draft head is given by the equation:

$$h' = A + \frac{v_2^2 - v_1^2}{2g} - a \qquad (4)$$

ere h' = the maximum allowable draft head in feet, measured from the lowest tail water level to the center line of gates, for vertical turbines; or to the highest point of the discharge space of the runner, for horizontal turbines.

A = the pressure of one atmosphere in feet of water, normally about 34 feet at sea level. It decreases with the altitude. Two feet should be subtracted from the normal weight to allow for reductions during meteorological disturbances.

v_1 = the average velocity of the water in feet per second at the exit of the runner, measured at the point of minimum internal diameter of the runner band.

v_2 = the average velocity at the end of the draft tube.

a = a margin allowed for disturbances during load changes and vapor tension, ordinarily adopted as five feet, but should be larger for long draft tubes, low pressure heads and sudden load changes.

Friction in the draft tube will increase h', but is too small for consideration.

Settings. — Reaction turbines are adaptable to many types of settings, and e choice of type is governed by the relative cost compared with the efficiency the turbine and ease of operation. Typical examples of turbine settings are licated in Figs. 1, 3, 5, 6 and 7. The following are some of the more common pes of settings, of which many combinations are possible.

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a. The turbines may be horizontal or vertical; that is, set with horizontal or vertical shaft.

b. One or more runners on the same shaft may be used.

c. For multiple runner turbines, there may be a separate draft tube for each runner, or each pair of runners may have a single draft tube located between them.

d. The turbines may be set in an open forebay or flume with shaft extending vertically to a generator above water surface, or horizontally through the wall to a generator on the opposite side.

e. The runners may be enclosed in a casing or prolongation of the pipe line. Such casings may be spiral or cylindrically shaped.

The tendency is towards single runner vertical turbines for low heads, and horizontal or vertical turbines with one or two runners for medium and high heads. More than one runner is seldom now used for vertical installations.

The open flume setting is common for very low-head installations utilizing small turbines. Such a setting is indicated in Figs. 5 and 6. In open flumes of ample size, the water approaches the turbine with low velocity and without disturbance. Consequently this type of setting possesses the highest degree of efficiency.

As the head becomes higher or the diameter of the curbine larger, the structural problems of open-flume construction become increasingly difficult. It is finally necessary to effect a reduction in size of conduit and a corresponding increase in velocity of flow, and some type of closed casing is then necessary.

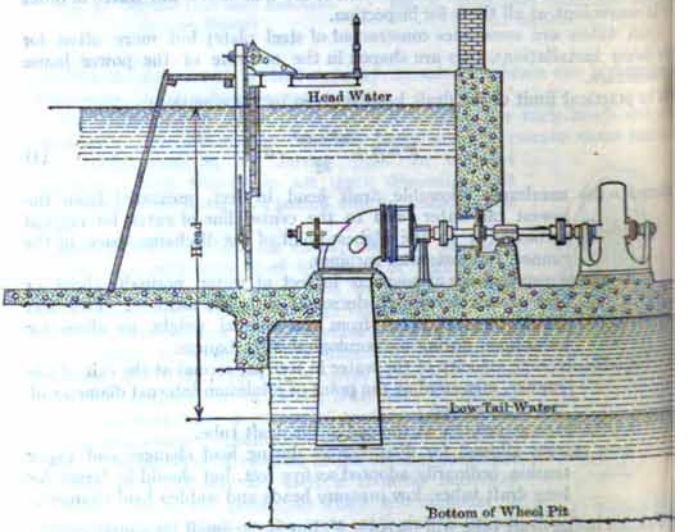


Fig. 5. Open-flume Setting for Horizontal Turbine

A cylindrical casing is indicated in Fig. 7. This type of casing cannot be made hydraulically efficient. Because of its shape, the water cannot enter the turbine with the absence of disturbance, so essential to best efficiency of operation. Cylindrical casings are less expensive than spiral casings, but are seldom

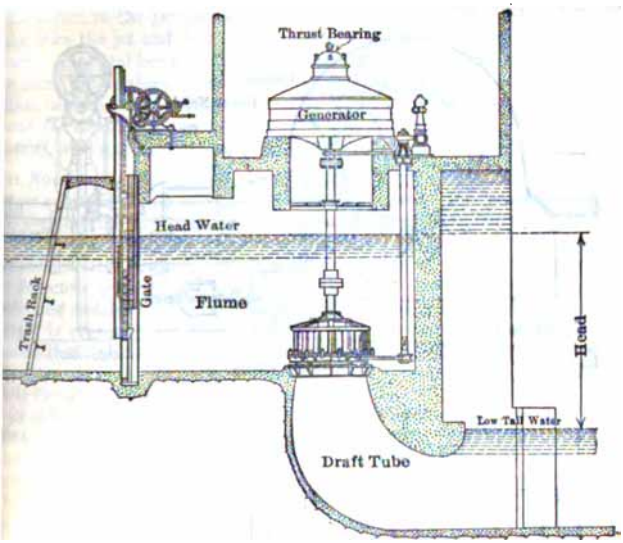


Fig. 6. Open-flume Setting for Vertical Turbine

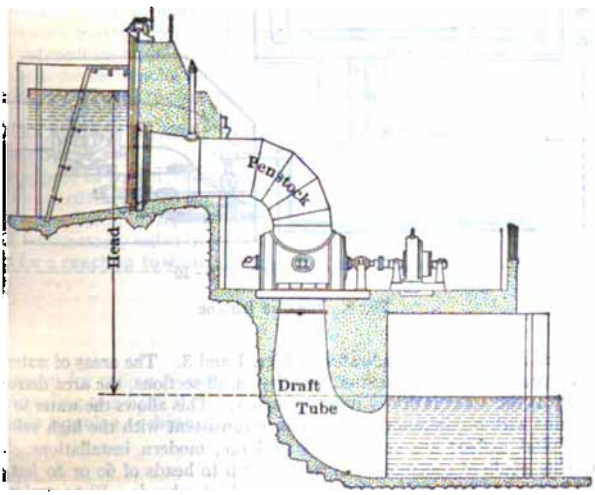
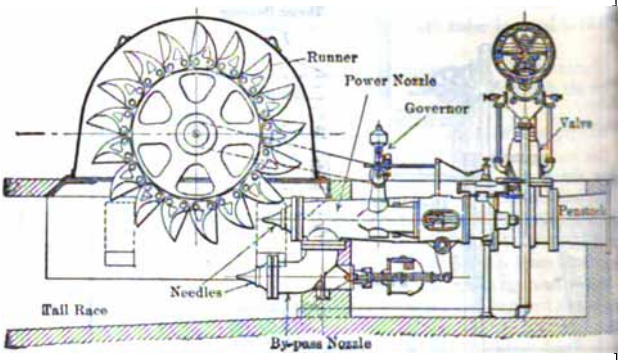


Fig. 7. Horizontal Cylinder-case Double-runner Setting

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now used for large units, except to effect a reduction in first cost at the expe of efficiency. They are usually made of plate steel or formed in the con of the toe of the dam.



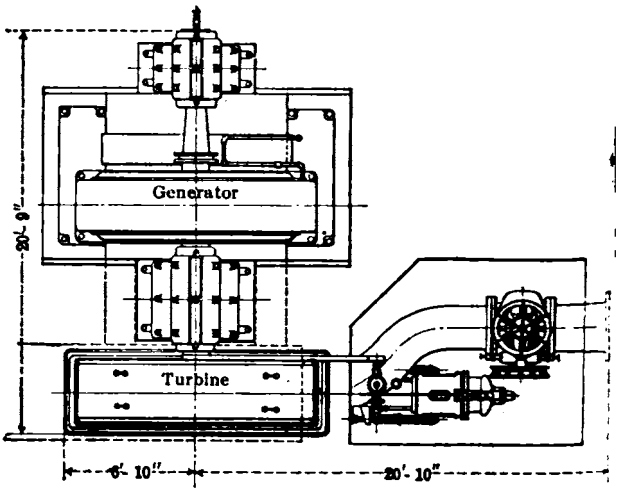


Fig. 8. Impulse Turbine

A typical spiral casing is indicated in Figs. 1 and 3. The areas of water pa sages are proportioned for constant velocity at all sections, the area decreasi gradually as the water is drawn into the runner. This allows the water to ent the turbine with a minimum of disturbance consistent with the high velociti used. Spiral casings are common to all large, modern installations. Th are usually made of concrete for large units up to heads of 60 or 80 feet. an of cast iron, cast steel or riveted plate steel for higher heads. Plate steel is co sidered inferior to the other materials for casings, but is often less expensive.

RACTERISTICS OF IMPULSE TURBINES. — The Runner. — s is shown a typical impulse runner, consisting of cast-steel or bronze bolted to the periphery of the wheel body. The buckets receive the from the jet and destroys its velocity, the water falling inertly to the The total head between the runner and the tail race is lost.

ch turbine there is one ratio of runner diameter to jet diameter which best efficiency. This ratio varies from about 12 to 15 depending upon and capacity of the unit. A ratio as low as 8 is practical under special s, with a sacrifice of a few per cent in efficiency.

ozzles. — The flow of water through the nozzle is controlled by a actuated needle valve as indicated in Fig. 8.

e turbines are commonly used for high-head installations with long in which the flow cannot be arrested quickly when a sudden reduction output is required. For this reason deflecting nozzles, by-pass valves ectors are used in order to eliminate the possibility of water-hammer. ing nozzles are provided with a ball joint, and when a sudden reduction is required, are made to deflect by the action of the governor, with that only part of the jet remains in contact with the buckets and the put is reduced. The needle valve then partly closes slowly, and coin- ie jet is returned to its normal position.

eflector acts on much the same principle as the deflecting nozzle. It a governor-actuated, hinged, curved vane which, upon a reduction nand, moves into and deflects part of the jet from the buckets. The hen returns to its normal position as the needle valve slowly closes.

st recent method of regulation consists of by-pass valves of various ney are usually operated by the governor synchronously with the the needle valve to an extent sufficient to retain a constant penstock hen are slowly closed automatically. Fig. 8 indicates a typical by- of the needle type.

s. — One or more runners may be used on the same shaft and one or les may be provided for each runner; but the usual arrangement, for medium capacity units, consists of a single runner with a single nozzle. urbines may be horizontal or vertical; but vertical installations are use the water cannot fall away as readily without interference.

ATING CHARACTERISTICS OF HYDRAULIC TURBINES.

peed.

eed of runner, in r.p.m.

t effective head, in feet.

eoretical horsepower developed.

constant, called the "unit speed" of the runner.

. **reaction turbine** at a given speed and gate opening,

$$\frac{R\sqrt{P}}{h\sqrt{h^{1/2}}} = K \qquad (5)$$

n for calling K the "unit speed" is that K is equal to the speed R ling to a head h of 1 foot and a power output P of 1 horsepower.

mpulse turbine,

$$\frac{R\sqrt{P}}{h\sqrt{h^{1/2}}} = 3.67, \qquad (5a)$$

cates the usual unit speed of impulse runners to be about 3.67.

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Values of Unit Speed. — In equation (5a), if k and P are unity, $R = K$. The speed of the runner when generating. Turbine builders use the value of the unit speed at full gate opening as a basis for representing the speed characteristics of the various types of runners. For each type of runner there is one unit speed near which occur the best efficiencies for ordinary conditions of operations. High-speed runners are those requiring a high full-gate unit speed for best efficiencies and vice versa. The practical maximum unit speed for the standard modern reaction-type runner, without considerable sacrifice of efficiency, is about 95. Special runners have been developed recently, both in this country and abroad, which are claimed to operate satisfactorily at a unit speed of 150 or over, and several small units have been installed. With unit speeds greater than 95, considerable saving can be made in the cost of generators because a large single runner unit operating at 95 unit speed under a low head requires a speed of revolution much too low for economical generator design.

Efficiency. — The methods of calculating, from test data, the performance of an hydraulic turbine are too complicated to be given in the limited space here

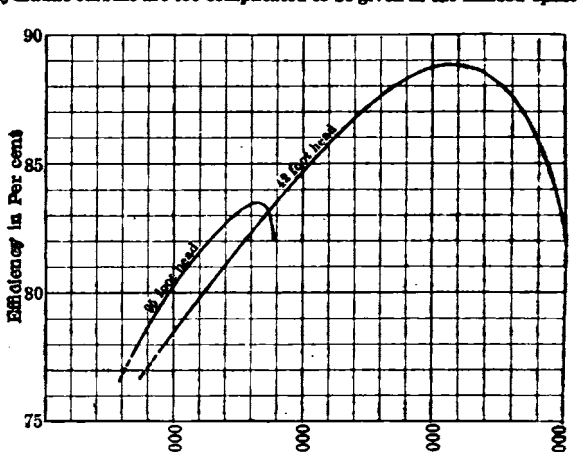


Fig. 9. Efficiency-power Curves of 46 In. Runner

available. Typical efficiency curves of a large reaction-type runner at two different heads are given in Fig. 9, and a typical efficiency curve for an impulse-type runner in Fig. 10.

It will be noted that the efficiency and power falls off quite rapidly as the head reduces. It is not possible to obtain a runner which will have good efficiencies for a wide range of heads for a constant speed.

The use of test data for the determination of probable turbine operating characteristics under practical conditions is influenced by the following considerations:

a. Other conditions being the same, the efficiency and capacity of a runner increases with its size, owing principally to the smaller influence of defects in fabrication and roughness of the water passages.

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Fig. 10. Efficiency-power Curves of an Impulse Water Wheel

› setting of the turbine may differ from that of the test, a condition ten has a marked influence on efficiency and power.

efficiency and capacity decrease with service, particularly if there is . in the water to wear the runner and increase clearances.

bine manufacturers have patterns for only a part of the possible runner loreover the best speed of the runner is not always the best speed for expensive type of generator. Consequently, in many installations, it ›le to sacrifice a certain amount of adaptability and efficiency in order the first cost of the installation.

s Affecting Choice of Runner. — Complete data for the final ıtion of the type and size of runner most suited for a particular instal- in the possession of turbine builders only, and advice from that source ›ariably be obtained.

of runner and turbine setting should be adopted which will have the ıcteristics for the conditions under which it must be operated for the rtion of the time, and also possess reasonable characteristics for unusual .. Among the influences governing the choice of type are:

›d of low-stream flow, during which maximum efficiency is essential.
‹l of high-stream flow, during which maximum capacity only is essential.
:e of fluctuation in head. The runner must have sufficient capacity at head and also have reasonable efficiencies at mean and high heads.

characteristics, or the part-gate-opening periods. The efficiency ıuite rapidly for small gate openings and best efficiency is not usually e power.

conditions affecting the type of turbine setting.

NG OF HYDRAULIC TURBINES. — The "Testing Code" of the Builders' Society has been adopted by most hydraulic turbine manu- ıs a basis for comparing actual operating characteristics with the of the manufacturer. The object of the test is to determine the

efficiency, equation (3), at fixed speed under different conditions of load and (where possible) head; the capacity of the unit; and its general performance.

Tests under varying heads are not always possible in power developments, and it is sometimes not even possible to test under the effective head stated in the guarantee. It is permissible, however, to test under other heads, differing by not over 10 per cent from the contract head, provided the speed is changed in proportion to the square root of the head. The operating characteristics under contract head and speed can then be computed from the result of the tests under test head and speed.

The power input is given by equation (2). The quantity of water Q, may be measured in a number of ways, the principal of which are,

a. Weirs in the head or tail race.
b. Current meter measurements in the head or tail race.
c. Pitot tube in the penstock or conduit.
d. Floating screen in an open conduit.
e. Venturi meter in the penstock.
f. Titration or chemical method, in which a salt solution is introduced at the inlet and measured in centration in the tail race.

The net head, h, is the difference between the elevation corresponding to the pressure in the penstock near the entrance to the turbine casing (or water surface immediately above the turbine in open flumes) and the elevation of the tail water, this difference being corrected by adding the velocity head in the penstock at the point of measurement and subtracting the residual velocity head at the end of the draft tube.

The output, P_0, is usually measured electrically if the turbine-driven generator has been previously tested. One of the many forms of Prony brakes may be used for small units.

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ER WHEELS, SPEED REGULATION OF.* — (*See also Hy-; Power Stations, Hydroelectric; Water Wheels and Their Settings.*) In a cial cases close speed regulation of water wheels is unnecessary, for ex- in pulp grinding, certain chemical processes and operating air com-. Even in these cases experience has shown that better results may be d when wheels are controlled by properly designed governors. For work, where the power is applied through the medium of belting, the of regulation is simplified by the large inertia effect of the pulleys ing.

ED VARIATION IN HYDROELECTRIC PLANTS. — For elec-nerators, which perhaps comprise the majority of installations, the ut-ety of speed regulation is required because the value of the electrical roduced is greatly lessened if the voltage and frequency are not uni-n the best large modern power plants speed variations greater than one per cent are exceptional. In smaller plants, since there are usually oportional load fluctuations, it is more difficult to maintain close speed n.

HOD OF REGULATION. — A change of load requires a change in ntity of water passing through the turbine in order that the power ill equal the new demand. This is effected through a change in the ing by the action of the governor.

ange in load demand occurs, and the turbine is not able at once to alter t to correspond, the surplus or deficiency of power will be absorbed or by the inertia of the rotating elements of the turbine and generator. n give up or receive energy only by means of a change in speed. Thus nanifestation of a change in load demand is a change in the speed of the

ors are sensitive to very slight changes of speed and start almost at djust the gate opening; but this cannot be done immediately. Conse-during the time required to make the adjustment, the change in the the rotating elements, corresponding to the surplus or deficiency of ust be made without too great a change in speed. Therefore the neces-ia of the rotating elements or "fly wheel effect" is fixed by the capacity t, the expected load change and the gate-closing speed of the governor. luences to be overcome in obtaining good regulation are:

: of sensitiveness of the governor, or the fact that the speed must m normal before the governor action starts.

governor cannot change the gate opening instantly. A common open flume settings or short penstocks is about two seconds. For h long penstocks, the speed of the governor must be much slower to inst excessive water hammer.

he case of long penstocks, a change in penstock velocity, resulting d change, necessitates a variation in head at the turbine to accelerate the velocity. This change in head is exactly opposed to that desired egulation.

Flume Setting. — In Fig. 1, assume the power demand, for an open allation to be represented by the line *ABCD*. After the instant, *X*, l change, the output of the unit is insufficient and the deficiency must d by the inertia of the rotating elements. Consequently the speed fall off as indicated. At *Y* the speed change is sufficient to affect the nd the gates begin to open. The rate of gate opening is not neces-stant, but will vary according to the characteristics of the governor en-flume conditions, the head is practically constant during the change the power output may be represented by the line *EFG*, which, for open

flumes, may be assumed to vary uniformly. The area *BCFE* represents the total deficiency in energy, ΔK, to be supplied by the fly-wheel effect of the unit. At Z the output is equal to the demand and, as indicated, no further reduction in speed occurs. As the speed is still below normal, the governor will continue to open the gates and the power will further increase. The excess output over demand, after time Z, will add to the speed of the unit until, at time W, the speed is again normal but the output is in excess of the demand. The speed will then rise above normal and the governor will start closing the gates. There is seen to be a tendency for the output to fluctuate above and below the new power demand. This feature is called "hunting" of the governor. In actual practice this does not occur to an objectionable extent, as the governors are provided with a compensating device or "anti-racing" mechanism which has the effect of dampening these fluctuations, and the speed is soon brought permanently to normal. This condition requires, however, that the capacity of the unit be somewhat in excess (usually 5 per cent to 10 per cent) of the maximum output to which the demand may suddenly change, otherwise there would not be available the necessary excess capacity to bring the speed back to normal after a sudden increase in demand to maximum demand occurs.

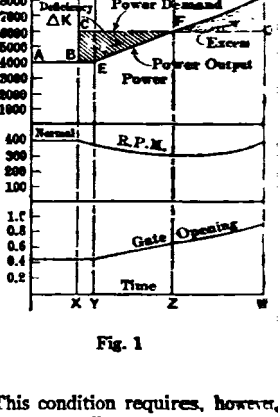


Fig. 1

Long Penstock Settings. — In Fig. 2, assume the power demand for a plant with a long penstock to be represented by the line *ABCD*. As in the previous case, the speed begins to be retarded at X, the moment of the load change, and at Y the governor action starts. The variations of gate opening and penstock velocities are indicated in the diagram. Part of the total head available for power is consumed in increasing the penstock velocity and the net head on the turbine decreases momentarily as indicated. The net result of the slowly accelerating velocity, combined with considerable reduction in net head, may be a momentary *reduction* in output as indicated by the output line. This reduction in net head, at the critical time when an *increase* in power output is most needed, is the chief influence opposed to good regulation with long penstocks. The velocity soon picks up, however, and the power output increases about as indicated by the line *EFG*.

As in the case of open-flume installations, the speed of the unit is a minimum at Z, when the output equals the demand; but the gate opening, penstock velocity and output continue to increase until the speed reaches normal at time W. The gates then start to close. The time interval between the sharp breaks in the head, penstock velocity, and output lines correspond to the time required for the wave of penstock velocity change to travel from the turbine to the upper end of the penstock and back again.* The deficiency in output ΔK, is indicated by the area *BCFE*.

For sudden *decreases* in load demand the characteristics indicated in Figs. 1 and 2 are simply reversed.

Water Hammer. —Water hammer is a term used to indicate the increase

* See article by N. R. Gibson, referred to in *Bibliography*.

ad caused by a reduction in penstock velocity. Negative water hammer e decrease in head resulting from an increase in penstock velocity. For en load changes the resulting water mer is very great and, for that reason, peed of gate movement must be very for long penstocks.

is not safe to use approximate equa- for the determination of water mer. Accurate methods are too in- te for presentation here and the r is referred to the article by N. R. on mentioned in *Bibliography*.

EGULATION APPLIANCES. — term "pipe line" is commonly used ndicate a long pipe extending from reservoir to the brow of the incline ng to the power house. The "pen- " extends from this point to the ines.

rge tanks are usually provided at the r end of long pipe lines in order to ict the excessive water hammer, or changes due to sudden load changes. f valves are often used at the lower of long penstocks for the same purpose.

rge Tanks. — A surge tank consists vertical pipe, considerably larger in eter than the pipe line, resting on the nd and connected to the pipe line, or ay be an elevated tank connected to pipe line by a riser pipe of the same naller diameter than the pipe line. fore-bays also serve the same purpose e surge tank. Surge tanks are feas- only when the difference in level between the lower end of the pipe line head water is not excessive.

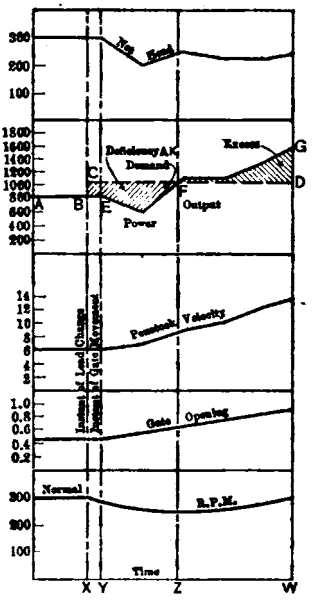


Fig. 2

he function of the surge tank is to store or supply water subsequent to a load ge pending the gradual adjustment of the flow in the pipe line.

he water surface in the surge tank is normally at the level of the hydraulic lent of the pipe line at that point. When a sudden demand for more power rs the deficiency of water is supplied by the tank and the water surface in tank lowers. The resultant increase in head between the tank and the ay serves to accelerate the velocity in the pipe line. When a reduction in ut occurs, the water surface in the tank rises and the induced head decreases low. The action is entirely automatic.

he influence of the rise and fall of water surface in the surge tank on the head at the turbine during a load change is also opposed to speed regulation; the head change with a surge tank is considerably less than corresponding r hammer without the tank.

eglecting the effect of friction, the rise or fall of water surface in the tank be expressed by the following equation:

$$h = v\sqrt{\frac{aL}{Ag}},$$

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where h = the rise or fall, in feet.

v = the velocity change in the pipe line corresponding to the change f load, in feet per second.

a = the area of the pipe line, in square feet.

A = the area of the surge tank, in square feet.

L = the length of the pipe line, in feet.

g = the acceleration due to gravity = 32.16.

The value, v, for use in this equation, is the difference between the orig pipe line velocity and the velocity required for the new load, the latter responding to the head on the turbine at the time of the maximum deviation water surface in the tank from normal. Its value therefore depends upon turbine characteristics and the value of h. Consequently the solution of equation can best be accomplished by the cut-and-try method.

Restricted orifices are usually provided between the pipe line and the tank to dampen the surges and prevent them from continuing indefinitely or piling up due to the action of the governor in endeavoring to compensate for the resultant head changes.

Friction in the pipe line and in the restricted orifices have considerable influence on the action of the surge tank and the foregoing equation gives results too large for loads thrown off, and considerably too small for loads thrown on. For more exact methods of design the reader is referred to R. D. Johnson's article on surge tanks referred to in *Bibliography*.

Relief Valves. — Relief valves are serviceable only to compensate for sudden decreases in load demand. They are appliances attached to the lower end of the penstock and are designed to open automatically when a sudden decrease in demand occurs. By this means, a sudden large decrease in penstock velocity is avoided, the surplus water not needed for power being by-passed through the relief valve to the tail race. After the output has been adjusted, the valve slowly close. They are sometimes actuated by the rise in pressure; but are preferably synchronously opened by the governor to an extent corresponding to the closure of the turbine gates, the penstock velocity remaining nearly constant during the load change. Relief valves are very wasteful of water. Deflecting nozzles and jet deflectors of impulse turbines, described in *Water Wheels and their Settings*, also serve the same purpose.

CALCULATION OF SPEED REGULATION. — Open Flume Settings. —In Fig. 1, let:

p_0 = the initial horsepower output.

p_1 = the new power demand after time X.

T_1 = the time interval, in seconds, XY, after load change before the governor action starts.

T_2 = the speed of the governor or time, in seconds, YZ, for the governor to adjust the gates to the new load demand.

R_0 = the normal speed of the unit in revolutions per minute.

R_1 = the speed of the unit at time Z corresponding to maximum deviation from normal.

s = the percentage change in speed of the unit.

K = the foot-pounds of kinetic energy in the rotating elements at speed R_0.

ΔK = the energy change in the rotating elements due to change in speed from R_0 to R_1.

I = the fly-wheel effect of the rotating elements in foot-pound units, usually expressed in pounds at one foot radius, i.e., the weight which, at a radius of one foot, would have an equivalent moment of inertia.

N = the regulation constant of the unit.

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For open flume settings, the average horsepower deficiency during the time erval XZ, assuming EF to be a straight line, is,

$$p = \frac{(p_1 - p_0)T_1 + (p_1 - p_0)\frac{T_2}{2}}{T_1 + T_2}.$$

The total deficiency in work for the interval XZ, which must be supplied from he inertia of the rotating elements, is:

$$\Delta K = 550(T_1 + T_2)p.$$

Therefore,
$$\Delta K = 275(p_1 - p_0)(2T_1 + T_2) \qquad (1)$$

From the laws of mechanics,

$$K = \frac{2\,I\pi^2 R^2}{g\,60^2} = 0.00017\,IR^2,$$

d
$$\Delta K = 0.00017\,I(R_1^2 - R_0^2).$$

Therefore,
$$R_1 = \sqrt{R_0^2 + \frac{\Delta K}{0.00017\,I}}.$$

From definition,
$$s = \frac{100\,(R_1 - R_0)}{R_0}.$$

Therefore,
$$s = \frac{\sqrt{R_0^2 + \frac{\Delta K}{0.00017\,I}} - R_0}{0.01R_0}. \qquad (2)$$

By neglecting T_1, which is small, Meade has shown that equation (2) may be itten, for small speed changes, in the following approximate form:

$$s = 81{,}000{,}000\,\frac{T_2}{IR_0^2}(p_1 - p_0) \qquad (3)$$

For full load change, equation (3) may be written,

$$I = \frac{81{,}000{,}000\,T_2 p_F}{S\,R_0^2} = N\frac{p_F}{R_0^2}.$$

ere
$$N = \frac{81{,}000{,}000\,T_2}{S}.$$

Therefore,
$$N = \frac{R_0^2 I}{p_F}. \qquad (4)$$

For open-flume plants or plants with negligible length of penstock as indicated Fig. 1, of the article on *Water Wheels and Their Setting*, I usually has a value ch that N will be at least 5,000,000.

A quick acting governor and a large fly-wheel effect make for good regulation. the fly-wheel effect is too small for the required regulation, the speed of the vernor must be increased or additional fly-wheel effect provided either in the m of a separate fly-wheel or by increasing the weight of the rotating parts of e generator. Either method requires additional expense and the choice uld be made to obtain the greatest economy.

Plants with Long Penstocks. — For plants with long penstocks, the out- t line, *BEF*, Fig. 2, and hence the deficiency of output, ΔK, cannot be

expressed by a simple equation. The fluctuations in head and penstock velo
are affected by the considerations of water hammer and stand pipe or s
valve characteristics. Each must be computed and plotted, from which
power output line can be determined from the turbine characteristics.
area *BEFC* or deficient work, ΔK, can then be computed for use in equation

HYDRAULIC-TURBINE GOVERNORS. — The governor proper
the device for automatically opening and closing the gates as the load on
turbine varies. The requirements to be met are (1) sensitiveness to s
variations in speed, (2) quickness in action, (3) steadiness and accuracy
moving the gates the proper amount, (4) ability to operate continuously w
minimum amount of attention.

Types of Governors. — There are two general classes of governors: (1)
"mechanical" type, which takes energy from the turbine itself, as requi
through a belt or gearing, and by means of friction clutches applies this en
at suitable times to the operation of the turbine gates; (2) the "hydrau
type, in which stored energy in the form of compressed air is made avail
when required to move the turbine gates through the medium of a liquid (usu
oil) acting against the piston in a hydraulic cylinder. The energy in the c
pressed air is thus transmitted by the liquid through a suitably controlled v
to do the work of moving the turbine gates, when necessary, and the ene
of the air is afterwards restored by pumping the same liquid back into the
tank. The operation of restoring the energy by pumping is gradual; while
operation of moving the turbine gates, by utilizing the energy of the compre
air, may be as rapid as desired.

Governors of the mechanical type were the first in the field, and, being sim
and cheaper to construct, have been very widely used. They have certain ob
tionable features, however, which have prevented them from being adop
under any conditions which require extreme nicety in speed regulation.
sequently, governors of the hydraulic type are almost exclusively used in la
and important power plants. When properly designed, they are capable
giving extremely accurate speed regulation and are thoroughly reliable. Su
governors are sometimes operated continuously night and day for weeks,
even months.

Connections between Turbine and Governor. — The connections betwe
a hydraulic turbine governor and the gates must be strong, direct and free fro
lost motion; otherwise the governor cannot perform its functions properl
Modern governors are built in many different types, so as to be readily adapt
for connections to any standard make of turbine. It is generally advantageo
to have the hydraulic cylinder of the governor located near the turbine gate
although for very large units the control mechanism of the governor may b
more conveniently placed on the floor above. For small turbines, which a
occasionally located in comparatively inaccessible places, it is sometimes nec
sary to place the governors at a considerable distance and connect them with th
turbine gates by means of rods and levers. Occasionally several turbines a
connected in this manner to a single governor.

Distant Control. — Large governors are frequently provided with suitab
electric devices by means of which the speed of the wheel may be adjusted fro
any distant point, thus permitting alternators driven by independent turbin
being brought to the same speed and angular position for parallel connection.

Rating of a Governor. — A hydraulic governor is usually rated in terms o
the energy, expressed in foot-pounds, which is developed by one stroke of th
piston, and the time, in seconds, required for a complete stroke (i.e., to com
pletely close or open the gates). The size of governor required for a given in

depends so largely upon the type of gate, head, etc., that no general be given here.

cations for Governor. — The following is taken from the standard ons of one of the large governor manufacturers:

ernors are each guaranteed to develop the energy, expressed in foot- ated below, and if not called upon to develop a greater amount of in that named, will completely open or close the gates to which they ed in the following number of seconds:

.....Governor,.....Foot-Pounds,.....Seconds,.....

vernors are further guaranteed: (*a*) to stand substantially steady speed does not vary; (*b*) to be dead beat in action and not to hunt; ct with maximum promptness for all load changes within the capacity bines to which they are attached; (*d*) to maintain the speed steady of one per cent under uniform load upon the turbines to which they d; (*e*) to begin to adjust the turbine gates when the speed has varied per cent; (*f*) after sudden decrease of load to bring the speed back in.....seconds; (*g*) to operate perfectly in parallel with other of the same make.

GRAPHY. — See the *Bibliography* in the article on *Water Wheels Settings*. In addition; Gibson, N. R., *Pressures in Penstock Caused ual Closing of Turbine Gates*, Trans. A.S.C.E., 1920; Vensano, H.C., *n Pipe Lines as Shown by Recent Tests*, Trans. A.S.C.E., 1918; John- , *The Differential Surge Tank*, A.S.C.E., 1915; Lauchli, E., *Tests puted Values of Surge*, Eng. Rec., March, 1915; Hillburg, A. G., *Problems Solved by New Methods*, Eng. Rec., Dec., 1916.

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WATTHOUR METERS. — (*See also Ampere-hour Meters; Electrodynamometers; Wattmeters.*) A watthour meter consists essentially of (1) a small electric motor, which may be either of the commutator type, mercury disc type, or induction type, (2) a brake system composed of a disc of non-magnetic material (usually copper or aluminum) mounted on the armature spindle and so arranged that its edge rotates between the poles of one or more permanent magnets, and (3) a system of gears with numbered dials forming a suitable registering mechanism for indicating the number of revolutions of the armature or disc. One winding, called the "potential" coil, is connected across * (in shunt with) the load and the other winding, called the "current" coil, is connected in series * with the load, the connections being the same as for an indicating wattmeter; see *Wattmeters*.

Principle of Operation. — Motor-type meters are so constructed that the average torque exerted by the motor is proportional to the average power taken by the load. The brake system is so designed that the opposing torque, due to the eddy or Foucault currents induced in the disc as it rotates between the poles of the permanent magnets, is proportional to the speed of the disc. When the disc acquires a given speed the driving torque must be just equal to the opposing torque, and must therefore be proportional to the speed. But the speed of the disc is proportional to the average power, and therefore the total number of revolutions which the disc makes during any interval must be proportional to the total energy input during this interval, whether the power remains constant or varies. To determine the energy input to the load in watt-hours or kilowatt-hours it is therefore only necessary to take the difference between the dial readings at the beginning and end of the given interval, and multiply by the proper constant if the meter is not direct reading.

Sources of Error. — In a d-c. watthour meter the chief sources of error are the friction of the brushes (which is more or less variable), friction of the bearings of the motor and gear train, and air friction, the brush friction being by far the most important. In a-c. watthour meters, the lack of exact 90° phase relation between the impressed voltage and the magnetic flux due to the current in the potential coil may cause additional errors which vary with the frequency, power factor and also with the distortion of the wave form; in well-designed modern meters these errors are practically negligible. Instrument transformers (*see Transformers, Instrument*), introduce additional sources of error which may be undesirably large if the transformers are not properly designed. Devices and methods for overcoming, or of correcting for, these errors are described below.

Classification According to Service. — Watthour meters may be classified according to the service in which they are used, viz., (1) service meters for use in residences or factories, (2) switchboard meters for use in central stations and (3) meters for use in individual power installations and isolated plants. Meters for house service are generally front-connected, separately-sealed devices which can be installed and sealed to prevent tampering. Switchboard meters are generally back connected and of such design as to match other switchboard devices. "Meter-boards," equipped with the necessary auxiliary or protective devices, are frequently used with house meters, in order to insure proper connections and sealing.

COMMUTATOR TYPE OF WATTHOUR METER. — The commutator type of meter is now used only on direct-current circuits, although both

* Either directly or through suitable instrument transformers; see *Transformers, Instrument.*

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tion meter was so highly perfected large numbers were used for alter-
rrent also. The motor consists of a set of stationary coils, commonly
ld coils, which carry the current, and an armature wound with small
h is connected across the terminals of the load or in shunt with the
rcuit; generally a series resistance is used to absorb part of the line
The connection to the armature is by a commutator and brushes, as
linary commutator type of shunt motor. Special attachments are
s added for very large capacities, such as double armatures astatically
and damping magnets inclosed in a laminated iron shield in order to
ay-field errors where heavy currents are used and heavy short-circuits
nt.
ld be noted that the operation differs from that of an ordinary shunt
hat the speed increases with increase of field strength, since its back
uch less than 50 per cent of the line voltage.
unt of the inductance of the windings of the commutator meter, it does
accurately on a-c. circuits unless properly compensated, the percentage
; greater the less the power factor.

sation for Friction; Light-load Adjustment.—Friction in a well-
atthour meter will be very small and will be noticeable only on light
per cent and below. To compensate for this friction, a "light-load
oil" is added, which is an auxiliary or compounding coil. This light-
connected in series with the armature. It is placed adjacent to the
› that its field strengthens the main field and produces a slight torque
t of the power and just sufficient to compensate for friction.

of Construction, Bearings, etc.—In the design of the modern
nt commutator type of watthour meter, great thought has been
: mechanical construction in order to obtain small air gaps between
ire and field coils, light-weight armatures and commutators and
ch will have very small friction and yet stand the wear and carry the
ie armature without undue sparking and pitting of the contact parts.
ur meter of the most approved design the field coils are wound with
pper strips and the armature winding is enamel-covered wire wound
sphere mounted on a spindle of light steel tubing. The lower bear-
all of the weight and the upper bearing is a guide bearing, as all
vertical shafts. The lower bearing consists of a steel pivot mounted
of the spindle or armature shaft, running on a jewel bearing. In
a good grade of sapphire is used for the jewel and is cupped and
as to provide a bearing with as little friction as possible. Of late
t deal of attention has been given to the bearings and in some cases,
on high-capacity meters with astatic armatures and a correspond-
weight, diamond jewels are being used with excellent results.
d jewel will last much longer than the sapphire before wearing
to increase the friction and thereby change the accuracy of the
cularly at light loads. See also section below on *Data on House-*
.

***of* Commutator Watthour Meters.**—Commutator-type direct-
rs are built in capacities ranging from 5 to 10,000 amperes, 100 to
Meters of this type are furnished with double current circuits for
rcuits, the maximum ampere capacity for three-wire meters being
mperes. Special meters have been supplied for 1200- and 2400-volt
its.

—Tests on direct-current commutator meters show that a meter
gn should start on two per cent of full load and should give accu-

racies about as follows: — To within 3 ¼ per cent from 5 per cent to ¼ lo
2 per cent from ¼ to full load. The Meter Code (*see Bibliography*) requi
d-c. watthour meters to run continuously on normal voltage and 2 per cen
rated current, and for higher loads to be accurate within the following limits

Per cent rated current.....	5	10	20	50	100	150
Maximum deviation, per cent..	7.5	3.0	2.0	2.0	2.0	2.0

For a summary of the meter accuracies required by commission regulati
city ordinances, and state statutes, see Circular No. 56 of the Bureau of Sta
ards, 1st ed., pages 234–5.

The Mercury-motor Watthour meter is manufactured for direct-curr
service. The motor element consists of a mercury chamber in which is submer
a copper armature. The line current enters and leaves the mercury through
electrodes diametrically apart. Since mercury has about fifty-five times
resistivity of copper, the major part of the current traverses the armature. T
mercury thus performs the function of the commutator and brushes of the co
mutator-type meter. A shaft attached to the armature passes through th
constructed to prevent the mercury from escaping when the meter is inver
Externally, this shaft carries a worm which engages with the register train, a
an aluminum damping disc moving in the field of a permanent magnet. T
copper armature is notched radially to direct the current flow in such a man
as to obtain the greatest torque, and carries a float so proportioned that th
is a slight upward thrust. In consequence, the lower bearing is a ring-st
jewel, while the upper end of the shaft is carried in a ring-stone end-stone be
ing. A laminated iron electromagnet having many turns of fine wire is connect
across the line, and sends through the copper armature a magnetic flux which va
in proportion to the line voltage. The driving torque is thus proportiona
the power supplied to the load. The damping at small and moderate loa
nearly all caused by the drag disc, but at full load and overloads the fluid f
tion of the mercury increases at such a rate as to cause a drop in the per c
registration curve unless compensated. Compensation is effected by pass
the line current through a few turns of heavy wire around the voltage elect
magnet.

Compensation for Friction, Light-load Adjustment. — For effecting
light-load compensation for friction, a thermal device is used in some cases, a
it is also possible to obtain compensation by shunting part of the potent
current through the armature. The thermal device employed is a therm
couple shunted around the mercury chamber, and heated from a resistance c
connected in series with the potential circuit. The small electromotive for
generated in the thermocouple sends a small current through the armatu
which is sufficient to overcome the friction of the moving parts.

Application of Mercury Meters. — Mercury-motor meters, on account
the low resistance of the current circuit, are particularly well adapted for u
with external shunts, since but a small potential drop in the shunt is requir
They are therefore used in comparatively large numbers for switchboard wo
where large currents are used and where external shunts can be conveniently
installed. They are much less subject to derangement by vibration than co
mutator meters.

Details of Construction. — The preceding description applies to the mercu
motor meter extensively used in the United States. Other designs differ
mechanical construction and in methods for obtaining light-load adjustment
The chief difference in mechanical construction is in the motor element, where
mercury chamber of non-metallic compound is used in some cases, and a Germa
silver chamber enameled on the inside in other designs. Armatures differ i

ne designs use a copper disc and others a copper drum or thimble. See tion below on *Data on House-Type Meters.*

city of **Mercury Watthour Meters.** — Direct-current mercury meters hemselves independent of ampere capacity, as external shunts are used. giving a capacity as high as 60,000 amperes have been furnished. Meters l for voltages up to 600 volts are regularly furnished and special meters :n supplied for 1200- to 3000-volt direct-current railway circuits.

racy. — The mercury-motor watthour meter above described is stated a load-accuracy curve at normal voltage which deviates from a straight ess than 1.5 per cent over a range of load of 5 per cent to 200 per cent

CTION WATTHOUR METER (Fig. 1). — This type of meter, the elements of which are illustrated in Fig. 1, has a laminated soft-iron which are mounted ent and potential . The current wind- its of a few turns of re, while the poten- has many turns of . The flux due to it coil is in phase load current, and ue to the potential approximately in e with the voltage load, since the coil is highly in- ee *Alternating Cur-* e poles from the igs are arranged e armature disc ween them and is cut by the alternating flux due to each wind-

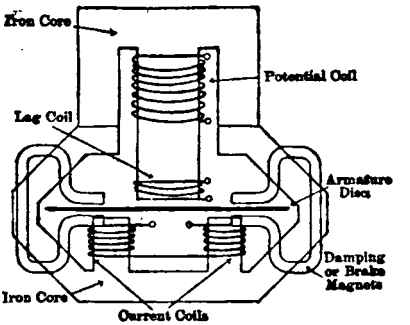


Fig. 1. Diagram of Induction Watthour Meter

le of Operation. — There are thus set up in the disc currents which each pole in approximately concentric circles, the induced currents two windings being in quadrature for a load of unity power factor ately only, unless a suitable phase compensator is used; see below). e current induced by the current coil passes under the pole of the oil and therefore through a magnetic field which is approximately in this current, and similarly part of the current induced by the poten- sses under the pole of the current coil and therefore through a mag- pproximately in phase with it; for power factors less than unity the rence between these currents and the magnetic fields through which s the same as the difference in phase between the load current and Hence a torque is produced on the disc having an average value pro- > the load supplied through the meter; see *Electricity and Magnetism. of.* A braking system similar to that employed in the commutator ter (see above) causes the speed of the disc to be proportional to this que, and therefore the number of revolutions is proportional to the plied.

Compensation; Lag Coil. — In order to make the induction watt- record correctly, especially for power factors less than unity, it is > cause the flux at the tip of the potential pole to lag 90 degrees behind

the voltage impressed on the potential coil. A method of securing this condition is to mount on the potential pole a closed winding the resistance of which can be varied by a resistance wire soldered to the terminals. This closed winding is sometimes called the "lag coil." In many designs it is a metal plate in the form of a closed loop.

Compensation for Friction; Starting Plate. — The light-load adjustment can be obtained by placing a short-circuited loop of copper adjacent to the potential pole so that it can be shifted in a plane at right angles to the axis of the potential coil. This loop has induced in it currents which produce a field out of phase with the flux from the potential coil, and the reaction between the two produces on the disc a slight turning moment independent of the current in the current coil. The amount of compensation can be varied by shifting the position of the light-load coil, or starting plate, as it is sometimes called.

Details of Construction. — The induction watthour meter is manufactured in several different types all based on the same principle of operation but differing in mechanical construction and electrical characteristics. The general type of construction is to mount the iron core and windings on a metal frame which carries the bearings for the armature, the core and windings being combined as a single unit in some designs, whereas in others the current and potential coils with their iron cores are mounted separately on a common frame or on the meter case. The other details of design consist of mounting the register train and damping magnets and arranging the full-load, light-load and power factor adjustments so that they are readily accessible. See also section below on *Data on House-Type Meters*.

Polyphase Induction Meters. — The polyphase induction meter in commercial use is nothing more than two single-phase meters with a common spindle connecting the two armature discs. The measurement of power with the meter is based on the two-wattmeter method for three-wire, three-phase and quarter-phase work (*see Wattmeters*), and a slight modification of the two-element meter is used quite extensively for four-wire, three-phase work. This modification consists of making a third current circuit by adding a winding to the current coils of both elements. Such a construction is quite accurate even on badly unbalanced voltages, the most accurate arrangement for such work being three separate single-phase meters, or a single meter which contains three single-phase elements.

Capacity of Induction Watthour Meters. — Induction watthour meters are supplied in standard capacities ranging from 5 to 300 amperes. Meters are generally used with self-contained potential circuits up to 600 volts and for higher voltages and current capacities potential and current transformers are used with 5-ampere 110-volt meters. When transformers are used, either a multiplying constant for the dial alone can be used in connection with the ratio of transformation of the transformers, or the ratio of the transformer can be included in the meter constant (see below), so that the register is direct reading with the transformers of proper ratio. For three-wire, single-phase circuits a

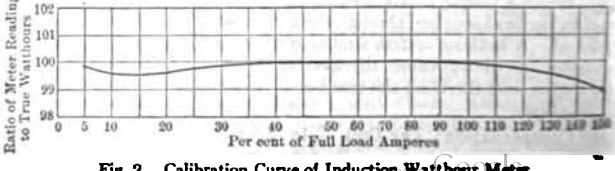


Fig. 2. Calibration Curve of Induction Watthour Meter

to obtain a special form of current transformer with double primary and a single secondary winding for connection to the meter.

acy. — Modern induction watthour meters are susceptible of a higher accuracy than the commutator or mercury-motor meter. Fig. 2 shows characteristic curve of an induction watthour meter. It is possible to special calibrations a combination of induction watthour meters and nt transformers which will be accurate to within 1 per cent over the range of commercial operation. The Meter Code (see *Bibliography*) a-c. watthour meters to run continuously, at rated voltage and frend unity power factor, with 2 per cent of rated current, and for higher e accurate within the following limits:

ent rated current.....	5	10	20	50	100	150
mum deviation.....	3.0	1.5	2.0	2.0	1.5	3.0

must also be adjusted for measurement on power factors of 75 per cent r cent to within 2 per cent and 4 per cent respectively. Other requireccuracy can be found in the Meter Code.

AYMENT METERS. — Standard watthour meters are sometimes a device whereby the circuit through the meter and load is closed the insertion of a coin into the device and remains closed only until redetermined amount of energy has been recorded by the meter, when again opens automatically. When so equipped the meter is called ent meter. The prepayment device may be either inserted in the neter, or it may be placed in a separate attachment electrically conhe meter.

R TYPES OF WATTHOUR METERS. — The descriptions of neters given above refer particularly to the types manufactured in States. Meters of the same general types are manufactured abroad, ertain other types. Among the latter, the Aron clock meter is worthy In this meter the potential coils are carried on two pendulums such a manner that they swing close to the coils carrying the line One pendulum must be retarded as the other is accelerated and to do tions are so made that the instantaneous polarity of the pendulum ays opposite while the current coils are always alike. The meter o iron and has no commutator and is, therefore, a very accurate device, although somewhat complicated and delicate of adjustment y commercial work.

ON SERVICE-TYPE METERS. — General data on service-type eters of different types are tabulated below. These data are approxire representative of modern practice in this country. The weights ions given refer to meters of 5 to 25 amperes rating, and are exceeded of greater rating.

G OF WATTHOUR METERS. — For laboratory tests the ld be mounted on a firm support and set level. These conditions obtain when the meter is permanently mounted for service; see below *llation*. For laboratory tests a bank of lamps or some form of rheoantom load" may be used for a load. The instructions given below th laboratory and service tests.

Instruments. — For d-c. measurements a portable ammeter and r a portable watthour meter may be used; for a-c. measurements ng wattmeter or portable watthour meter may be used. Two pacities should be provided, one sufficient to take care of the full

COMMERCIAL SMALL CAPACITY SERVICE-TYPE METERS

Item	Commutator type	Mercury type *	Induction type
Total weight, pounds	13 to 15	10 to 15	8 to 10
Height, inches	13	9	8
Width, inches	7.5	7	6
Depth, inches	7.5	6	5.5
Torque of motor element at full load, millimeter-grams	170	60	30 to 50
Weight of moving element, grams	100	3 †	10 to 15
Watts loss in potential circuit at 110 volts	5	5	1 to 2
Watts loss in current circuit at full load	5.5	0.3 ‡	0.3 to 0.4
Resistance of potential circuit, ohms	2400	2400	.....
Drop across shunt, millivolts	.....	60 to 75	.....

* The data on the mercury type also apply to meters used with shunt of [illegible] capacity.

† Upward thrust.

‡ Not including shunt.

load of the meter and the other small enough to read the light load with a pro[illegible] degree of accuracy.

The use of a portable watthour meter is now recognized as the stand[illegible] method for testing watthour meters up to 100-ampere capacity. There is [illegible] question as regards the accuracy of this method, since it is not necessary t[illegible] the load be constant. With the portable watthour meter, indicating instrum[illegible] and stop watches are unnecessary, and personal errors in reading are thus [illegible] reduced.

When indicating instruments are employed, a reliable stop watch is essen[illegible] for taking the meter speed. As a matter of safety, it is advisable to have [illegible] least two stop watches, one to serve as a check on the other in test. Too mu[illegible] care cannot be used in the handling of these watches and in giving them cons[illegible] checks with some local jeweler's standards. In checking the stop watch it [illegible] advisable to check at different points of the dial.

Precautions. — In order to insure accuracy, d-c. meters should not be test[illegible] until they have been connected in circuit with the voltage on for fully 15 to [illegible] minutes before the test is made. This enables the heating effect of the curre[illegible] in the potential circuit to become constant. If the meters are tested before th[illegible] consecutive readings may not check.

The testing instruments should not be allowed to measure the losses of t[illegible] potential circuit of the meter under test, or vice versa. In order to avoid th[illegible] the current circuits of the testing instrument should be connected in series wi[illegible] the meter under test, while the potential circuits of the testing instrument a[illegible] of the meter under test must both be connected across the line at the same ph[illegible] and between the generator and the nearer instrument.

A number of revolutions should be taken so that the time of observation s[illegible] be at least from 40 to 60 seconds. If the time is materially less than 40 second[illegible] undesirably large errors in the measurement of time are probable; a time interv[illegible] longer than 120 seconds is generally unnecessary.

Test Constant. — In checking a watthour meter the speed of the disk[illegible]

rectly, since too long a time would be required to obtain a suitable n the dials of the register. The relation between the number of revolu- the disc and the corresponding dial reading may be expressed by a multiplier, called the "test constant," which depends only upon the etween the disc and dial. Various manufacturers express this constant , viz.:

neral Electric Test Constant (K). — The number of watthours by the register per revolution of disc; its value is marked on the disc.

estinghouse Test Constant (K). — Westinghouse meters (except -6) are all adjusted for a certain speed at rated full load, which is on the nameplate. Meters of modern manufacture have a speed of and older forms of 50 r.p.m. Let N be the number of revolutions e corresponding to a rating of P kilowatts, then the test constant K er of watt-seconds per revolution of disc), as given in the instruction ied by this company, is $K = 60{,}000\,P/N$. For type CW-6 (direct- eters the test constant is the number of watthours per disc revolution.

t Wayne Test Constant (C). — For type K meters the number of for 36 revolutions of the disc; for types K_1, K_2, K_3, K_4 and K_5 the watthours for 1 revolution of the disc; the constant is marked on the

ican Test Constant (K). — The number of watthours per revolu- disc; it is marked on the meter name plate.

gamo Test Constant (K). — The number of watt-seconds per of disc; it is now marked on the name plate in the D-5 mercury- rs and on the register of the type H induction meters.

ion Formulas. — Let R = number of revolutions of disc, S or T = seconds for R revolutions, K or C = meter constant as defined above: ower corresponding to the speed of the meter is:

Type of meter	Meter watts
General Electric	$\frac{3600\,KR}{S}$
Westinghouse	$\frac{KR}{T}$
Fort Wayne, Type K	$\frac{100\,CR}{S}$
Fort Wayne, Types K_1, K_2, K_3, K_4 and K_5	$\frac{3600\,CR}{S}$
Duncan	$\frac{3600\,KR}{S}$
Sangamo	$\frac{KR}{S}$

Accuracy. — The meter watts as thus calculated divided by the as read on the test meter, and multiplied by 100, gives the per cent f the per cent accuracy is less than 100 the meter is running slow; n 100 it is running fast. The term "per cent accuracy" is open to

some objection, and "per cent registration" is coming to be preferred entirely satisfactory name has yet been found for this quantity.

Adjusting Speed of Meter. — If the error in the meter reading at full is in excess of the permissible error the speed should be altered by adjusting position of the permanent magnets or shunting part of their flux by the provided therefor. If the error at light load, say 5 per cent load, is excessive light-load adjustment should be altered to bring the speed to its correct va

Method of Using the Portable Watthour Meter. — The dial of the able meter reads directly in revolutions of the meter disc. At the instant mark on the disc of the service meter passes some arbitrarily chosen fixed p note the dial reading of the portable meter. Count the number of revolu of the disc of the service meter, and at the instant when a suitable whole nu of revolutions are completed note the dial reading of the portable meter a Let R_0 be the difference in the two dial readings of the portable meter, K_0 test constant of the portable meter, R the number of revolutions of the se meter and K its test constant. Then the per cent accuracy is KR/K_0R_0. course the test constants of the two meters must be expressed in the manner, i.e., as watthours per revolution or as watt-seconds per revolution

Testing of Three-wire and Polyphase Meters. — A three-wire meter be tested as a two-wire meter by connecting the current coils in series. three-wire meter will then read twice the number of watts actually supplied the test load. By using two sets of instruments three-wire meters may tested as actually used.

A polyphase meter is most readily tested as a single-phase meter with current circuits in series and the potential circuits in parallel. The read the meter is then twice the number of watts actually supplied to the test

INSTALLATION OF WATTHOUR METERS. — A watthour should always be mounted on a firm support, should be set with the dis and in a place where it will not be liable to be injured or subjected to m A firm support is particularly essential, as continual vibration of the meter cause it to "creep," since vibration tends to lessen the friction, and the compensation may then be excessive.

Meters should not be installed closer than about fifteen inches be centers, and should not be too close to conductors carrying heavy curre in the vicinity of iron girders, posts, water or steam pipes.

A check on its accuracy should always be made after the installation of a

Determination of the Capacity of Meter. — Before installing a some tests or accurate estimates should be made to determine the correct ca of meter, as it is not advisable to run a meter continuously above its capacity, and too large a meter means in general poor accuracy on light As a rough guide, the capacity of the meter should be one-half the total nected load for ordinary residences, three-fourths the total connected loa stores and offices, and 1 ½ times the connected load for elevator, hoist and motors taking a large starting current. When several such motors are on meter, the diversity factor will often permit the use of a meter capacity than their combined current capacity.

Precautions in Connecting Polyphase Meters. — Direct-current single-phase alternating-current meters are comparatively simple to instal connect properly, but all installations on polyphase circuits require con ably more care and knowledge to insure proper connections. Polyphase in tion meters must be connected properly in regard to phase relations, as o wise very inaccurate results will be obtained, which may not be apparent casual examination of the meter. The manufacturer's instructions show

ery carefully and the phase relations traced out to make sure that orrect. Practically all instrument transformers are now marked in inctive manner to indicate the relative instantaneous polarity of the nd secondary windings, in order to facilitate making connections.

TENANCE, REPAIRS AND DEPRECIATION. — It has been m experience that except for the very smallest central stations or g companies it is economy to maintain some systematic method of d caring for all meters on the system. For ordinary house service cept very large installations, readings are taken about once a month rs are examined and tested as required. Commutator-type and otor meters should undoubtedly be tested and put in good condition ce a year; induction meters may be left for two years and perhaps e examination, as the very slight change in accuracy is not enough to e expense of the test. With very large capacity meters, where the money involved is large, frequent tests are made and in some cases check and adjustment is made, and whenever necessary the meter complete overhauling and a spare meter installed in the meantime.

. — In making repairs on watthour meters, it is practically necessary n considerable equipment and a department for this class of work. h a department is available it is preferable to return meters to the er for all repairs except those of a minor nature, such as cleaning of rs on direct-current meters and inserting new jewels and pivots for earing. Manufacturers will usually supply repair parts at reasonable quite extensive repairs can be made by the central stations if they are uipped. In service the attention and care necessary vary with the ter, induction meters being by far the cheapest to repair and under ions such meters require the least attention of any type.

OF WATTHOUR METERS. — Ordinary service type com- eters for direct current range in price from $16 to $170. Switch- nutator meters in capacities from 800 to 6000 amperes range in price to $500. Shunted type commutator meters range from $100 for a meter to $200 for one of 5000 amperes capacity.

motor meters usually have external shunts. The meter itself is of apacity and sells for about $16 in the service type and $55 to $70 in oard type. Prices of shunts for these meters are approximately o-ampere, $30 for a 500-ampere, $40 for a 1000-ampere and $100 for ere meter.

acity single-phase service-type induction meters are sold for about ch; larger capacities and polyphase meters range from $35 to $70. l induction meters sell for $40 to $100; they are 5-ampere, 110-volt ned for use with instrument transformers, q.v.

e prices are approximate, and should be used only as a rough guide. of installing and connecting the meter varies considerably with s or requirements. Where no protective devices are used, and the irs the cost of the main line cutout and cutout box, the installation ompany may be about $2. Where the company furnishes the main ind box, with protective devices to prevent tampering, the instal- ill be about $10.

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See also an extensive bibliography on electrical instruments and meters the 1914 report of the Meter Committee of the National Electric Light Association.

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[ETERS. — (*See also Ammeters; Electrodynamometers; Electrometers; ks; Voltmeters; Watthour Metres.*) A wattmeter is a device for electric power and is particularly useful for measuring alternating- wer. Usually some form of electrodynamometer is used in which in the circuit or a known part of it is sent through one winding, the l; and a small current in phase with the e.m.f. across the terminals of is sent through the other winding, or potential coil; see Figs. 1 and 2. current in the potential circuit is drawn through a resistance as in r. For voltages above 150 to 750 volts, potential transformers (*see rs, Instrument*) are usually employed. In some cases specially-con- sistances, or multipliers, are employed in testing work up to 25,000 n higher. The moving coil is generally used for the potential circuit e convenient to carry through it a small current than a large one.

e of Operation. — In an instrument constructed and used as above he current in the current coil is practically proportional to the load each instant and the current in the potential coil is practically pro- the voltage v across the load at that instant. Hence the instan- que acting on the moving element at this instant is proportional to instantaneous power. The average torque acting on the moving ing each cycle of the current and voltage is then proportional to the er. If the free period of the moving system is large compared with f the current and voltage, then the steady reading will also be pro- the average power.

UCTION OF WATTMETERS. — The electrodynamometer ument is built in several forms, e.g., the original Siemens electro- r in various forms in which the moving coil is brought back to zero a torsion head from which the reading is obtained; deflection in- which the moving coil is allowed to advance through an angle until erted on it by the currents in the instrument windings is balanced ing torque developed in a spring or equivalent device. In the latter ument the position of the moving coil is usually read by means of pointer passing over a scale, graduated to read directly in watts or iples. In very sensitive instruments for laboratory use a beam of lescope and scale like those used with mirror galvanometers is em- lso *Electrodynamometers.*

n to the electrodynamometer type of instrument, induction watt- ating on the same general principle as the induction watthour *atthour Meters*), are sometimes used for switchboard and even for k, but they are not so generally useful through wide ranges of fre- voltage as electrodynamometer instruments.

n limited conditions electrostatic wattmeters (*see Electrometers*) ccessfully used; in this general class of wattmeters for special pur- included the cathode-ray oscillograph or Braun tube (*see Braun*

wattmeters, having two or more sets of current and potential wind- ting torque to a common shaft, are made for use on polyphase below under *Measurement of Three-phase Power.*

Different Types of Wattmeters. — Reflecting electrodynamom- rs for laboratory use are made for currents up to 100 or 200 amperes n circuits from a fraction of a volt up to 150 volts. Such instru- een specially constructed for larger currents and higher voltages. *Electrodynamometers.* Such instruments are chiefly useful for on circuits of low voltage and of low power factor where even

the small power required to operate the instrument makes the use of ord portable instruments inconvenient or impossible.

Portable wattmeters are usually made to give a full-scale deflection about two-thirds of the product of their rated amperes and volts, i.e., as i ment rated as 5 amperes and 150 volts would usually have a 500-watt For determining core losses and other service where the power factor wattmeters may be had giving full-scale reading with one-third or even one-fifth of the product of the rated amperes and volts. It is custom supply such wattmeters with a certificate showing the values of the equi phase angle α (*see below*) that have been determined, so that they may be where a high degree of precision is required on low power factor work.

Portable wattmeters are made in ranges up to 200 amperes and 750 Extra potential terminals are often supplied so that the instruments used on more than one voltage, e.g., 125 or 250 volts. Double current wi are also supplied, with a switch or links for changing the current range, a also usual to construct wattmeters having two current ranges and two ranges. This construction greatly increases the usefulness of the instru and is particularly useful when applied to the low power factor wattmet it makes it possible to use them for higher power factors by using say th ampere, 250-volt range for a load of 5 amperes at 125 volts.

Portable wattmeters for currents larger than 200 amperes and voltages than 750 volts have been successfully constructed but are not generally because the higher ranges can usually be taken care of with 5-ampere ra wattmeters in connection with calibrated instrument transformers.

Switchboard wattmeters are made single-phase up to 200 amperes a volts, and polyphase up to 50 or 100 amperes and up to 750 volts. ranges are usually taken care of by using 5-ampere wattmeters in con with instrument transformers.

METHODS OF CONNECTING WATTMETER TO LOAD; RECTION FOR POWER LOST IN WATTMETER. — A wattmet be connected to the load which it is to measure in either of the two ways trated in Figs. 1 and 2. When connected as in Fig. 1 the current thro

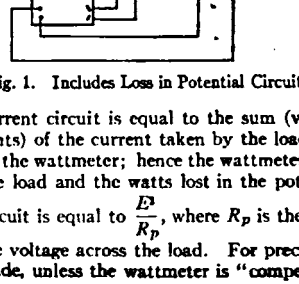


Fig. 1. Includes Loss in Potential Circuit

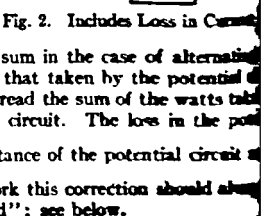


Fig. 2. Includes Loss in Curr

current circuit is equal to the sum (vector sum in the case of alternating rents) of the current taken by the load and that taken by the potential of the wattmeter; hence the wattmeter will read the sum of the watts take the load and the watts lost in the potential circuit. The loss in the pot circuit is equal to $\frac{E^2}{R_p}$, where R_p is the resistance of the potential circuit a the voltage across the load. For precise work this correction should alwa made, unless the wattmeter is "compensated"; see below.

In the second scheme of connection, Fig. 2, the current through the cu circuit is the same as that taken by the load, but the voltage across the pot

ait is higher than the voltage across the load by the voltage drop through the ent circuit of the instrument, and the wattmeter reads too high by an amount al to the watts lost in the current circuit. This loss is equal to $R_a I^2$, where s the resistance of the current circuit and I the load current. This loss is ally less than the loss in the potential circuit which occurs when the first me of connection is used. If no correction is made for the wattmeter loss scheme of connections shown in Fig. 2 should therefore be used. If the est precision is required, especially when a small-capacity wattmeter is used, connections shown in Fig. 1 should be used, and a correction should be ap-l. The resistance of the potential coil is usually stated on the case of the ument.

hen a voltmeter is connected to the load across AA' in Fig. 1, while the meter reading is being taken, a correction should also be made, if appre-le, for the power taken by the voltmeter. Calling R_v the resistance of the meter and multiplier, if any, and E the voltage across the load, the loss in oltmeter is $\frac{E^2}{R_v}$. In most cases the potential circuit losses in the watt-r and voltmeter are best determined by a direct measurement with the meter, using the test voltage and leaving the current circuit open. If the meter is connected across BB' in Fig. 2, then the power lost in it is not by the wattmeter, but the voltmeter reading is not exactly equal to the ge across the load, but equals the load voltage plus the resistance drop impedance drop, added vectorially, in the case of an alternating-current nt) through the current circuit of the wattmeter.

mpensation for Wattmeter Loss. — In the so-called compensated watt-rs a stationary compensating coil inside the instrument is connected in s with the potential coil, this compensating coil being so placed that the nt through it produces on the moving element a torque equal and opposite nt produced by this same current when it passes through the current coil. mpensated wattmeter should always be connected to the circuit, as shown g. 1; when so connected no correction for the loss in the wattmeter is ssary.

OURCES OF ERROR. — Due to the unavoidable inductance in the ntial circuit of a wattmeter, the current in the moving coil is not exactly hase with the e.m.f. impressed on the circuit; in addition there are other l inherent defects in wattmeters, such as eddy currents in windings, sup-s, etc., which tend to make commercial wattmeters more or less imperfect. e imperfections are more serious as the frequency of the circuit is raised the power factor is lowered.

r precision testing under service conditions when the best obtainable accu-is required, it is often desirable to apply corrections to wattmeter observa-to eliminate the errors due to phase displacement, or its equivalent, in the ntial circuit; when instrument transformers are used, additional phase dis-ment occurs, rendering such corrections especially important. In other where corrections cannot well be applied, it is useful to consider the mag-le of the error that will occur under any given conditions, in order to select ble instruments and transformers and to arrange the burdens connected to secondaries in such a way as to produce as near as may be the desired ts. In many cases indications that would otherwise be considerably in may be made to give results of satisfactory accuracy by correcting for phase acement in the wattmeter, and particularly in the instrument trans-ers.

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here are many ways in which the necessary corrections may be determined applied but the following has been found satisfactory in practical work

Equivalent Phase Angle of Wattmeter. — All the errors in wattme may be considered as due to a certain phase displacement between the curr in the potential coil and the impressed e.m.f. of the circuit. This equival angle of phase displacement may be due to a variety of causes, but can be de mined for any given instrument from the following relations. Consider a w meter in which the current in the potential circuit lags α degrees behin e.m.f. impressed on the potential circuit, the meter being in all other resp perfect. If such a meter is used to measure the watts P supplied by a curre at a voltage E, this current lagging behind E by an angle θ, the wattmeter read $P_2 = EI \cos \theta_2$ watts, where $\theta_2 = \theta - \alpha$. Hence if a wattmeter is used measure a known load of P watts with I amperes and E volts, and the w meter reads P_2 watts, the equivalent phase angle of the wattmeter may defined by the relation

$$\alpha = \cos^{-1}\left(\frac{P}{EI}\right) - \cos^{-1}\left(\frac{P_2}{EI}\right).$$

This angle α is to be taken positive when the wattmeter reads too high on inductive load and negative when it reads too low on an inductive load.

For a given wattmeter and given potential coil this equivalent phase angle practically constant for all currents, voltages and load power factors, provi the frequency remains constant.

In the best portable and reflecting instruments α is usually + and very sm In a portable instrument built for a 125- to 150-volt circuit, when used o 60-cycle circuit, α may have a value of from +2 minutes to as much as + minutes. The phase angle varies directly as the frequency and inversely the voltage rating.

The phase angle of a wattmeter may be compensated by shunting a denser of capacity C around a portion R of the resistor in the potential ci If the equivalent inductance of this circuit be L, the relation for compensati

$$C = \frac{L}{R^2}.$$

Correction for Phase Angle of Wattmeter and of Instrument Tra formers. — Let α = the phase angle of the wattmeter, as defined above, β = phase angle of the current transformer, γ = the phase angle of the poten transformer (*see Transformers, Instrument*), P_2 = wattmeter reading correc for scale error and multiplied by the product of the corrected ratios of the c rent and potential transformers, E = voltmeter reading corrected for scale e and multiplied by the ratio of the potential transformer, and I = ammeter re ing corrected for scale error and multiplied by the corrected ratio of the curr transformer. Then the apparent power factor is

$$\cos \theta_2 = \frac{P_2}{EI},$$

and the true power is

$$P = P_2 \frac{\cos(\theta_2 + \alpha + \beta + \gamma)}{\cos \theta_2}.$$

The angle θ_2 is to be taken positive when the current lags behind the volt and negative when the current leads. Note that α, β and γ may also be p tive or negative angles. Values of the correction factor $\frac{\cos(\theta_2 + \alpha + \beta + \gamma)}{\cos \theta_2}$ given in Tables I and II. Note carefully the conditions, stated at the head each table, to which each table applies.

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On three-phase systems (*see pp. 1932 and 1933*), when badly unbalanced

TABLE I. CORRECTION FACTORS FOR PHASE ANGLE

$$\frac{\cos(\theta_2 + \alpha + \beta + \gamma)}{\cos\theta_2}$$

For lagging current when $(\alpha+\beta+\gamma)$ is positive
For leading current when $(\alpha+\beta+\gamma)$ is negative

$\beta+\gamma$	Apparrent power factor $\cos\theta_2$										
	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90
5′	0.9855	0.9904	0.9929	0.9944	0.9954	0.9967	0.9975	0.9981	0.9985	0.9989	0.9993
10′	0.9711	0.9808	0.9857	0.9887	0.9907	0.9933	0.9950	0.9961	0.9970	0.9978	0.9986
15′	0.9566	0.9712	0.9786	0.9831	0.9861	0.9900	0.9924	0.9942	0.9955	0.9967	0.9979
20′	0.9421	0.9616	0.9715	0.9775	0.9815	0.9867	0.9899	0.9922	0.9940	0.9956	0.9972
25′	0.9276	0.9520	0.9643	0.9718	0.9768	0.9833	0.9874	0.9903	0.9926	0.9945	0.9965
30′	0.9131	0.9424	0.9572	0.9662	0.9722	0.9800	0.9848	0.9883	0.9911	0.9934	0.9957
40′	0.8842	0.9232	0.9429	0.9549	0.9629	0.9733	0.9798	0.9844	0.9881	0.9912	0.9943
50′	0.8552	0.9040	0.9286	0.9436	0.9536	0.9666	0.9747	0.9805	0.9851	0.9890	0.9929
60′	0.8262	0.8848	0.9143	0.9323	0.9444	0.9599	0.9696	0.9766	0.9820	0.9868	0.9914
10′	0.7972	0.8656	0.9000	0.9209	0.9350	0.9531	0.9645	0.9726	0.9790	0.9845	0.9899
20′	0.7682	0.8464	0.8857	0.9096	0.9257	0.9464	0.9594	0.9687	0.9760	0.9823	0.9885
30′	0.7392	0.8271	0.8714	0.8983	0.9164	0.9397	0.9543	0.9648	0.9730	0.9800	0.9870
40′	0.7102	0.8079	0.8571	0.8869	0.9071	0.9329	0.9492	0.9608	0.9699	0.9778	0.9855
50′	0.6812	0.7886	0.8428	0.8756	0.8978	0.9262	0.9441	0.9568	0.9668	0.9755	0.9840
60′	0.6521	0.7694	0.8284	0.8642	0.8884	0.9194	0.9389	0.9529	0.9638	0.9732	0.9825
10′	0.6231	0.7501	0.8141	0.8529	0.8791	0.9127	0.9338	0.9489	0.9607	0.9709	0.9810
20′	0.5941	0.7308	0.7997	0.8415	0.8697	0.9059	0.9287	0.9449	0.9576	0.9686	0.9795
30′	0.5650	0.7115	0.7854	0.8301	0.8603	0.8991	0.9235	0.9409	0.9545	0.9663	0.9779
40′	0.5360	0.6923	0.7710	0.8187	0.8510	0.8923	0.9183	0.9369	0.9515	0.9640	0.9764
50′	0.5069	0.6730	0.7566	0.8073	0.8416	0.8855	0.9132	0.9329	0.9483	0.9617	0.9748
60′	0.4779	0.6537	0.7422	0.7959	0.8322	0.8787	0.9080	0.9288	0.9452	0.9594	0.9733
10′	0.4488	0.6344	0.7279	0.7845	0.8228	0.8719	0.9028	0.9248	0.9421	0.9570	0.9717
20′	0.4198	0.6151	0.7135	0.7731	0.8134	0.8651	0.8976	0.9208	0.9390	0.9547	0.9701
30′	0.3907	0.5957	0.6991	0.7617	0.8040	0.8583	0.8924	0.9167	0.9359	0.9523	0.9686
40′	0.3616	0.5764	0.6847	0.7503	0.7946	0.8514	0.8872	0.9127	0.9327	0.9500	0.9670
50′	0.3326	0.5571	0.6702	0.7388	0.7852	0.8446	0.8820	0.9086	0.9296	0.9476	0.9654
60′	0.3035	0.5378	0.6558	0.7274	0.7758	0.8377	0.8767	0.9046	0.9264	0.9452	0.9638
10′	0.2744	0.5185	0.6414	0.7160	0.7663	0.8309	0.8715	0.9005	0.9232	0.9429	0.9622
20′	0.2453	0.4991	0.6270	0.7045	0.7569	0.8240	0.8663	0.8964	0.9201	0.9405	0.9605
30′	0.2163	0.4798	0.6125	0.6930	0.7474	0.8171	0.8610	0.8923	0.9169	0.9381	0.9589
40′	0.1872	0.4604	0.5981	0.6816	0.7380	0.8103	0.8558	0.8882	0.9137	0.9357	0.9573
50′	0.1581	0.4411	0.5837	0.6701	0.7285	0.8034	0.8505	0.8841	0.9105	0.9333	0.9556
60′	0.1290	0.4217	0.5692	0.6586	0.7191	0.7965	0.8452	0.8800	0.9073	0.9308	0.9540
10′	0.0999	0.4024	0.5548	0.6472	0.7096	0.7896	0.8400	0.8759	0.9041	0.9284	0.9523
20′	0.0708	0.3830	0.5403	0.6357	0.7001	0.7827	0.8347	0.8717	0.9008	0.9260	0.9507

TABLE II. CORRECTION FACTORS FOR PHASE ANGLE

$$\frac{\cos(\theta_2+\alpha+\beta+\gamma)}{\cos\theta_2}$$

For lagging current when $(\alpha+\beta+\gamma)$ is negative
For leading current when $(\alpha+\beta+\gamma)$ is positive

$\alpha+\beta+\gamma$	Apparent power factor $\cos\theta_2$									
	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80
5′	1.0145	1.0096	1.0071	1.0056	1.0046	1.0033	1.0025	1.0019	1.0015	1.001
10′	1.0289	1.0192	1.0142	1.0113	1.0092	1.0067	1.0050	1.0039	1.0030	1.002
15′	1.0434	1.0288	1.0214	1.0169	1.0139	1.0100	1.0075	1.0058	1.0044	1.003
20′	1.0579	1.0383	1.0285	1.0225	1.0185	1.0133	1.0101	1.0077	1.0059	1.004
25′	1.0723	1.0479	1.0356	1.0281	1.0231	1.0166	1.0126	1.0097	1.0074	1.005
30′	1.0868	1.0575	1.0427	1.0338	1.0277	1.0200	1.0151	1.0116	1.0089	1.006
40′	1.1157	1.0766	1.0569	1.0450	1.0369	1.0266	1.0201	1.0154	1.0118	1.008
50′	1.1446	1.0958	1.0711	1.0562	1.0461	1.0332	1.0251	1.0193	1.0147	1.010
1° 00′	1.1735	1.1149	1.0853	1.0674	1.0553	1.0398	1.0301	1.0231	1.0177	1.012
10′	1.2024	1.1340	1.0995	1.0787	1.0645	1.0464	1.0351	1.0269	1.0206	1.013
20′	1.2313	1.1531	1.1137	1.0898	1.0737	1.0530	1.0400	1.0308	1.0235	1.017
30′	1.2601	1.1722	1.1279	1.1010	1.0829	1.0596	1.0450	1.0346	1.0264	1.019
40′	1.2890	1.1913	1.1421	1.1122	1.0921	1.0662	1.0500	1.0384	1.0292	1.021
50′	1.3178	1.2104	1.1562	1.1234	1.1012	1.0728	1.0549	1.0421	1.0321	1.023
2° 00′	1.3466	1.2294	1.1704	1.1346	1.1104	1.0794	1.0598	1.0459	1.0350	1.025
10′	1.3755	1.2485	1.1845	1.1457	1.1195	1.0859	1.0648	1.0497	1.0379	1.027
20′	1.4043	1.2675	1.1986	1.1569	1.1286	1.0925	1.0697	1.0535	1.0407	1.029
30′	1.4331	1.2866	1.2127	1.1680	1.1377	1.0990	1.0746	1.0572	1.0435	1.031
40′	1.4618	1.3056	1.2268	1.1791	1.1469	1.1055	1.0795	1.0610	1.0464	1.033
50′	1.4906	1.3246	1.2409	1.1902	1.1560	1.1120	1.0844	1.0647	1.0492	1.035
3° 00′	1.5194	1.3436	1.2550	1.2013	1.1650	1.1185	1.0893	1.0684	1.0520	1.037
10′	1.5481	1.3626	1.2691	1.2124	1.1741	1.1250	1.0942	1.0721	1.0548	1.039
20′	1.5768	1.3816	1.2832	1.2235	1.1832	1.1315	1.0990	1.0758	1.0576	1.041
30′	1.6056	1.4005	1.2972	1.2346	1.1923	1.1380	1.1039	1.0795	1.0604	1.043
40′	1.6343	1.4195	1.3113	1.2456	1.2013	1.1445	1.1087	1.0832	1.0632	1.045
50′	1.6630	1.4384	1.3253	1.2567	1.2103	1.1509	1.1136	1.0869	1.0660	1.047
4° 00′	1.6916	1.4573	1.3393	1.2677	1.2194	1.1574	1.1184	1.0906	1.0687	1.049
10′	1.7203	1.4763	1.3533	1.2788	1.2284	1.1638	1.1232	1.0942	1.0715	1.051
20′	1.7489	1.4952	1.3673	1.2898	1.2374	1.1703	1.1280	1.0979	1.0742	1.053
30′	1.7776	1.5141	1.3813	1.3008	1.2464	1.1767	1.1328	1.1015	1.0770	1.055
40′	1.8062	1.5329	1.3953	1.3118	1.2554	1.1831	1.1376	1.1052	1.0797	1.057
50′	1.8348	1.5518	1.4092	1.3228	1.2644	1.1895	1.1424	1.1088	1.0824	1.059
5° 00′	1.8634	1.5707	1.4232	1.3337	1.2733	1.1959	1.1472	1.1124	1.0851	1.061
10′	1.8920	1.5895	1.4371	1.3447	1.2823	1.2023	1.1519	1.1160	1.0878	1.063
20′	1.9205	1.6083	1.4510	1.3557	1.2912	1.2086	1.1567	1.1196	1.0905	1.065

ctions should be applied separately, as above, to each wattmeter. When ircuit is balanced a single correction based on cos θ_2 for the whole circuit be used.

Example No. 1. — Given a single-phase circuit with lagging current in h the wattmeter reading corrected for scale error and multiplied by the cor- d ratios of current and potential transformers equals 24,520 watts, and the uct of the voltmeter and ammeter readings, similarly corrected, equals 35,600 amperes. Then $\cos \theta_2 = \frac{24,520}{35,600} = 0.689$. If the equivalent phase angle α e wattmeter is $+4'$ and if from examination of characteristic curves the nt transformer phase angle β is found to be $+48'$ and the potential trans- er phase angle γ is $-10'$, then $\alpha+\beta+\gamma = +42'$, and from Table I, the correc- 'actor is 0.9871. Whence the true power equals $24,520 \times 0.9871 = 24,204$ watts.

Example No. 2. — Given a single-phase circuit with leading current, in h the wattmeter reading, corrected as in example No. 1, equals 12,266 watts the product of the voltmeter and ammeter readings, similarly corrected, ls 24,532 volt-amperes. Then $\cos \theta_2 = \frac{12,266}{24,532} = 0.5$. If the equivalent : angle α of the wattmeter is $+5'$, the phase angle β of the current trans- er $+2° 33'$ and the phase angle γ of the potential transformer is $+38'$, $\alpha+\beta+\gamma = +3° 16'$ and therefore from Table II the correction factor to be is 1.0971. Whence the true power equals $12,266 \times 1.0971 = 13,457$ watts.

rors Due to Stray Fields. — Stray magnetic fields influence the reading wattmeter in much the same way as such disturbances influence the readings ther electrical instruments; see *Ammeters*. In unshielded instruments s due to stray fields may be quite large. Considerable errors are often d by the effect of neighboring instruments on one another. To avoid these s, high-grade American wattmeters are magnetically shielded.

CURACY OF WATTMETERS. — The question of the accuracy of rical instruments is discussed in detail in the article on *Ammeters*. High- e portable wattmeters may be obtained having a stated accuracy of 0.25 ent of full-scale value for single-phase or 0.5 per cent for polyphase watt- rs. It is not practicable to obtain as high accuracy in the latter, on account e impossibility of making both elements of the polyphase wattmeter follow tly the same scale law. This theoretical disadvantage of the polyphase meter is more than offset in practical use by its greater convenience and reduction in number of observations necessary, and its service accuracy, cially on fluctuating power, may even exceed that of single-phase watt- rs used for polyphase measurements. High-grade switchboard wattmeters be obtained having a stated accuracy of 1 per cent of full-scale value. Of se the higher the degree of accuracy demanded the more costly is the meter.

ESTING OF WATTMETERS. — Wattmeters are usually tested by g compared with other standard wattmeters, which have in turn been ained by special methods and their behavior under various conditions of determined. For examining the effect of low power factor on wattmeters, e-shifting transformers or generators having shifting fields are conveniently loyed. By these means low power factor conditions may be produced on ruments without the necessity of troublesome adjustments of reactances, lensers, etc.

fter a given instrument is known with certainty to give no sensible error on rating current due to structural defects, it is usually more convenient to te subsequent checks to detect any change in the instrument by using direct rent. The current and voltage are in this case determined by means of

suitable standard ammeter and voltmeter or by direct reference to potentiometer and standard cells; see *Potentiometers*.

MEASUREMENT OF THREE-PHASE POWER. — (*See also article by L. T. Robinson in General Electric Review, 1912, Vol. 15, p. 350.*) The measurement of the power supplied to a three-phase load may be effected in one or more of the following ways. The connections in each case may be made either directly or through proper instrument transformers, the latter being used for heavy currents or high voltages, or both.

Single (One-element) Wattmeter on Three-wire System. — The current circuit of the wattmeter is connected in series with one of the mains supplying the load and the potential circuit of the wattmeter is connected between the corresponding terminal of the load and the neutral. If the neutral point of the load, or of the transformers supplying the load, is not available, a "Y-box" (see below) can be used to establish an artificial neutral. If the load is perfectly balanced (*see Alternating Currents*) the power input is then three times the wattmeter reading. However, a three-phase load is seldom sufficiently well balanced even in the case of a three-phase motor load, to render this method of measurement an accurate one. In most practical cases it gives merely a rough approximation to the true power.

Y-Box. — The simplest form of Y-box consists of two equal non-inductive resistors connected in series, each of the free ends and the junction point being connected to a binding post. Each resistor has a resistance equal to that of the potential circuit of the wattmeter. One terminal of the potential circuit of the wattmeter is connected to the junction terminal of the Y-box and the other terminal of the potential circuit to the line wire in which the current circuit of the wattmeter is connected. The other two terminals of the Y-box are connected to the other two line wires respectively.

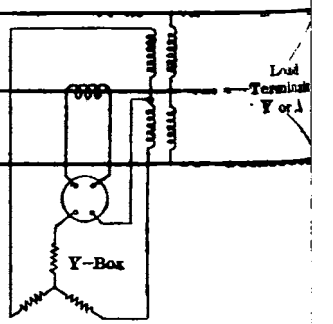


Fig. 3. Single-phase Wattmeter and Y-box for Three-phase Circuit

In the case of wattmeters designed especially for use with a Y-box, part of the resistance of the potential circuit of the wattmeter is placed in the Y-box, being connected permanently to the junction point between the other two resistors. A similar arrangement may be used as a multiplier. The connections of such a Y-box, wattmeter and instrument transformers are shown diagrammatically in Fig. 3.

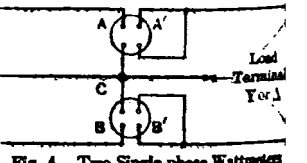


Fig. 4. Two Single-phase Wattmeters for Three-phase Circuits

Two-wattmeter Method for a Three-wire System. — The simple arrangement of two wattmeters shown in Fig. 4 will give exactly the total power in *any three-wire* circuit, provided each wattmeter by itself gives accurate indications. Aside from the sources of error, as noted above, which may affect the accuracy of a wattmeter on a single-phase circuit, the arrangement

it shown in Fig. 4 will give the true power for any condition of unbalan-
, wave-form, frequency, etc. It is also immaterial whether the load be Y
connected. The connections may be made directly as shown or through
current transformers and two potential transformers, the connections being
same as in Fig. 5, except that two separate wattmeters instead of a poly-
se wattmeter are used.

Rule for Adding or Subtracting Readings. — With the arrangement
wn in Fig. 4 the total power is always the *algebraic* sum of the readings of
two wattmeters. Since a wattmeter reads only in one direction, usually
he right, the two instruments must be so connected to the line that the needle
each instrument is deflected over the scale. For a balanced three-phase
l having a power factor greater than 50 per cent, the sum of the two watt-
ter readings, when the connections are thus made, gives the total power;
a power factor less than 50 per cent the difference of the two readings must
taken. When the power factor is not known, one can determine whether
sum or the difference of the readings should be taken by interchanging the
wattmeters, leaving unaltered the potential connections to the third wire
in Fig. 4); if the pointers of the two wattmeters deflect in the same direction
before add the two readings, if the pointers deflect in the opposite direction
, against the stop) take the difference. In making this test, care must he
en to connect the source side of each of the two lines (in which the current
l of each wattmeter is connected in succession) to the same binding post of
given wattmeter in each of the two positions.

When the load is *balanced*, and the two wattmeters are connected, as in Fig. 4,
that each gives a positive reading, the question as to whether the power
tor is above or below 50 per cent can be determined by changing the poten-
l lead of the lower reading meter from the common connection C to the line
which the current coil of the other wattmeter is connected. If the reading
is obtained is positive, the power factor is more than 50 per cent and the
dings should be added; if the reading is negative the power factor is less
an 50 per cent and the readings should be subtracted.

**Phase Difference between Voltage and Current in the Wattmeter
indings.** — In case the load is balanced it can be shown that if θ is the
wer-factor angle of the load, I the line current (current per wire) and E the
e voltage (voltage between wires), then the power read by one wattmeter is
$=EI\cos(\theta-30°)$, and the power read by the other is $P_2=EI\cos(\theta+30°)$.
he performance of the first wattmeter is the same as it would be on a single-
ase load having a power factor of $\cos(\theta-30°)$ and the performance of the
ond is the same as it would be on a single-phase load having a power factor
$\cos(\theta+30°)$. These relations should be borne in mind when making any
rrections for errors due to low power factor (see above).

Measurement of Power Factor by Two-wattmeter Method. —
rom the above relations it can be shown that the power factor of the load,
hen the load is balanced, may be calculated from the two wattmeter readings
and P_2 by the formula

$$\text{Power factor} = 100\cos\left[\tan^{-1}\left(\sqrt{3}\,\frac{P_1-P_2}{P_1+P_2}\right)\right] \qquad \text{per cent,}$$

hen the power factor is greater than 50%; and by the formula

$$\text{Power factor} = 100\cos\left[\tan^{-1}\left(\sqrt{3}\,\frac{P_1+P_2}{P_1-P_2}\right)\right] \qquad \text{per cent,}$$

hen the power factor is less than 50%, P_1 and P_2 both being taken as positive
n both cases and P_2 being the smaller reading.

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Two-element Polyphase Wattmeter on Three-wire System. — Inst
of using two separate wattmeters, as shown in Fig. 4, the two wattmeters may
combined into a single instrument with but one shaft and pointer. The connections for such a two-element wattmeter, when instrument transformers are used, are shown in Fig. 5. For measurements where the power is badly fluctuating and especially when accompanied by low power factor, polyphase wattmeters may be more accurate and convenient. For ordinary polyphase service a polyphase wattmeter is not capable of as high accuracy as two single-phase wattmeters.

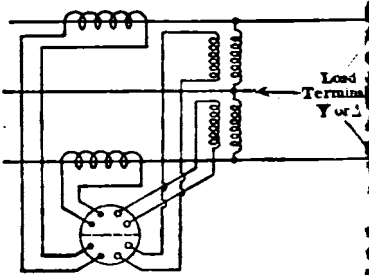


Fig. 5. Two-element Polyphase Wattmeter wi
Instrument Transformers

Determination of Power Factor with Two-element Wattmeter.
The two-element wattmeter reads directly the sum P_1+P_2, using the notat
in the previous paragraph. By reversing the connections of one set of poten
terminals to the corresponding potential transformer the meter may be made
read P_1-P_2. Hence by the use of a suitable reversing switch the power fa
of the load may be readily determined by taking two readings; see preced
paragraph.

Three Wattmeters for Three-wire System. — As noted above, where t
wattmeters, or a two-element polyphase wattmeter, is used on a three-
system, the phase difference between the voltage and current in each wattm
or element may differ greatly from the power-factor angle of the load.
example, in the case of a balanced load having a 50 per cent power factor,
current in one wattmeter differs by 90° from the voltage on the potential circuit of this wattmeter, and it should read zero watts, i.e., this wattmeter operates under the worst possible conditions as regards power factor, and consequently the phase-angle error (see above), particularly when instrument transformers are used, may be quite large when expressed as a percentage. It should be noted, however, that the reading of the wattmeter or element in which the large phase difference occurs contributes proportionally less to the total reading as this phase difference approaches 90°, and consequently the percentage error of the tota reading will be only a correspondingly small part of the error in this wattmeter or element.

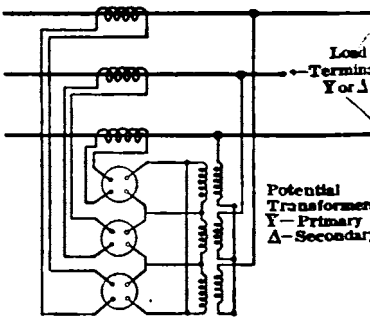


Fig. 6. Y-Δ Connections for Three Wattmeters
on Three-wire System

Where the highest accuracy is demanded, it is therefore theoretically advisable to use three wattmeters connected as shown in Fig. 6. It should be noted, however, that for most practical purposes the very slight gain in accuracy by such an

ment over the two-element wattmeter does not justify the expense of the nal wattmeter and instrument transformers. Again, a precision measure- f power with the three-wattmeter arrangement requires the accurate cali- and the accurate reading of three wattmeters instead of one.

asurement of Power in Four-wire Circuits. — When part of the load returns through a fourth wire, e.g., in an unbalanced three-phase system a neutral wire, at least three wattmeters or wattmeter elements are d to obtain a theoretically accurate measurement of the power. A two- : wattmeter having three current circuits may be used for the measure- f power on a four-wire system, and if the vectors representing the three s to neutral form a triangle will give results having as high an accuracy e obtained with a two-element wattmeter on a three-wire system. a three wattmeters are used, they should be connected in a manner to that used for two wattmeters on a three-wire system, i.e., each of the tential circuits should be connected between a main wire and the neutral id each of the three current circuits should be connected in series with responding main wire. When instrument transformers are used the es of the potential transformers are connected in Y, with the neutral nnected to the neutral wire, the three branches being connected to the res; the secondaries and the potential circuits of the wattmeters are also ed in Y, with the wattmeters Y-connected to the Y made by the second-

Two-element Wattmeter on Four-wire System. — When used on a e system the current coil of each element is divided into two like sections, section of each coil is connected with one section other coil, thus three groups of oils. Each group cted to a current ner as shown in which also shows nections of the l transformers, o of which are . With this ar- nt the instru- easures correctly ver supplied by aches of the sys- t for the third the power meas- that correspond-

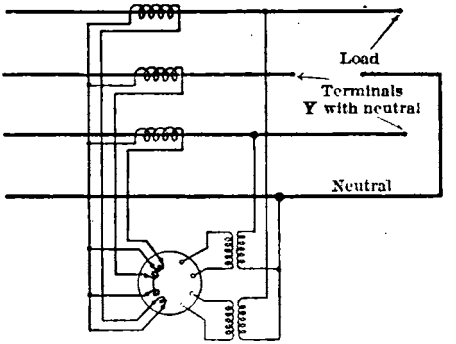


Fig. 7. Connections for Two-element Wattmeter on Four-wire System

ne current in this branch and the resultant (vector sum) of the voltages ral in the other two branches. Voltage unbalance or badly distorted and voltage waves will cause this resultant voltage to differ from the oltage to neutral in the third branch, producing an error in the measure- this third of the total power. Under ordinary conditions, however, or is not objectionably large for commercial measurements.

PHIC WATTMETERS. — These instruments are designed to draw art a curve of power against time, without any appreciable time lag. ruments of this type consist of a wattmeter element and of a time ele- The curve-drawing pointer is actuated either directly by the motion of

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the moving part of the wattmeter element, or indirectly by a system of solen or a small motor, energized through relay contacts on the wattmeter moving p The purpose of the time element is to produce a steady motion of the paper the point where the curve-drawing pointer (pen) is in contact with it. T clock, which turns the paper rolls, is either of the hand-wound type or of t electric self-winding type. In several types the rate of the paper feed may t varied from ¾ inch per hour to as high as 6 inches per minute.

Semi-portable forms of graphic wattmeters are on the market, but the m accurate instruments are for switchboard use only. Large errors due to fricti between paper and curve-tracing pen or pointer, or due to change in level of t instrument, are not uncommon with certain types of graphic wattmeters.

PRECAUTIONS IN USE OF WATTMETERS. — In addition to t general precautions given under *Ammeters* (p. 37), the following special pa must be noted. A wattmeter has three distinct limits, namely, current, volta and power, no one of which should be exceeded. The potential of the movi coil must not be greatly different from that of the fixed coil, and the connecti must always be such as to ensure this condition, both in the use and in t checking of a wattmeter. This precaution is especially necessary when a external multiplier is used for high voltages.

COSTS, WEIGHTS AND DIMENSIONS OF WATTMETERS. — of 1920). — The following figures give a rough idea of the cost of wattmeters

Indicating wattmeters	Portable	Switchb
Single-phase:	$	$
Small size, unshielded or partially shielded	45- 72	32- 35
Regular size, shielded, high grade	72- 141	...
Round pattern, 7-inch diameter	...	52 100
Round pattern, 9-inch diameter	...	69- 103
Horizontal edgewise	...	54- 72
Polyphase (two-element):		
Regular size, shielded, high grade	132-197	...
Round pattern, 7-inch diameter	...	75 115
Round pattern, 9-inch diameter	...	96 124
Horizontal edgewise	...	75- 87

Current transformers are required for single-phase switchboard wattmeters of the electrodynamic type when the current exceeds 200 amperes or the volta exceeds 600 to 750 volts. The upper limit of current for polyphase switchboa wattmeters of the electrodynamic type ranges from 60 to 200 amperes. Fo induction wattmeters as now made, both single-phase and polyphase, the cu rent limit is 10 amperes. Potential transformers are required for all curre ratings when the voltage exceeds 600 to 750 volts.

Switchboard wattmeters are made in 4-inch, 7-inch, and 9-inch round patter and in horizontal edgewise pattern occupying a space on the panel 6 by 8 inches and projecting 7.6 inches from the panel.

High-grade shielded portable single-phase wattmeters measure about 5 by 9 by 6 inches high, and weigh from 9 to 12 pounds; polyphase wattmeters of the same grade measure from 8 by 8 by 10 inches high to 9.5 by 10.5 by 8 inches high, and weigh from 14 to 17.5 pounds.

BIBLIOGRAPHY. — See the Bibliographies in the articles on *Ammeters* and *Watthour Meters;* also Robinson, L. T., *Metering on Three-phase Systems*, Gen. Elec. Rev., 1912, Vol. 15, p. 350.

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VE ANALYSIS. — (*See also Alternating Currents.*) Any sine func- y of a variable t, that is, any function of the form $y = Y \sin(\omega t + \phi)$, be plotted as a wave, as shown in Fig. 1. The constant Y is called the

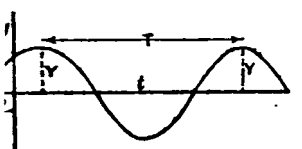


Fig. 1.

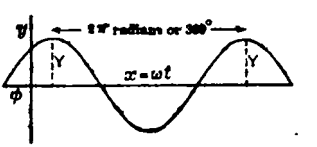


Fig. 2.

ximum value" of the wave, the constant ϕ the "phase" of the wave, and constant ω is called the "periodicity" of the wave. The distance between essive positive maxima (or between successive negative maxima) of such a e is called the "period" of the wave, and is usually represented by the ol T. The reciprocal of the period is called the "frequency," and is lly represented by the symbol $\frac{1}{T}$.

riod, frequency and periodicity are related as follows:

$$\omega = 2\pi f = \frac{2\pi}{T}.$$

he phase (ϕ) of the wave is also equal to the product of the periodicity by distance to the left of the origin at which the wave first crosses the t axis in ising direction; see Fig. 1.

plotting a wave it is usually more convenient to take as the distance along horizontal axis, not the value of the variable t, but the value of ωt. That is, ting $x = \omega t$, the equation for the wave may be written $y = Y \sin(x + \phi)$ Fig. 1 then reduces to Fig. 2. When the wave is thus plotted the distance ween successive positive maxima (or between successive negative maxima) qual to 2π radians or 360°, and the phase is the distance to the left of the in at which the wave first crosses the axis of x in the rising direction.

OURIER'S SERIES. — Any periodic function y of a variable t may be tted as a wave as shown in Fig. 3. If the function y and its first derivative h respect to t (that is, dy/dt) are finite l continuous for all values of t, then the ction y may be represented by a series of ns of the form

$$= Y_1 \sin(\omega t + \phi_1) + Y_2 \sin 2(\omega t + \phi_2) + Y_3 \sin 3(\omega t + \phi_3) + \text{etc.},$$

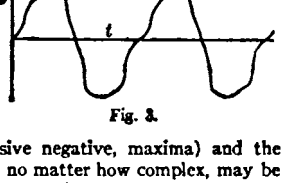


Fig. 3.

which $\omega = 2\pi/T$, where T is the period the given wave (i.e., the distance be- en successive positive, or between successive negative, maxima) and the and ϕ's are constants. That is, the wave, no matter how complex, may be resented by the sum of a number of sine waves whose frequencies are even ltiples of the period of the given wave.

This theorem is of great value in the theory of alternating currents (q.v.), ce any alternating current or voltage satisfies the above conditions. The ies is known as Fourier's Series.

As in the case of simple sine waves, it is usually more convenient in plotting

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ıe distance along the horizontal, not the variable t, but the value of ωt, putting $x = \omega t$, the series for y may be written

$$y = Y_1 \sin(x + \phi_1) + Y_2 \sin 2(x + \phi_2) + Y_3 \sin 3(x + \phi_3) + \text{etc.}$$

mental and Harmonics. — The first term of the series, which has y equal to that of the given complex wave, is called the fundamen ceeding terms, having frequencies which are multiples of the fundame ency, are called harmonics. For example, the third term, or the one ing this term, has a frequency three times that of the fundament erm or sine wave is called the third harmonic, etc.

complex wave is such that the successive positive values of y for half wave are numerically equal to the successive negative values o ucceeding negative half wave, only the *odd* harmonics occur. Such called a symmetrical wave. Voltage and current waves are usual ical, and therefore contain only the odd harmonics.

ERMINATION OF MAXIMUM VALUES AND PHASES O ARMONICS BY INTEGRATION. — Consider the nth harmonic

$$y = Y_1 \sin(x + \phi_1) + Y_2 \sin 2(x + \phi_2) + Y_3 \sin 3(x + \phi_3) + \text{etc.}$$

value of $u_n = y \sin nx$ between the limits $x = 0$ and $x = 2\pi$, and int resultant curve, by planimeter, between these limits 0 and 2π. C U_n. Similarly, plot the value of $v_n = y \cos nx$ between the limits x $= 2\pi$, and integrate the resultant curve, by planimeter, between the nd 2π. Call this area V_n. Then

$$Y_n = \frac{1}{\pi}\sqrt{U_n^2 + V_n^2}$$

$$\phi_n = \frac{1}{n}\tan^{-1}\left(\frac{V_n}{U_n}\right).$$

ıe wave length of the fundamental corresponds to 360°. If the wav only the *odd* harmonics, as is usually the case in current and volta *e preceding paragraph*), U_n and V_n need be plotted only between th nd π. Calling U_n' and V_n' the corresponding areas, then

$$Y_n = \frac{2}{\pi}\sqrt{(U_n')^2 + (V_n')^2},$$

$$\phi_n = \frac{1}{n}\tan^{-1}\left(\frac{V_n'}{U_n'}\right).$$

ıethod, though cumbersome, is applicable to the determination of th n value and phase of any harmonic.

HER-HINNEN METHOD OF ANALYSIS.— (*Elec. Journal, 190 age 386; Electrotechnische Zeitschrift, 1901, Vol. 22, page 396.*) Thi s quite simple when the wave contains only the fundamental and th h and seventh harmonics. When even harmonics are present, or whe st higher odd harmonics than the seventh, certain corrections must b Since voltage and current waves usually contain only odd harmonics ɔm contain higher harmonics than the seventh, the simple metho corrections is usually sufficiently accurate.

s Containing only the Third, Fifth and Seventh Harmonics. — nine the nth harmonic (n equals 3, 5 or 7) divide the base of a half

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into 2 n equal parts and measure the ordinates of the wave at the beginning of each of these sections of the base. Call these ordinates y_1, y_2, y_3 . . . y_{2n}, taking the y's positive if above the base line, negative if below. ll be zero, since the first section begins where the resultant wave crosses ase line.

en the ordinates of this harmonic at the points 1 and 2 are, respectively,

$$A_n = \frac{1}{n}[(y_2 + y_6 + \ . \ . \ . \ y_{2n-1}) - (y_3 + y_7 + \ . \ . \ . \ y_{2n-3})],$$

$$B_n = \frac{1}{n}[(y_2 + y_4 + \ . \ . \ . \ y_{2n}) - (y_4 + y_8 + \ . \ . \ . \ y_{2n-2})].$$

maximum value of this harmonic is

$$Y_n = \sqrt{A_n^2 + B_n^2},$$

the phase angle, calling the wave length of the fundamental 360°, is

$$\phi_n = \frac{1}{n}\tan^{-1}\frac{A_n}{B_n}.$$

hese formulas give the third, fifth and seventh harmonics (n = 3, 5 and 7 ectively). The fundamental is found by calculating

$$A_1 = -(A_3 + A_5 + A_7),$$
$$B_1 = y_0 + B_2 - B_4 + B_6,$$

re y_0 is the mid-ordinate of the half wave. Then

$$Y_1 = \sqrt{A_1^2 + B_1^2},$$
$$\phi_1 = \tan^{-1}\frac{A_1}{B_1}.$$

he equation of the given wave is then

$$Y_1 \sin(x + \phi_1) + Y_3 \sin 3(x + \phi_3) + Y_5 \sin 5(x + \phi_5) + Y_7 \sin 7(x + \phi_7).$$

e *effective* value of the given wave is

$$Y = \sqrt{\frac{Y_1^2 + Y_3^2 + Y_5^2 + Y_7^2}{2}},$$

d the *average* value is

$$Y_{av'ge} = \frac{2}{\pi}\left[Y_1 \cos\phi_1 + \frac{1}{3}Y_3 \cos 3\phi_3 + \frac{1}{5}Y_5 \cos 5\phi_5 + \frac{1}{7}Y_7 \cos 7\phi_7\right].$$

In using the above formulas strict attention must be paid to algebraic signs.

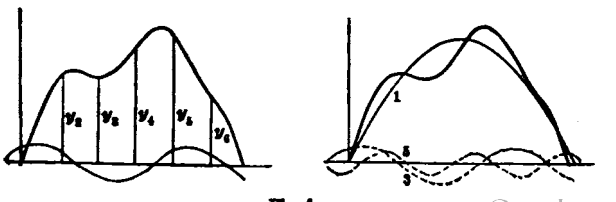


Fig. 4.

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Example. — Find the third harmonic in the wave shown in Fig. The values of the six ordinates are found by measurement to be 0, 676, 940, 1004 and 554 respectively. Then

$$A_3 = \tfrac{1}{3}(1004 - 660) = 114.7,$$
$$B_3 = \tfrac{1}{3}(676 + 554 - 940) = 96.7,$$
$$Y_3 = \sqrt{(114.7)^2 + (96.7)^2} = 150,$$
$$\phi_3 = \tfrac{1}{3}\tan^{-1}\frac{114.7}{96.7} = 16.6°.$$

Similarly, for the fifth harmonic,

$$A_5 = -92.8 \text{ and } B_5 = 37.4,$$
$$Y_5 = 100 \text{ and } \phi_5 = -13.6°.$$

For the fundamental,

$$A_1 = -114.7 + 92.8 = -21.9,$$
$$B_1 = 940 + 96.7 - 37.4 = 999.3,$$
$$Y_1 = \sqrt{(21.9)^2 + (999.3)^2} = 1000,$$
$$\phi_1 = \tan^{-1}\frac{-21.9}{999.3} = -1.25°.$$

Hence the complete expression for the given wave, taking as the origin point at which the resultant wave crosses the base line in the rising direction

$$y = 1000\sin(x - 1.25°) + 150\sin 3(x + 16.6°) + 100\sin 5(x - 13.6°).$$

The *effective* value is then 718 and average value 673.

Waves Containing Any Number of Harmonics, Odd or Even. — *Electric Journal*, 1908, Vol. 5, p. 386; and *Electrotechn. Zeit.*, 1913, Vol. 34, p.

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WEIGHTS (MASSES) OF MATERIALS. — (*See also Mechanics, Principles of.*) The density of any substance is the mass of that substance per unit volume. Or, using weight in the ordinary sense as equivalent to mass, the density may also be defined as the *weight* per unit volume. The numerical value of the density of any substance depends upon the unit in which the mass or weight is expressed and also upon the unit of volume used; see *Units and Conversion Factors*. However, it is quite common to state the density of a substance in grams per cubic centimeter, without naming the units, and when so expressed the density is numerically equal (practically) to the specific gravity.

The "specific gravity" of a substance is defined as the ratio of the weight (mass) per unit volume of that substance to the weight (mass), expressed in the same unit of an equal volume of water. To make such a statement exact the temperature of the water should be specified. There is no general agreement as to the temperature of reference, though water at 0° C. is commonly taken as the reference temperature. For gases, air at 0° C. and 760 mm. mercury pressure is frequently taken as the reference substance instead of water.

Variation of Density of Water with Temperature. — The following table gives the results of measurements by Thiesen, Scheel and Diesselhorst (*Landolt, Börnstein and Roth, Physikalisch-chemische Tabellen, 1913*).

DENSITY OF WATER; GRAMS PER CU. CM.

Degrees Cent.	0	1	2	3	4	5	6	7	8	9
0	0.99987	0.99993	0.99997	0.99999	1.00000	0.99999	0.99997	0.99993	0.99988	0.99981
10	0.99973	0.99963	0.99953	0.99940	0.99927	0.99913	0.99897	0.99880	0.99862	0.99843
20	0.99823	0.99802	0.99780	0.99756	0.99732	0.99707	0.99681	0.99654	0.99626	0.99597
30	0.99567	0.99537	0.99505	0.99473	0.99440	0.99406	0.99371	0.99336	0.99299	0.99262
40	0.99224	0.99186	0.99147	0.99107	0.99066	0.99025	0.98982	0.98940	0.98896	0.98852
50	0.98807	0.98762	0.98715	0.98669	0.98621	0.98573	0.98525	0.98475	0.98425	0.98375
60	0.98324	0.98272	0.98220	0.98167	0.98113	0.98059	0.98005	0.97950	0.97894	0.97838
70	0.97781	0.97723	0.97666	0.97607	0.97548	0.97489	0.97429	0.97368	0.97307	0.97245
80	0.97183	0.97121	0.97057	0.96994	0.96930	0.96865	0.96800	0.96734	0.96668	0.96601
90	0.96534	0.96467	0.96399	0.96330	0.96261	0.96192	0.96122	0.96051	0.95981	0.95909
100	0.95838	0.95765	0.95693	.....	.....	.....	.....	.....	.....	.....

* Example: The density of water at 33° C. is 0.99473.

Weights per Cubic Foot and Specific Gravity. — In the following table are given the values of the density in pounds per cubic foot of the more commonly used substances. The specific gravity, or density in grams per cubic centimeter, corresponding to any weight per cubic foot w is equal to $w/62.43$; for the conversion factors necessary to convert these figures into densities for other units of mass and volume, see *Units and Conversion Factors*.

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SPECIFIC GRAVITY AND POUNDS PER CUBIC FOOT OF VARIOUS MATERIALS AT ROOM TEMPERATURES

Specific Gravities all referred to water at 0° C.

(See References at end of table)

Material	Lb. per cu. ft. From	Lb. per cu. ft. To	Average spec. grav.
Air* (2)	0.0809	0.00129	
Acetylene gas* (2)	0.0733	0.00117	
Aluminum, cast (1)	160	161	2.57
" wire (6)	168		2.70
Ammonia* (2)	0.0482	0.000771	
Antimony (1)	414		6.64
Asbestos (2)	125	175	2.40
Asphaltum (1)	69	94	1.30
Basalt (3)	176	181	2.86
Bismuth (2)	604	618	9.78
Brass (1)	511	542	8.45
Brick, red (3)	111	128	1.92
" fire (3)	110		1.76
Bronze (1)	545	555	8.80
Carbon (2)	125	144	2.15
" dioxide* (2)	0.124		0.00199
" monoxide* (1)	0.0782		0.00125
Caoutchouc (1)	57	62	0.955
Cement, loose (1)	72	105	1.42
" set (1)	168	187	2.85
Charcoal (1)	17	35	0.421
Clay, hard (3)	129	133	2.10
" soft (3)	118		1.89
Coal, anthracite (5)	81	106	1.50
" anthracite piled loose (5)	47	58	0.84
Coal, bituminous (5)	78	88	1.33
" bituminous, piled loose (5)	44	54	0.79
Coal, lignite (3)	52		0.83
Cobalt (2)	530	563	8.77
Coke (1)	62	105	1.34
" piled loose (5)	23	32	0.45
Concrete, 1:2:4 (3)	146		2.34
" 1:1½:3 (3)	139		2.23
" 1:3:6 (3)	156		2.50
Copper, cast (1)	549	558	8.87
" wrought (1)	552	558	8.90
" wire (1) (6)	555	558	8.89†
Cork (5)	15.6		0.25
Ebonite (1)	72		1.15
Flint (1)	162		2.61
German silver (1) (52 Cu+26 Zn+22 Ni)	527		8.44
Glass, common (1)	150	175	2.6
" flint (1)	180	280	3.7
Gold, cast (2)	1200		19.3
Granite (1)	125	187	2.5
Gravel (5)	90	147	1.9
Gutta percha (5)	61.1		0.980
Gypsum or plaster of Paris (5)	142	143	2.28
Hydrogen* (2)	0.00562		0.00009
Ice (1)	55	57	0.895
Iridium (2)	1399		22.4
Iron, pure (1)	490	492	7.86
" gray cast (1)	439	445	7.08
" white cast (1)	473	482	7.65
" wrought (1)	487	492	7.85
" steel (1)	474	494	7.76
Lead (1)	710		11.4
Leather, dry (1)	54		0.86
" greased (1)	64		1.02
Lime (5)	53	75	1.03
Limestone (3)	156	162	2.55
Loam (3)	65	88	1.23
Marble (1)	157	177	2.68
Masonry (5)	100	165	2.12
Mercury at 0° C. (1)	849		13.6
Mercury at 20° C. (1)	846		13.5
Mica (1)	165	200	2.9
Molybdenum (2)	524	536	8.5?
Mortar, hard (5)	103		1.75
Muck (3)	40	74	0.915
Mud (5)	80	130	1.68
Nickel (1)	540	550	8.75
Nitrogen* (2)	0.0782		0.00125
Nitrous oxide* (2)	0.0838		0.00134

* At a temperature of 0° C. and a pressure of 760 mm. mercury.

† This value has been adopted internationally as representing the average density at 20° C.; see reference.

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SPECIFIC GRAVITY AND POUNDS PER CUBIC FOOT OF VARIOUS MATERIALS AT ROOM TEMPERATURES

Specific Gravities all referred to water at ° C.

(See References at end of table)

Material	Lb. per cu. ft.		Average spec. grav.
	From	To	
Oil, cotton-seed (1)	60.2	....	0.962
" gasoline (1)	41	43	0.675
" lard (1)	57.4	....	0 920
" linseed (1)	58.8	....	0 942
" mineral, lubricating (1)	56.2	57.7	0.912
Oil, petroleum (1)	54.8	....	0.878
" turpentine (1)	54.2	....	0.873
" whale (1)	57.3	....	0.918
Osmium (2)	1400	....	22.5
Oxygen* (2)	0.0895	....	0.00143
Palladium (2)	686	749	11.4
Paper (1)	44	72	0.92
Paraffine (1)	54	57	0.89
Pitch (1)	67	....	1.07
Platinum (1)	1320	1350	21.4
Porcelain (1)	143	156	2.4
Pumice stone (1)	23	56	0.63
Quartz (1)	165	....	2.65
Rhodium (1)	686	755	11.5
Salt (5)	50	70	0.965
Sand (5)	90	120	1.68
Sandstone (1)	124	200	2.6
Selenium (2)	300	....	4.8
Silver (1)	650	657	10.5
Slate (1)	162	205	2.85
Snow, fresh fallen (5)	5	12	0.136
" wet compact (5)	15	50	0.520
Soapstone (1)	162	175	2.7
Steel (*see Iron*)	....	....	....
Sulphur (1)	120	130	2.05
Tantalum (2)	1040	....	16.7
Tar (5)	62.4	....	1.00
Tile, hollow terra cotta, building block (3)	26	38	0.51
Tile, flat and segmental arches (3)	31	45	0.608
Tile partitions† (3)	12	26	....
Tin (1)	455	....	7.29
Trap rock (5)	187	190	3.02
Tungsten (1)	1160	1190	18.8
Turf (5)	20	30	0.400
Water, max. density (2)	62.4	....	1.00
" sea (5)	64.0	64.3	1.03
Wax, bees (1)	60.5	....	0.965
Wood, ash (4)	45	47	0.737
" butternut (4)	28	....	0.448
" cedar (4)	37	38	0.600
" chestnut (4)	38	41	0.633
" cypress (4)	32	37	0.553
" elm (4)	35	36	0.569
" fir (4)	34	35	0.553
" hemlock (4)	25	29	0.432
" hickory (4)	53	58	0.890
" lignum vitae (4)	78	83	1.29
" mahogany (4)	32	40	0.577
" maple (4)	49	50	0.793
" oak (4)	37	56	0.715
" pine, white (4)	24	25	0.392
" " yellow (4)	34	45	0.633
" poplar (4)	24	27	0.424
" red wood (4)	30	....	0.481
" spruce (4)	25	32	0.457
" walnut (4)	38	45	0.619
Zinc (1)	428	448	7.10

* At a temperature of 0° C. and a pressure of 760 mm. of mercury.

† Including air spaces.

REFERENCES.—(1) *Smithsonian Physical Tables*, (2) *Physikalisch Chemische Tabellen*, Landolt-Börnstein-Roth; (3) *Investigation of Weights of Building Material*, Thesis, Mass. Inst. of Tech., 1913, Orr, S. W., and Muterspaugh, A. M.; (4) *Publications of Forestry Division, U. S. Dept. of Agriculture* Bulletin No. 10; Circular No. 32; Circular No. 115; (5) Trautwine, J. C *Civil Engineers' Pocket Book*; (6) *Copper Wire Tables*, Cir. No. 31, Bureau of Standards.

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G, ELECTRIC. — The heat of the electric current is used in ocesses for welding metals, both ferrous and nonferrous. The ıay be tabulated as follows:

lesignation	Varieties		Kind of current at weld
e welding	Butt welding		A-C.
	Spot welding		A-C.
	Seam (or line) welding		A-C.
: welding	Using discharge from static condenser		D-C.
	Using electro-magnetic discharge		D-C.
ng	Carbon arc		D-C. (though A-C. may be developed)
	Metal arc	With bare electrodes	Usually D-C. but occasionally A-C.
		With flux covered electrodes	Either D-C. or A-C.

APPLICATIONS OF ELECTRIC WELDING. — Arc Welded , good many years ago the Seamless Steel Boat Company of Wakefield uilt successful all-steel life boats in which the joints in the shell re welded by the carbon arc process before being pressed into ıe *Dorothea M. Geary*, a boat with a length of 42 feet and a width nd driven by a 50 horsepower gasolene engine, was built with most nting done by arc welding using bare metal electrodes. It was n Lake Erie in 1915.

the British Admiralty, using flux-covered electrodes, built an arc ton Cross Channel barge. It is 125 feet in length and 16 feet wide. re was built in France an arc-welded barge 65 feet long by 15 feet welding work was all done by women. In 1920 the *Fullagar*, a ster built by Messrs. Cammell Laird and Company, and entirely was launched at Birkenhead. The *Fullagar*, which is driven by an bustion engine of the type designed by the late Mr. H. F. Fullagar, of 10 knots and a length of 150 feet.

cases are mentioned as being of interest because the displacement of arc-welding for making the joints in the shell plating, foreshadows y immense field for arc welding.

y there is a very large amount of arc welding in ship construction In the space of this article their mere enumeration would be impospical may be mentioned: repairs of boilers, stern frames, stems, s, windlasses, shaft-brackets, rudder gudgeons, and fuel tanks. s, anti-submarine bulges have been attached to hulls and their

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ıell plates have been arc welded, such undertakings exceeding in magni-
ıe welding of complete vessels of moderate tonnage.
The Times Engineering Supplement," for April, 1920, Caldwell enumer-
follows the advantages of arc welding in ship construction:
With the elimination of marking off, drilling or punching, countersinking
ulking, a considerable economy in time and labor can be effected.
By the reduction in width of laps and size of butt straps a saving of from
per cent of material can be effected.
Welded joints can be made to withstand greater stresses than similar
joints, and can be made equal in strength to the ship plating.
Once the practice is standard a reduction in the weight of the shell plating
possible without reducing the safety factor.
A welded joint is oil and water tight up to its breaking point, whereas
and caulked joints are liable to leak badly at as low as 25 per cent of
ıtimate strength.
While these may be described as general advantages, there are specific
here electric arc welding possesses even greater attractions. For example,
sent expensive smith-work involved in making complicated knees, angle
frames, etc., can be replaced by notching, bending up, and welding the
ıt a fraction of the present cost, and it provides an ideal method of secur-
ngs, etc., to water-tight bulkheads without piercing them, and of making
ight joints round pipes, etc., where these have to pass through bulkheads.

Welding in Railway and Other Shops. — Several of America's great
s each employ many dozens of arc welding operators in repair work on
:ives and are thereby effecting great economies. In street railway shops
economies are obtained; as also in boiler shops, foundries, blast furnaces,
es, machine shops and mines.

ding in Manufacturing. — Not alone arc welding, but also (already on a
rge scale) resistance welding, are being applied in the manufacturing of
s of products of steel and other metals. The use of such methods is
ng at an enormous rate.

ding Steel Buildings. — In England the steel work of the roofs of several
uildings has been joined entirely by arc welding and the saving of time
ney as compared with riveting has been shown to be very great. This
r to be a very important field for electric welding, both arc welding and
ıce welding.

SISTANCE WELDING. — The art of welding metals by passing a
tage alternating current across the surface of contact of the metals to be
was worked out and made a commercial success by Professor Elihu
on in the 80's. This process, which is known as resistance welding, is in
ide use and is so familiar to all engineers that there is no occasion for
ıan the briefest review.
any given application of resistance welding, the engineering problems
relate chiefly to the design of machines for holding the parts, bringing
ıto suitable juxtaposition, regulating the mechanical pressure and rate of
e of the parts toward one another at various stages of the process of
; the metal at the surfaces of contact, arresting the process at the proper
, and the regulation of the current to the most suitable amount at all
of the process. Careful consideration requires also to be given to the
ıl shapes of the two surfaces to be brought together and of the proportions
parts in the neighborhood of these surfaces. For some applications the
sults are obtained by welding a third (and otherwise superfluous) piece of
to each of the two parts to be joined.

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Most metals in reasonable states of purity can be joined to one another by the resistance process. Welds can also be made between some alloys. Practically all grades of steel are readily welded. Different metals can also, in some instances, be welded to one another. The current, for resistance welding, is usually supplied from the low-voltage secondary of an alternating current transformer, but direct current might under certain circumstances be used to advantage.

Butt Welding. — When, in the resistance process, the parts to be welded to one another are "butted" together, the current passing through the entire section of metal near the weld, the term butt welding is often employed. In all resistance welding the heat is generated within the metal and not brought to it from the outside as in other processes.

Spot Welding. — When, in resistance welding, the current is passed transversely across two plates which it is desired to joint at many places (or spots) the term spot welding is employed. Spot welding has been employed for many years for thin plates of metal. It has recently been applied to the welding of steel plates of thicknesses up to one inch. This latter development is described more fully in a later paragraph.

Seam Welding. — When, in resistance welding, the point of introducing and carrying away the current moves along a line so as to make a continuous weld along that line, the term seam welding, or line welding, is employed.

SPOT WELDING OF THICK PLATES. —Spot welding of thick plates is an alternative to the long established process of riveting and bids fair to be very extensively employed in most kinds of work now using rivets. As important examples may be mentioned the construction of steel ships, steel buildings and, in general, in many uses of structural steel. Where the parts can be brought to the welding machine, the process is especially attractive. But portable spot welders have been developed and have been used with success in ship construction.

Duplex Spot Welder. — (Fig. 1). — The usual construction of commercial spot welders for use in shipbuilding is similar in general appearance to so-called bull-riveters. The largest spot welder yet built for actual use in ship fabrication has a six-foot gap and operates from a 60-cycle circuit. This outfit is a stationary machine in the frame of which two transformers are incorporated and to which the steel plates and shapes are brought. Bulkheads, frames, floors and other parts are constructed with it, and are then transported by cranes to their places in the ship. This six-foot-gap machine has the capacity to weld two three-quarter-inch-thick plates. It provides a pneumatic pressure of 60,000 pounds and a current of 50,000 amperes. It is called a duplex welder and welds simultaneously two spots, each of some 1.5 inch diameter, in about 30 seconds.

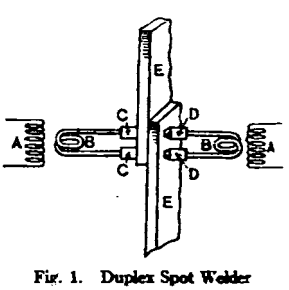


Fig. 1. Duplex Spot Welder

The arrangement is shown diagrammatically in Fig. 1. The outfit comprises two transformers, one located on each side of the plates to be welded. The current crosses the plates in one direction between two electrodes and then back again between two other electrodes. Thus the two secondaries and the two joints make four elements connected in series.

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represent the two primaries.
represent the two secondaries (which, in the actual construction, ...ve only one turn each).
and *DD* represent water-cooled, copper electrodes.
represent the two plates to be joined.

above-described duplex feature was introduced in this spot-welder to se the inductance of the long loop of conductor which otherwise would been necessary and which would have involved proportioning the trans- secondary for a higher voltage to overcome the inductive drop.

table Spot Welder. — Fig. 2 is a diagram of the circuits of an ordinary ex) spot welder which welds only one spot at a time. In this figure:

presents the primary of the transformer.
presents its secondary.
id *D* represent water-cooled copper electrodes.
id *F* represent the two plates to be welded.

ypical 60-cycle portable welder of this type ving a 27-inch gap weighs only 2800 pounds, ng the transformer (which is embodied in the ire), and welds plates of a thickness of half h with a current of about 30,000 amperes. quired pressure for such work is some 25,000

experimental work, currents up to 100,000 s have been employed in improvised spot g machines, and pairs of one-inch-thick steel have been welded.

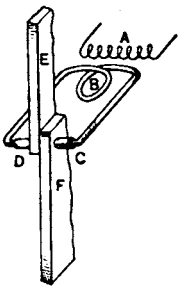


Fig. 2. Simplex Spot Welder

ght Car. — Although until very recently elding has generally been employed only for thin plates, mention should be made of the 50-ton gondola freight ich was completely spot welded in 1911 by Mr. J. A. Osborne, Chief er of the American Car and Foundry Company of St. Louis, Mo. ince that time, this car has been in regular service on the C. B. & Q. y. In 1918, Mr. Osborne reported that the welded joints have suc- y withstood the severe stresses of continuous hard use. The spot built by Mr. Osborne in 1911 for this undertaking was demonstrated to ible of making sound welds with plates of ¾-inch thickness. It had a throat and housed an 85-kw. transformer with a secondary giving s on open circuit. The welding points of the copper electrodes had a er of ¾ inch.

Welding Versus Riveting. — Spot welding would appear to have l advantages over riveting for a great variety of important work now done by riveting. By employing spot-welding great savings are l through eliminating the laying out and punching of the rivet holes, e subsequent reaming when the holes do not match up. Furthermore s avoided the reduction in cross-section and strength occasioned by the ty for the rivet holes. With spot welding there is a great saving in al through the reduction in overlap made practicable as compared with) or three rows of rivets which often have to be employed. Tests show eater strength can be obtained with a single row of spot welds than with ıt triple riveting.

ed of Spot Welding. — At p. 175 of Vol. 38 (1919) of the Trans. A.I.E.E., hn Martin of the American Bureau of Shipping reports as follows:
one test performed in the writer's presence, 32,000 amperes with a volt-

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age of 4, successfully spot-welded pairs of ⅝ inch to 2.5 inches ship steel plates together, the diameter of the spots being 1 inch, the pitch 3 inches, and the hydraulic pressure 7½ tons. The time of the current was 15 seconds. 15 feet was welded in 30 minutes. The spots sheared at 56,000 pounds, or partly pulled and sheared at 60,000 pounds. Water and oil-tight joints resulted without calking. For plates of the same pitch, calking or arc fillet welds would be required for water-tight joints; though by lessening the pitch and decreasing the diameters of the spots, practically the same water-tight results could be had."

Power Required for Spot Welding. — In a paper entitled *Practical Applications of Electric Welding*, read by F. P. Vaughan on October 15, 1920, before the Engineering Institute of Canada, the following table of data applying to the spot welding of mild steel plates is given:

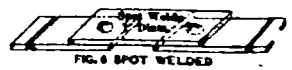
Thickness of plates, S.W. gage	Total welded thickness, inch	Power, kw.	Time, seconds
24	0.044	4.3	0.6
22	0.056	4.6	0.8
20	0.072	4.7	1.0
18	0.096	5.3	1.2
16	0.128	6.3	1.8
14	0.160	6.6	1.8
12	0.208	8.0	2.5
10	0.256	9.0	3.0

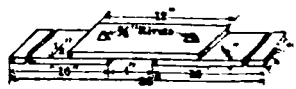
Spot Welding Combined with Arc Welding. — Arc welding (described later) may be used in combination with spot welding, the former being relied upon not only for calking but to contribute to the total strength of the weld. Some tests comparing ordinary riveted joints with this method of spot and arc jointing are described at page 95 of Vol. 38 (1919) of the Trans. A.I.E.E. as follows:


FIG. 3 FILLET AND SPOT WELDED


FIG. 4 FILLET WELDED


FIG. 5 RIVETED AND FILLET WELDED


FIG. 6 SPOT WELDED


FIG. 7 RIVETED JOINT

The specimens were made up of the following combination:

1. Spot and fillet welded, Fig. 3 (two samples made).

2. Fillet welded—made by welding fillets about two inches in length at the ends of the plates, Fig. 4 (two samples made).

3. Riveted and fillet welded, Fig. 5 (one sample made).

4. Spot welded—made by welding two spots approximately one inch in diameter, on the plates, Fig. 6 (two samples made).

5. Riveted joint, made by riveting a 0.5-inch by 4-inch by 12-inch plate with two plates 0.5-inch by 4-inch by 16-inch, using two ¾-inch rivets and a 4-inch lap. Fig. 7 (one sample made).

esults of the test show the comparative strength of the joints as follows:

	Ultimate load, Pounds
ınd fillet welded (average of tests on two samples)	50,350
welded (average of tests on two samples)	37,500
d and fillet welded (only one sample made)	35,000
relded (average of tests on two samples)	28,000
d joint (only one sample made)	13,000

Use of Resistance Welding. — At p. 146 of Vol. 38 (1919) of the .I.E.E., Mr. Hermann Lemp, a pioneer in resistance welding, in compar- ance welding with arc welding (described later), writes as follows:

ı one considers the vast quantities of mild steel products daily welded iited States alone (by the resistance process of Professor Elihu Thomson) , with unskilled persons operating automatic and semi-automatic y, with a speed unexcelled by the arc-welding process, the writer may ned for drawing attention to one characteristic feature of the process; that parts to be welded are substantially protected against contact oxygen of the air, and what few oxides may be formed near the edges ively squeezed out of the joint by the pressure exerted on completing

In addition, all kinds of metals and alloys, some of which are termed le, are successfully welded thereby. Crane chains, harness rings, le rims, bicycle tubing, wire fences, carriage tires, metal wheels, etc., d daily in such quantities as would astonish any one when confronted ıal figures. In the welding of valve flanges to cylinders of Liberty motors at Detroit, the Thomson Process (of resistance welding) easily the gas and electric-arc processes, as regards both speed and excellence l product."

D OF BUTT WELDING BY RESISTANCE PROCESS AND T OF ELECTRICITY CONSUMED. — Mr. Vaughan gives ing table as applying to the butt welding of "ordinary bar iron, wheel ;, cycle rims, shafting and piping and various forms of rods, etc." by ınce process.

ection of metal at the weld, square inches	Approximate power consumption		
	Maximum kw. per weld	Duration of weld, seconds	Kw.-hr. per weld
0.25	10	15	0.075
0.50	15	20	0.13
0.70	20	30	0.2
1.0	25	35	0.3
2.0	40	60	0.7
3.0	50	90	1.25
5.0	65	208	3.75
7.0	80	315	7.0
9.0	95	400	10.5
10.	105	428	12.5
11	115	453	14.5
12	125	475	16.5

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For butt welding round copper rods by the resistance process, Mr. Vaugh values are:

Size		Power, kw.	Time, seconds
Diameter, inches	Area, square inches		
¼	0.05	5	4
⅜	0.11	7	5
½	0.20	14	7
⅝	0.31	19.5	9
¾	0.44	28	12
⅞	0.60	35	14
1	0.79	48	17
1⅛	0.99	63	21

SEAM (OR LINE) WELDING. — A seam welder may be so desig as to have the weld made between a wheel rolling on a bar, or between t wheels rolling together. For thick plates, the design with two wheels roll together is probably the most suitable. Mr. R. E. Wagner, who has had w experience in the design and use of seam welders, has given the writer the follo ing tabulated data applying to the seam welding of mild steel plates:

Thickness of each plate, inch	Speed making line weld, in feet, per minute	Corresponding current, amperes	Pressure in pounds per square inch
0.0140	5	3500	2,200
0.0625	2.5	7000	13,000
0.0938	2.5	8000	22,500

In the above table the pressure is calculated on the basis of having a contac area in each case of 1/32 square inch.

The voltage of the welding circuit on open circuit may vary from 2 to 10 volt depending upon the impedance introduced into the welding circuit by its desig The actual drop across the weld will vary between ¼ and 1 volt. The plat at the line of welding must be free from scale and rust. A properly mad seam weld has a strength at least equal to that of the plates which are welde together.

PERCUSSIVE WELDING. — Mr. L. W. Chubb invented the process o percussive welding in 1905.

Percussive Welding with Static Condenser. — At that time the method consisted in discharging a static condenser simultaneously with the delivering o a percussive blow in a direction to force together the two metal parts to be welded The process was applied chiefly to welding together relatively small wires, th largest being No. 12 B. & S. gauge. The ends of the wires are cut with suitabl

ters and the resulting chisel edges arranged to make a right-angle inter- thus starting the discharge of energy at a central point of contact. urrent density is stated to be about 400,000 amperes per square inch. xcess is suitable for welding together wires of utterly different material platinum to lead, tungsten to aluminum, and aluminum to copper.

romagnetic Percussive Welding. — More recently an electromagnetic of percussive welding has been developed by Mr. Chubb and is adapted heavy work. Stored up electromagnetic energy is released under such is as to establish a short arc between the surfaces to be welded. This iversed by a very heavy current for less than a tenth of a second and in that time to melt these surfaces. They are immediately forged by a hammer blow. The secondary current approximates 30,000 per square inch at an arc drop of from 20 to 40 volts, and it only flows ll fraction of a second. The heat is so localized that the weld is effected expenditure of a minimum of energy. It is claimed that the energy l per weld is only a very small part of that required in resistance weld- th the electromagnetic process of percussive welding parts up to ½ ieter are readily welded and it is anticipated that the method will soon ped to be applicable to much larger welds.

of Application for Percussive Welding. — It is claimed that percus- ing permits of readily welding together very unequal sections, since duration of the process precludes difficulties due to unequal heating n or difference in melting points. For example, small rods may be heavy plates. In tool manufacture, steel alloys may be welded to l steel. Brass and copper parts may, by the percussive process, be steel parts. Percussive welding has been described in more detail er presented by Mr. Chubb before the American Electrochemical October, 19 nd more recent developments have been described . F. Miner before the A.I.E.E., in June, 1920.

TRIC ARC WELDING. — The technique of electric arc welding cally nothing in common with that of butt and spot welding, although lly identical objects are in some cases obtained by both methods. wever, the associated circumstances will indicate which of the two lectric welding should be employed. While butt welding and spot re applicable to almost all kinds of metals, electric arc welding is nfined to the welding of steel.

ntering upon the consideration of electric arc welding, it should be it that it is one of the two main subdivisions of an art which is often **autogenous welding**, but which will here be designated **fusion**

Welding. — The term fusion welding is employed to comprise gas nd electric arc welding. Gas welding does not come within the scope icle, and it must suffice to state that the process in its simplest form simultanelusly fusing with an oxyacetylene flame (1) the material r the surfaces which it is desired to join, and (2) some material (which similar in composition) in the form of a rod, the tip of which is sub- the heat of the flame. The oxyacetylene flame is directed with one the welding rod is manipulated with the other hand.

of Electric Arc Welding. — Electric arc welding may be subdivided al classes. The two broadest classes are:

a. Carbon arc welding.
b. Metal arc welding.

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In carbon arc welding, an arc (usually several tenths of an inch in length established between a carbon or graphite electrode (usually a carbon electrode and the two pieces of steel which it is desired to join. This carbon electrode manipulated with one hand and a welding rod is fed into the weld by the other hand. The manual activities in carbon arc welding are seen to be quite similar to those in gas welding. In neither case is it necessary for the material of the welding rod to traverse the arc.

In metal arc welding, there is a fundamental difference in this latter respect since in metal arc welding of mild steel, instead of having a carbon electrode for one terminal of the circuit, the arc is established between a steel welding rod (or welding electrode) and the two steel parts requiring to be joined. There is always a distance of preferably not over one-tenth of an inch between the end of the welding rod and the work. This distance is bridged by an electric arc.

Kinds of Work Not Requiring Welding Rod. — Both for carbon arc welding and gas welding, the edges of the parts to be joined sometimes may be so designed as to obviate the need for any additional material; in other words no welding rod is necessary in such cases. In Fig. 8 is shown a case where it is not necessary to use a welding rod, since it suffices to simply melt the adjacent flanges with an arc.

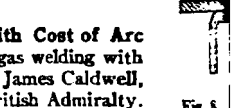


Fig. 8.

Comparison of Cost of Gas Welding with Cost of Arc Welding. — Quite a thorough comparison of gas welding with metal arc welding was made in 1917 by Major James Caldwell, then of the Controller's Department of the British Admiralty. This comparison is reproduced at p. 85 of Vol. 38 (1919) of the Trans. A.I.E.E. Since that date there has been a great deal of careful study given to the subject. For thoroughly first class welds, the speeds formerly credited to gas and arc welding are not obtained even by the most skilful operators. The author has made every effort to arrive at reasonable values for the various data involved and has compiled the results in the following table as representative of his opinion. The table indicates that gas welding has the advantage over metal arc welding for plates of 1/16 inch thickness, both as regards speed and cost. From 1/8 inch to 3/4 inch thickness, the author credits both methods with the same speed, but the advantage as regards lower cost increases rapidly for the metal arc method with increasing thickness of plate. For thicknesses of 7/16 inch and 1/2 inch both speed and cost are very decidedly in favor of metal arc welding. The costs (1921 basis) by the two methods are plotted in the curves in Fig. 9. Plenty of authority can be found for differing with the present author's results, since speeds over twice as great as those in the table have often been claimed by welding specialists as being representative. The speeds in the table are such as can be maintained by a fairly skilled welder during an eight-hour day and under thoroughly favorable conditions. The plates to be welded are assumed to be laid flat and at a convenient height for the operator to work. It is also assumed that the edges have been prepared and that the plates are clamped and all ready for welding. As regards the consumption of electricity it is assumed that the welding is done from a 110 volt circuit with a rheostat in series with the electrode. With a motor generator set the consumption would not be enough different to much affect the aggregate cost of (1) electricity, (2) electrodes, and (3) labor.

Welding Machinery. — The voltage at the arc is only some 15 to 20 volts, consequently while welding, some 85 per cent of the electricity consumed is wasted in the rheostat when operating from a 110-volt circuit. By interposing a motor-generator set transforming to lower voltage, the efficiency while welding may be considerably increased notwithstanding the losses in the motor

Thickness of metal in inches	Oxy-Acetylene							Metal arc (bare electrodes)					
	Cubic feet of gas per hour		Speed of welding, feet per hour	Component costs, cents per foot run			Total cost, in cents per foot run	Speed of welding, feet per hour	Kw.-hr. per foot of weld	Component costs, cents per foot run			Total cost, cents per foot run
	Oxygen at 2 ½ cts.	Acetylene at 2 ½ cts.		Gas	Iron wire 12 cts. per pound	Labor 80 cts. per hour				Electricity 3 cts. kw.-hr.	Electrodes 12 cts. per pound	Labor 80 cts. per hour	
1/16	6	5 ½	24	1.2	0.3	3.3	4.8	16	0.20	0.6	0.4	5.0	6.0
1/8	13	12	13	4.8	0.6	6.2	11.6	13	0.35	1.1	0.7	6.2	8.0
3/16	19	17	10	9.0	0.9	8.0	17.9	10	0.60	1.8	1.2	8.0	11.0
1/4	30	27	8	17.8	1.1	10.0	28.9	8	0.80	2.4	1.6	10.0	14.0
5/16	36	32	6	28.5	1.3	13.3	43.1	6	1.10	3.3	2.2	13.3	18.8
3/8	40	36	4 ½	42.2	1.5	17.8	61.5	4 ½	1.45	4.4	2.9	17.8	25.1
7/16	43	39	3	68.3	1.7	26.6	96.8	3 ½	2.00	6.0	4.0	22.9	32.0
1/2	45	41	2 ½	86.0	1.9	32.0	119.9	3	3.00	9.0	6.0	26.7	41.7

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generator set. But in the intervals between welds there are no losses with t former outfit, while with the latter outfit the running light losses in the mot generator set detract from the "all-day" efficiency. It will be readily s

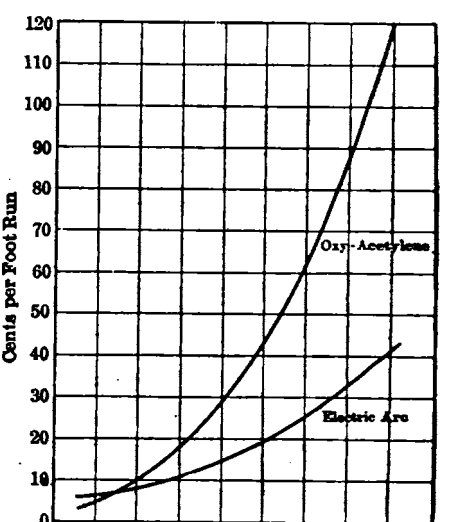


Fig. 9.

that all the attendant circumstances must be taken into consideration in det mining upon the most suitable plant to install for arc welding.

Each of several manufacturers has placed on the market types of weldi apparatus with characteristics for which advantages are claimed and realiz Even brief descriptions would occupy too much space for this article. Furth more it is the author's opinion that substantially equally good arc welding c be done with any of the best known types of machines, and it resolves it down to a question of relative costs and economy of operation. These featu should be given careful comparative study before purchasing a welding plan but it is much more a question of economics than of obtaining the best weld This latter object depends chiefly on having good operators and good materia

With a-c. welding a transformer is employed, but while the efficiency is goo the power factor is very bad. This does not disqualify a-c. arc welding, bu should be taken into account in balancing the advantages and disadvantages.

Speed of Arc Welding and Energy Consumption. — The speeds of makin butt welds by the arc process with various thicknesses of steel set forth in th preceding table are not necessarily applicable to other than the material the employed and all the attendant circumstances. The attainable speed for firs class arc welds is a function of (1) the skill and disposition of the operator, (2 the kind of circuit from which he welds and the characteristics of the intermedi ary welding apparatus and the voltage, (3) the length of the arc which the opera

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olds (the shorter the arc, the better the work, but the slower the speed), he kind and quality of the electrodes employed, (5) the positions of the s to be joined (whether flat on a bench at a convenient height as the one me, or overhead or inaccessible as the other extreme), (6) the kind and ity of the steel to be welded, (7) the kness or size of the material to be ed, (8) the preparation of the edges surfaces.


Fig. 10



Fig. 11



Fig. 12

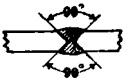


Fig. 13

an article by Mr. William Spraragen led *Speed of Metal Arc Welding*, pub- d at p. 44 of the *Welding Engineer* June, 1920, the author refers to Figs. 11, 12 and 13 as typical designs for led joints and, based on some exten- tests which he has made, suggests as age speeds capable of being sustained hours when welding half-inch thick ship plates, and allowing reasonable for changing electrodes and making minor adjustments.

Number of figure	Speed of welding
10	1.7 feet per hour
11	1.5 feet per hour
12	2.3 feet per hour
13	2.5 feet per hour

peed of Arc Welding in Pounds of Electrode Material Deposited Hour. — Spraragen states that the average results of a vast amount of show that an operator can deposit about 1.2 pounds of metal per hour n working out in the open (as on ships), with the usually attendant general nvenience and also the disadvantage of liability of air currents; as against ut 1.8 pounds of metal per hour in the shop. Both these figures are based he assumption that the work has been lined up and is ready for welding.

TIME, METAL AND CURRENT USED WITH WELDS OF DIFFERENT BEVELS

otal opening of bevel in degrees	30	60	90	120
ltimate strength in pounds per sq. in.	44,000	51,000	45,300	48,800
ngle of bend in degrees at which cracks first start	9	15	13	14
mperes	160	145	118	125
eight of electrode used up (pound)	2.56	3.83	4.63	6.63
eight of metal deposited (pound)	1.70	2.53	3.63	5.08
eight of metal wasted (pound)	0.86	1.28	0.98	1.55
ounds deposited per hour	1.82	1.61	1.82	1.81
eet welded per hour	3.22	1.90	1.50	1.07
ircuit kilowatts	9.91	9.00	7.68	8.25
ilowatt-hours per foot of weld	3.10	4.70	5.10	7.70
ounds deposited per foot of weld	0.57	0.85	1.21	1.69
ounds deposited per kw. hour	0.18	0.18	0.24	0.22
ounds of electrode used up per kw. hour	0.27	0.27	0.30	0.29

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Allowance for Waste of Electrode Material. — Based on researches involving the welding of ten tons of half-inch-thick ship plate, Spraragen has concluded that out of 100 per cent weight of electrode,

70 per cent is deposited in the weld,
12 per cent is burned or vaporized,
18 per cent is wasted as short ends.

Angle of Bevel of Welding Edges. — As to the effect of the preparation of the welding edges on the speed of welding and the quality of the weld, tests were made by Spraragen at the author's request. In each case ½-inch thick ship plate was used, and a weld 3 feet long was made in a flat position with 5/32-inch diameter bare electrode and a "free distance" of ⅛ inch. The welded plates were cut up and subjected to standard tensile and bending tests. The results are shown in the table at bottom of page 1955.



Fig. 14



Fig. 15

Preparation of Bottom Edges. — In Figs. 14 and 15, Spraragen shows two specimens of half-inch plate both prepared with 60-degree edges, and with the same "free distance" of ⅛ inch. In Fig. 14 the bottom edges are sharp, while in Fig. 15 shoulders are provided. The results were:

Fig. No.	Speed of welding, feet per hour	Pounds of electrode wire needed per foot of weld	Pounds of electrode wire used up per hour
14	2.3	1.1	2.5
15	2.8	0.9	2.5

Wagner's Tests of Relation of Speed to Current. — With skilled welders the speed of arc welding may be increased considerably when larger currents are employed. Also, up to a certain value, the strength of the weld is greater the greater the current. This is brought out by Mr. R. E. Wagner in a series of tests on ½-inch tank-steel plates. The plate edges were prepared with

Current in amperes	Size of electrode, inch	Tensile strength in pounds per sq. in. after grinding off the raised parts of the welds
80	5/32	37,000
125	5/32	50,000
150	5/32	57,000
180	5/32 and 3/16	63,000
220	5/32 and 3/16	66,000
275	3/16	62,000
300	3/16	58,000

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le V. Two sizes of Roebling electrodes were used, 5/32-inch and 1
pressure was maintained constant and the d-c. current was vari
mperes up to 300 amperes.
results are shown in the
ding table.
e type of joint is illus-
d in Fig. 16 under the
plotted with currents as
ssæ and tensile strength
rdinates. Wagner stated
"reduction in tensile
gth beyond 220 amperes
e apparently to the in-
ed porosity of the de-
ed metal and difficulty
manipulation." For a
complete record of Mr.
ner's investigations ref-
e should be made to pages 157 to 160 of Vol. 38 (1919) of
E.E.

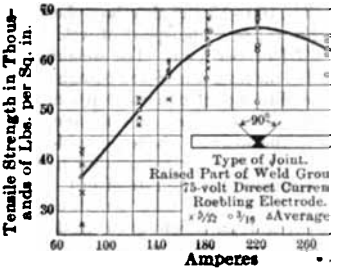


Fig. 16. Tensile Strength versus Current
Welding.

rther Data of Speed and Cost of Arc Welding with Bare Ele

n a 1920 General Electric Company bulletin the following data are
speed and cost of metal arc welding with bare electrodes and of gas

Metal arc welding			Comparative cost per foot for acetylene welding
Thickness of plate, inch	Speed, in feet per hour	Cost per foot, cents	
1/16	20	2.1	1.8
1/8	16	3.1	4.7
1/4	10	7.1	13
3/8	6.5	12	36
1/2	4.3	20	Much higher
3/4	2.0	42	Much higher
1	1.4	61	Much higher

uitable Size of Electrode and Current for Various Thickne
el. — In the following table Spraragen gives representative value
of electrode and the current to be employed in welding mild steel

Electrode diameter, inch	Plate thickness, inch	Amperes
1/16	up to 1/8	25 to 40
5/32	up to 1/4	50 to 90
1/8	3/16 to 1/2	75 to 160
5/32	3/16 up	125 to 200
3/16	1/2 up	175 to 250

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Data of Speed and Cost of Welding a Large Steel Tank with Bare Electrodes. — In 1918, Wagner welded a 12-foot-cube tank of half inch steel and purposely employed a great variety of types of joint including those already shown in Figs. 10 to 13 and also those shown below in Figs. 17 to 20, and a number of other types. The speed of welding was 3.0 feet per hour. The weight of the steel in the tank was 16,000 pounds, and the weight of electrode used up was 334 pounds, of which 299 pounds was deposited in the welds. The total welding time was 165 hours, corresponding to using up electrodes at the rate of just 2 pounds per hour. The total length of weld was 501 feet, the weight of electrode used up per foot of weld thus being 0.60 pound. 0.29 pound of welding wire was deposited and 0.33 pound was used up per kilowatt hour of electricity. The diameter of the welding wire was 5/16 inch. Six different operators worked on the job and the average current per operator (when actually welding), was 13 amperes. The per cent of time welder was welding was ascertained to be 6 per cent.



Fig. 17



Fig. 18

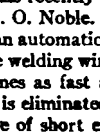


Fig. 19

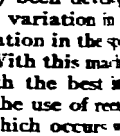


Fig. 20

Automatic Arc Welding. — Machinery has been developed permitting automatically feeding the welding wire at such a rate as to maintain a steady and very short arc. A direct current type has recently (1920) been developed for the General Electric Company by Mr. P. O. Noble. Any variation in the length of the arc is immediately corrected by an automatic alteration in the speed of the motor controlling the rate of feed of the welding wire. With this machine the speed of welding is from two to five times as fast as with the best hand operators. Time lost in changing electrodes is eliminated by the use of reeled welding wire. This also eliminates the waste of short ends which occurs with hand welding with the usual 18-inch straight welding rods. As further advantages may be mentioned the even deposit of the electrode metal which minimizes defects and produces uniform welds which are stronger and more effective than with the hand process. The uniform arc and uninterrupted feed reduce the power consumption.

At pages 150 to 157 of Vol. 38 (1919) of the Trans. A.I.E.E., Mr. H. D. Morton describes his work in the development of automatic and semi-automatic arc welding machinery and gives illustrations of a semi-automatic machine and of some work done with it.

Flux-covered Electrodes. — In America practically all metal arc welding is done with bare-wire electrodes. In England, on the contrary, flux-covered electrodes are much the most extensively employed. The limits of space will not permit describing the nature and variety of the flux coverings employed.

From the lack of interest displayed in America on the subject of flux-covered electrodes, it may be inferred that for the great bulk of electric arc welding entirely adequate results are obtained by the much cheaper bare electrode. The author's opinion is, however, that a higher grade of work can be obtained by the use of suitable flux-covered electrodes in the hands of operators skilled in their use. Especially with respect to ability to withstand tests of their ductility and to withstand fatigue tests he believes that welds can be made with flux-covered electrodes which can probably not be equalled with bare wire electrodes. It would not appear that this justifies the greater outlay, for ordinary

:. The use of electrodes with other than the very best flux-coverings may y lead to welds much inferior to those obtained with bare electrodes of good ity.

ıe present (1921) cost of flux-covered electrodes ranges from 60 cents per ıd for electrodes with steel cores of ⅛-inch diameter down to 40 cents per ıd for those of 0.16-inch diameter. Taking a mean value of 50 cents per ıd of steel in the electrodes, and assuming for the speed of welding, quantity ectrodes and amount of electricity per foot of weld, the values taken in table previously given for bare electrodes, there results for the cost per in the two cases the following values:

COMPARATIVE COSTS OF MANUAL BUTT WELDING FOR VARIOUS THICKNESSES OF MILD STEEL

Thickness of metal, inches	Speed of welding, feet per hour	Outlay in cents per foot of weld, for (1) electricity, (2) electrodes, and (3) labor	
		Using bare electrodes	Using flux-covered electrodes
1/16	16	6.0	7.3
1/8	13	8.0	10.2
3/16	10	11.0	14.8
1/4	8	14.0	19.0
5/16	6	18.8	25.7
3/8	4 1/2	25.1	34.2
7/16	3 1/2	32.9	45.5
1/2	3	41.7	60.7

D-C. and A-C. Electricity for Arc Welding. — Arc welding is, in America, ıally done with d-c. electricity. In England a-c. electricity is in much greater than in America for arc welding. It is more difficult for the welder when . is used, especially when he employs bare electrodes. But with some kinds flux-covered electrodes, a-c. may be used without any notable difficulty in nipulation as compared with direct-current. When a-c. is used, every pre- ution should be taken to guard the operator from shock, notwithstanding the r voltage employed.

Comparison of Strengths of Riveted and Arc Welded Joints. — p. 870 of the *General Electric Review*, for December, 1918, Mr. H. Jasper Cox Lloyd's Register of Shipping, published the following tabular comparison of : tensile strengths of riveted and arc welded joints of ship plates of half-inch d three-quarter inch thickness,

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Thickness, inches	Diameter of rivet, inches	Total sectional area, square inches	Breaking stress, pounds per square inch	Strength of plain plate, pounds per square inch	Percent strength of joint
		Triple-riveted lap joints			
0.49	¾	.....	42,400	61,400	69.0
0.53	¾	.....	38,300	54,700	61.5
		Lap weld with full fillet at both edges			
0.514	.....	10.02	45,300	63,600	71.0
0.73	.....	8.76	40,330	59,600	68.0
		Butt weld (not strapped)			
0.505	.....	10.66	61,000	63,600	96.0
0.76	.....	9.88	54,680	59,600	91.5

Comparative Costs of Joining Ship Plates by Riveting and Welding. The following are British figures and would not necessarily apply in America but they give a good illustration of tendencies. They are taken from an article by Caldwell in *The Times Engineering Supplement* for April, 1920.

Thickness of plate in inches	Description of joint	Diameter of rivets, inches	Cents per foot *
5/16	Single riveted lap	¾	43
	Light welded lap	.....	30
	Double riveted lap	¾	81
	Heavy welded lap	.....	40
½	Single riveted lap	⅞	51
	Light welded lap	.....	38
	Double riveted lap	⅞	91
	Heavy welded lap	.....	47
	Double butt strap	⅞	120
	Heavy butt weld	.....	47

* On the basis of one pound sterling = $4.

CARBON ARC WELDING. — Where carbon electrodes are used, the electrode is connected to the negative terminal of the circuit. The process is especially suitable for quick work requiring the melting of large quantities of material, such as in filling blow holes and in salvaging defective castings and forgings. It is also used for much other work, such as welding long seams which may be so designed with abutting edges as to permit of effecting the weld by simply fusing these edges without adding electrode material. An example of such a joint has already been given in Fig. 8.

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carbon arc welding the arc is very long (of the order of an inch or so), and considered that this entails the disadvantage that the weld may be badly ed.

rrent Employed in Carbon Welding and Size of Elec-s. — A reliable trade bulletin the accompanying data as ble values for the current for n arc welding.

Class of work	Amperes
Light welding	150 to 250
Medium welding	250 to 350
Heavy welding	400 to 600
Very heavy welding	600 to 1000

e same bulletin gives the ac-anying data for the maximum nt for carbon electrodes of var-izes.

Diameter of carbon electrode, inch	Maximum current, amperes
¼	100
½	300
¾	500
1	1000

ll higher currents can be used by employing graphite electrodes, but their r cost usually disqualifies them for use as welding electrodes.

eed of Carbon Arc Welding. — It is found that for depositing or build-p metal on flat surfaces where the work is accessible and under otherwise able conditions the following data hold:

Current in amperes	Pounds of metal deposited per hour	
	For continous work	For short jobs of 10 minutes or less
200	1.5	3
300	3.0	6
400	4.5	9
500	6	12

us carbon arc welding, in virtue of the higher current customarily employed, nuch faster process than metal arc welding.

utomatic Welding with the Carbon Arc. — Automatic machinery has in use for several years for welding together abutting flanges with the carbon With the kinds of joint shown in Fig. 8 it is not necessary to supply any ional metal. The carbon simply travels along parallel to the abutting es and the arc raises their temperature to the point where they flow together. rbon arc welding is usually performed with direct current but sufficient rch will probably lead to the development of successful welding with carbon rodes and an a-c. arc.

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In the Journal of the American Welding Society, first published in 1922, will be found recorded the most recent developments in Electric Wel

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ND PRESSURE. — *(See also Structures, Simple; Transmission Lines.)* d pressure is a subject upon which little exact information exists, although y experiments have been made and much study given to the subject by engi- s and scientists. Among the unsettled questions are:

The relation between pressure and velocity.
The variation of pressure with size and shape of exposed plane surfaces.
The direction and intensity of pressure upon non-vertical surfaces.
The intensity of pressure upon non-planar surfaces.
The total pressure upon a number of parallel bars or other members placed by side.
The decrease of pressure upon leeward surfaces.
The lifting power of the wind.

ELATION BETWEEN INDICATED (U. S. WEATHER BUREAU) ID VELOCITY AND ACTUAL VELOCITY.—The indications of the nometers used by the U. S. Weather Bureau do not give the *actual* wind city, but give values considerably higher than the actual velocities, as n in the following table:

LATION BETWEEN INDICATED AND ACTUAL WIND VELOCITY

Indicated Velocity, mi. per hr.	Actual Velocity, mi. per hr.	Indicated Velocity, mi. per hr.	Actual Velocity, mi. per hr.
10	9.6	60	48.0
20	17.8	70	55.2
30	25.7	80	62.2
40	33.3	90	69.2
50	40.8	100	76.2

n the U. S. Weather Bureau reports the indicated and not the actual wind cities are given. However, as the anemometers used give the *average* velocity several minutes, the instantaneous velocities due to sudden gusts may be siderably greater than the indicated velocities; the indicated velocity prob- y more nearly represents the "gust" velocity than the actual average velocity. ll calculations of maximum wind pressure it is therefore recommended that *indicated* velocity be used.

ELATION BETWEEN PRESSURE AND VELOCITY. — The pres- e varies about as the square of the velocity, the results given by different erimenters for the pressure due to a *normal wind on a plane surface* rang- from

$$P = 0.005V^2 \quad \text{to} \quad P = 0.0032V^2,$$

ere P = pressure in pounds per square foot,
V = actual wind velocity in miles per hour.

The latter of these values represents the results of unusually careful experi- nts by Stanton (*see Minutes of Proceedings of the Institute of Civil Engineers, ls. 156 and 171*) upon the intensity of pressure on plates varying in size from to 100 square feet and is probably more nearly correct than the higher value. the Stanton formula the values are reduced to correspond to a temperature 60° F. and an atmospheric pressure of 14. 7 pounds per square inch.

The influence of size and shape of exposed surface is an important question d is not well understood, although it is known that the resultant pressure a large surface may be taken as less per square foot than that on a small

surface, since the maximum intensity of the wind is due to gusts of comparatively small cross-section.

Formulas for Pressure on Plane Surfaces when Wind is not Normal. — The pressure upon vertical plane surfaces may be taken as normal to the surface and equal in intensity to the assumed wind pressure. Upon surfaces which are not vertical, the pressure is usually considered to be normal to the surface but lower in intensity than upon vertical surfaces. The variation in pressure with respect to the slope is not well understood and a number of empirical formulas are in use, among which are the Duchemin formula

$$P_n = P \frac{2 \sin i}{1 + \sin^2 i},$$

and the Hutton formula

$$P_n = P (\sin i)^{(1.84 \cos i - 1)},$$

where P = intensity of normal pressure upon the vertical surface,
P_n = intensity of normal pressure upon the given surface,
i = angle made by surface with the horizontal.

The following theoretical formula results from the assumption that the wind always blows in horizontal lines, and that if the pressure be resolved into normal and tangential components, the tangential component may be neglected:

$$P_n = P \sin^2 i.$$

This formula gives lower values than the empirical formulas and probably gives too low results since it makes no allowance for the reduction in pressure on the leeward side which is known to occur, and which may in part be attributed to the influence of the tangential component. It should also be noted that the wind does not blow uniformly in horizontal lines but may deviate considerably from the horizontal.

The values given by these three formulas are tabulated for comparison, with an assumed value of 30 pounds per square foot for P. In the absence of further experience upon this phase of wind pressure it would seem wise to use one of the empirical formulas instead of the theoretical one. The Hutton formula is used quite generally by structural engineers in England and the United States.

Pressure on Non-Planar Surfaces. — The pressure upon non-planar surfaces is important in the case of chimneys, standpipes, and other similar objects.

Upon the same assumptions as made in the preceding paragraph it may be demonstrated that theoretically the pressure on a cylinder is two-thirds of the total pressure on a plane diametrical section. This value is quite generally used. The pressures thus obtained lack experimental proof but are probably more nearly correct than the pressure obtained by the same method upon plane surfaces.

Effect of Reduction of Pressure on Leeward Side. — The pressure upon the windward side of an exposed surface is a function of the density and velocity of the air currents. The pressure on the leeward side is also a function of the shape of the surface, and has been shown by numerous experiments to be less than the static pressure of the air current. The resultant total pressure upon a surface is in consequence not only a function of the direct pressure on the windward side, but also of the pressure on the leeward side, which in turn is a function of the form of the surface. No algebraic formula can be given which will give the pressure on surfaces of varying shape with any considerable degree of precision.

Wind Pressure on Wires. — H. W. Buck (*Trans. Int. Elec. Cong. St. Louis, 1904, Vol. 2, p. 318*) gives the following formula for the pressure due to a normal wind on a stranded wire:

$$P = 0.0025 V^2,$$

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WIND PRESSURE IN POUNDS PER SQUARE FOOT

$P = 30$ pounds per square foot

Angle I, degrees	Theoretical $P \sin^2 I$	Duchemin $P\frac{2 \sin I}{1+\sin^2 I}$	Hutton $P(\sin I)^{(1.84\cos I - 1)}$
5	0.0	5.2	3.9
10	0.9	10.1	7.3
15	2.0	14.6	10.5
20	3.5	18.4	13.7
25	5.3	21.5	16.9
30	7.5	24.0	19.9
35	9.9	25.8	22.6
40	12.4	27.3	25.1
45	15.0	28.3	27.0
50	17.6	29.0	28.6
55	20.1	29.4	29.7
60	22.5	....	....
65	24.6	Above 60 deg.	Above 60 deg.
70	26.4	use 30 lb.	use 30 lb.
75	28.0		
80	29.1		
85	29.7		
90	30.0		

here P is the pressure in pounds per square foot of projected area of wire ength times diameter) and V is the velocity in miles per hour. This formula based upon tests made on a 950-foot span at Niagara Falls; the wind elocities were measured by a U. S. Weather Bureau anemometer corrected give actual average velocities.

PRACTICAL RULES FOR WIND PRESSURE ALLOWANCE. — he many uncertainties connected with wind pressure make worthless the ttempts to specify with precision its magnitude and direction. In the lack of dditional information and further theoretical studies there seems to be no eason for deviating from the common rules which have been used for many ears with satisfactory results.

Bridges. — The portal, vertical and horizontal bracing are usually proporioned for a wind pressure of 30 lb. per sq. ft. on the surface of the applied load, nd on the exposed surfaces of the floor system and both trusses. The pressure n the applied load is considered as a moving live load, and the other pressure is a dead load. For structures of ordinary spans the wind stresses are computed upon the unloaded structure for a pressure of 50 lb. per sq. ft. In the lesign the maximum stress computed by either of the above methods is used.

Buildings. — For wind pressure on roofs and buildings it is common practice to allow 30 lb. per sq. ft. acting horizontally upon the sides and ends of buildings, or on the vertical projection of roofs. It is also very important to figure the wind stresses on the steel frame considering it as an independent structure without walls, floors or partitions, since failures often occur in erection.

Transmission Poles and Towers. — For transmission towers a pressure as low as 13 lb. per sq. ft. has been used. This is perhaps warranted by the

fact that such towers are comparatively low and not exposed to the highest wind pressure. In the report of the Joint Committee on Overhead Line Construction (*Trans. N.E.L.A., 1911, Vol. 2, p. 521*) the following is recommended: "The wind pressure on the poles, or towers, shall be assumed at 13 lb. per sq. ft. of the projected area of solid or closed structures and 1½ times the projected area of latticed structures."

Wire Spans. — In the report of the Joint Committee just referred to it is recommended that the spans be designed for "a wind pressure of 8.0 lb. per sq. ft. on the ice-covered diameter (ice coating ½ inch in thickness), at a temperature of 0° F."

LIFTING POWER OF WIND. — In the case of a very rapid reduction of atmospheric pressure, as in a tornado, it is often observed that building roofs are lifted and walls blown outward. This phenomenon is due to the air in the building which is under more or less restraint, changing pressure less rapidly than the outside air and thereby producing a difference in pressure. This lifting action doubtless occurs to a greater or less degree whenever the external pressure is reduced, and should be guarded against by anchoring roofs securely to the walls.

BIBLIOGRAPHY. — *Minutes of the Proceedings of the Institute of Civil Engineers*, Vol. 156, 1903, and 171, 1907; Eiffel, *La Resistance de L'Air et L'Aviation*, Paris, 1911 (English Translation, by Hunsaker, Boston and London, 1914); Buck, H. W., *Trans. Int. Elec. Cong.*, St. Louis, 1904, Vol. 2, p. 315.

[C. M. Stofford.]

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RES AND CABLES, BARE. — (*See also Aluminum; Copper; Gages, es; Resistance and Conductance; Standardization Rules of the A.I.E.E.; s and Cables, Insulated; Wires, Resistance.*)
he following is a brief table of contents of this article:

Dimensions, Weights and Resistance of Wires and Cables:
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Copper Cables, A. W. G. (B. & S.) Gage 1969
Solid Copper Wire, A. W. G. Gage in Metric Units 1970
Copper Cables, A. W. G. Gage in Metric Units 1971
Solid Copper Wire, British Standard Gage 1972
Solid Copper Wire, Millimeter Gage 1973
Solid Copper Wire, Ohms per Unit Weight 1974
Solid Copper Wire, Weight per Ohm 1975
Solid Aluminum Wire, A. W. G. (B. & S.) Gage 1976
Aluminum Cables, A. W. G. (B. & S.) Gage 1977
Solid Aluminum Wire, A. W. G. Gage in Metric Units 1978
Solid Steel Wire, American Steel Wire Gage 1979
Copper-clad Steel Wire, A. W. G. (B. & S.) Gage 1981
Trolley-wire Standard Sections 1982
Factors Affecting Dimensions, Weight and Resistance of Stranded Wires 1982
Strength, Elasticity and Expansion Coefficient 1987
Current-carrying Capacity of Bare Wires 1990
Tests 1994
Specification for Annealed Copper Wire 1994
Specification for Hard Drawn Copper Wire 1996
Specification for Bare Concentric Copper Cable: Hard, Medium-Hard, or Soft 1998
Installation 2000

l wire may be either solid or stranded, i.e., made up of a number of smaller es twisted or braided together. A large bare stranded wire is usually called are cable. Data on the insulation and protection of wires and cables will found in the article on *Wires and Cables, Insulated*. Data on resistance es will be found in the article on *Wires, Resistance*, and data on the prop-ies of the various metals will be found in the articles on *Aluminum*, *Copper*, d *Steel*.

PER CENT CONDUCTIVITY. — The definitions, constants and tables in s article are all in accord with the 1920 edition of the *Standards of the A.I.E.E.* r cent conductivity refers to the "International Annealed Copper Standard." the assumption of a resistivity temperature coefficient of 0.00393 at 20° C. is per cent conductivity is only 0.283 per cent higher than the conductivity erred to Matthiessen's Standard (*see Resistance and Conductance*). If the gth of a given wire is L cm., its cross-section A sq. cm. and its resistance at ° C. is R_{20} ohms then the per cent conductivity of this wire is

$$C = \frac{15.328\,L}{88{,}900\,AR_{20}} \quad \text{per cent.}$$

Annealed or soft-drawn copper usually has a conductivity of 100 per cent, rd-drawn copper a conductivity of about 97 per cent. Ordinarily hard-awn aluminum has a conductivity of 61 per cent. The conductivity of iron steel wire ranges from 8 to 16 per cent.

DIMENSIONS, RESISTANCE AND WEIGHT. — The following bles for copper and aluminum are compiled from the tables in *Circular o. 31 of the Bureau of Standards*, except that for stranded aluminum on p. 1977. he table for steel wire is compiled from that published by the American Steel nd Wire Co.

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SOLID COPPER WIRE

A. W. G. or B. & S. Gage; English Units

100 Per Cent Conductivity; Density 8.89 at 20° C.

Gage No.	Diameter in mils.	Cross-section		Resistance at 20° C. or 68° F.*		Weight in pounds		
		Circular mils	Square inches	Ohms per 1000 feet	Ohms per mile	per 1000 feet	per mile	
0000	460.0	211,600	0.1662	0.04901	0.259	640.5	3380	
000	409.6	167,800	0.1318	0.06180	0.326	507.9	2680	
00	364.8	133,100	0.1045	0.07793	0.411	402.8	2130	
0	324.9	105,500	0.08289	0.09827	0.519	319.5	1680	
1	289.3	83,690	0.06573	0.1239	0.654	253.3	1340	
2	257.6	66,370	0.05213	0.1563	0.825	200.9	1060	
3	229.4	52,640	0.04134	0.1970	1.04	159.3	841	
4	204.3	41,740	0.03278	0.2485	1.31	126.4	667	
5	181.9	33,100	0.02600	0.3133	1.65	100.2	529	
6	162.0	26,250	0.02062	0.3951	2.09	79.46	420	
7	144.3	20,820	0.01635	0.4982	2.63	63.02	333	
8	128.5	16,510	0.01297	0.6282	3.32	49.98	264	
10	101.9	10,380	0.008155	0.9989	5.28	31.43	166	
12	80.81	6,530	0.005129	1.588	8.38	19.77	104	
14	64.08	4,107	0.003225	2.525	13.3	12.43	63.3	
15	57.07	3,257	0.002558	3.184	16.8	9.858	52.0	
16	50.82	2,583	0.002028	4.015	21.2	7.818	41.3	
17	45.26	2,048	0.001609	5.064	26.7	6.200	32.7	
18	40.30	1,624	0.001276	6.385	33.7	4.917	26.0	
19	35.89	1,288	0.001012	8.051	42.5	3.899	20.6	
20	31.96	1,022	0.0008023	10.15	53.6	3.092	16.3	
21	28.46	810.1	0.0006363	12.80	67.6	2.452	12.9	
22	25.35	642.4	0.0005046	16.14	85.2	1.945	10.3	
23	22.57	509.5	0.0004002	20.36	108	1.542	8.14	
24	20.10	404.0	0.0003173	25.67	135	1.223	6.46	
25	17.90	320.4	0.0002517	32.37	171	0.9699	5.12	
26	15.94	254.1	0.0001996	40.82	216	0.7692	4.06	
27	14.20	201.5	0.0001583	51.46	272	0.6100	3.22	
28	12.64	159.8	0.0001255	64.90	343	0.4837	2.55	
29	11.26	126.7	0.00009953	81.84	432	0.3836	2.03	
30	10.03	100.5	0.00007894	103.2	545	0.3042	1.61	
31	8.928	79.70	0.00006260	130.1	687	0.2413	1.27	
32	7.950	63.21	0.00004964	164.1	866	0.1913	1.01	
33	7.080	50.13	0.00003937	206.9	1090	0.1517	0.801	
34	6.305	39.75	0.00003122	260.9	1380	0.1203	0.635	
35	5.615	31.52	0.00002476	329.0	1740	0.09542	0.504	
36	5.000	25.00	0.00001964	414.8	2190	0.07568	0.400	
38	3.965	15.72	0.00001235	659.6	3480	0.04759	0.251	
40	3.145	9.888	0.000007766	1049	5540	0.02993	0.158	

*Let C = per cent conductivity, R_{100} = resistance of 100 per cent conductivity wire at 20° C. (from table), R_t = resistance of wire of conductivity C at any temperature t° C. then

$$R_t = R_{100}\left[\frac{100}{C} + 0.00393\,(t - 20)\right]$$

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COPPER CABLES, CONCENTRIC-LAY

Cir. Mils and A. W. G. or B. & S. Gage; English Units

100 Per Cent Conductivity: Density 8.89 at 20° C. (*See p. 1982.*)

ber s d . G.	Resistance at 25° C. or 77° F.°		Weight in pounds, bare		Standard strands			Flexible strands		
	Ohms per 1000 feet	Ohms per mile	per 1000 feet	per mile	Number of wires	Diameter of wires in mils	Outside diameter, in mils	Number of wires	Diameter of wires, in mils	Outside diameter, in mils
,000	0.00539	0.0285	6180	32600	127	125.5	1631	169	108.8	1632
,000	0.00568	0.0300	5870	31000	127	122.3	1590	169	106.0	1590
,000	0.00599	0.0316	5560	29300	127	119.1	1548	169	103.2	1548
,000	0.00634	0.0335	5250	27700	127	115.7	1504	169	100.3	1504
,000	0.00674	0.0356	4940	26100	127	112.2	1459	169	97.3	1460
,000	0.00719	0.0380	4630	24500	91	128.4	1412	127	108.7	1413
,000	0.00770	0.0407	4320	22800	91	124.0	1364	127	105.0	1365
,000	0.00830	0.0438	4010	21200	91	119.5	1315	127	101.2	1315
,000	0.00899	0.0475	3710	19600	91	114.8	1263	127	97.2	1264
,000	0.00981	0.0518	3400	17900	91	109.9	1209	127	93.1	1210
,000	0.0108	0.0570	3090	16300	61	128.0	1152	91	104.8	1153
,000	0.0114	0.0600	2930	15490	61	124.8	1123	91	102.2	1124
,000	0.0120	0.0633	2780	14670	61	121.5	1093	91	99.4	1094
,000	0.0127	0.0670	2620	13860	61	118.0	1062	91	96.6	1063
,000	0.0135	0.0712	2470	13040	61	114 5	1031	91	93.8	1031
,000	0.0144	0.0759	2320	12230	61	110.9	998	91	90.8	999
,000	0.0154	0.0814	2160	11410	61	107.1	964	91	87.7	965
,000	0.0166	0.0876	2010	10600	61	103.2	929	91	84.5	930
,000	0.0180	0.0949	1850	9780	61	99.2	893	91	81.2	893
,000	0.0196	0.1036	1700	8970	61	95.0	855	91	77.7	855
,000	0.0216	0.1139	1540	8150	37	116.2	814	61	90.5	815
,000	0.0240	0.1266	1390	7340	37	110.3	772	61	85.9	773
,000	0.0270	0.1424	1240	6520	37	104.0	728	61	81.0	729
,000	0.0308	0.1627	1080	5710	37	97.3	681	61	75.7	682
,000	0.0360	0.1899	926	4890	37	90.0	630	61	70.1	631
,000	0.0431	0.228	772	4080	37	82.2	575	61	64.0	576
000	0.0509	0.269	653	3450	19	105.5	528	37	75.6	533
000	0.0642	0.339	518	2735	19	94.0	470	37	67.3	471
00	0.0811	0.428	411	2170	19	83.7	418	37	60.0	420
0	0.102	0.540	326	1720	19	74.5	373	37	53.4	374
1	0.129	0.681	258	1364	19	66.4	332	37	47.6	333
2	0.162	0.858	205	1082	7	97.4	292	19	59.1	296
3	0.205	1.082	163	858	7	86.7	260	19	52.6	263
4	0.259	1.365	129	680	7	77.2	232	19	46.9	234
5	0.326	1.721	102	540	7	68.8	206	19	41.7	209
6	0.410	2.170	81.0	428	7	61.2	184	19	37.2	186
7	0.519	2.74	64.3	339	7	54.5	164	19	33.1	166
8	0.654	3.45	51.0	269	7	48.6	146	19	29.5	147

°Let C = per cent conductivity, R_{25} = resistance of 100 per cent conductivity cable at 25° C. (from table), R_t = resistance of cable of conductivity C at any temperature t° C.,

$$R_t = R_{25}\left[\frac{100}{C} + 0.00385\,(t - 25)\right].$$

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SOLID COPPER WIRE

A. W. G. or B. & S. Gage in Metric Units

100 Per Cent Conductivity; Density 8.89 at 20° C.

Gage No.	Diameter in mm.	Cross-section in sq. mm.	Ohms per kilometer, 20° C*	Kilograms per kilometer
0000	11.68	107.2	0.1608	953.2
000	10.40	85.03	0.2028	755.9
00	9.266	67.43	0.2557	599.5
0	8.252	53.48	0.3224	475.4
1	7.348	42.41	0.4066	377.0
2	6.544	33.63	0.5126	299.0
3	5.827	26.67	0.6464	237.1
4	5.189	21.15	0.8152	188.0
5	4.621	16.77	1.028	149.1
6	4.115	13.30	1.296	118.2
7	3.665	10.55	1.634	93.78
8	3.264	8.366	2.061	74.37
10	2.588	5.261	3.277	46.77
12	2.053	3.309	5.211	29.42
14	1.628	2.081	8.285	18.50
15	1.450	1.650	10.45	14.67
16	1.291	1.309	13.18	11.63
17	1.150	1.038	16.61	9.226
18	1.024	0.8231	20.95	7.317
19	0.9116	0.6527	26.42	5.803
20	0.8118	0.5176	33.31	4.602
21	0.7230	0.4105	42.00	3.649
22	0.6438	0.3255	52.96	2.894
23	0.5733	0.2582	66.79	2.295
24	0.5106	0.2047	84.22	1.820
25	0.4547	0.1624	106.2	1.443
26	0.4049	0.1288	133.9	1.145
27	0.3606	0.1021	168.8	0.9078
28	0.3211	0.08098	212.9	0.7199
29	0.2859	0.06422	268.5	0.5709
30	0.2546	0.05093	338.6	0.4527
31	0.2268	0.04039	426.9	0.3590
32	0.2019	0.03203	538.3	0.2847
33	0.1798	0.02540	678.8	0.2258
34	0.1601	0.02014	856.0	0.1791
35	0.1426	0.01597	1079	0.1420
36	0.1270	0.01267	1361	0.1126
38	0.1007	0.007967	2164	0.07083
40	0.07987	0.005010	3441	0.04454

* Let C = per cent conductivity, R_{20} = resistance of 100 per cent conductivity wi at 20° C. (from table), R_t = resistance of wire of conductivity C at any temperature t then

$$R_t = R_{20}\left[\frac{100}{C} + 0.00393\,(t - 20)\right].$$

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COPPER CABLES, CONCENTRIC-LAY

Cir. Mils and A.W.G. or B. & S. Gage in Metric Units

100 Per Cent Conductivity; Density 8.89 at 20°C. (*See p. 1982.*)

ar).	Total cross-section in mm.²	Ohms per kilometer at 25°C.	Kilograms per kilometer, Bare	Standard strands			Flexible strands		
				Number of wires	Diameter of wires, in mm.	Outside diameter, in mm.	Number of wires	Diameter of wires, in mm.	Outside diameter, in mm.
00	1013	0.0177	9190	127	3.19	41.4	169	2.76	41.4
00	963	0.0186	8730	127	3.11	40.4	169	2.69	40.4
00	912	0.0197	8270	127	3.02	39.3	169	2.62	39.3
00	861	0.0208	7810	127	2.94	38.2	169	2.55	38.2
00	811	0.0221	7350	127	2.85	37.1	169	2.47	37.1
00	760	0.0236	6890	91	3.26	35.9	127	2.76	35.9
00	709	0.0253	6430	91	3.15	34.7	127	2.67	34.7
00	659	0.0272	5970	91	3.04	33.4	127	2.57	33.4
00	608	0.0295	5510	91	2.92	32.1	127	2.47	32.1
0	557	0.0322	5050	91	2.79	30.7	127	2.36	30.7
0	507	0.0354	4590	61	3.25	29.3	91	2.66	29.3
0	481	0.0373	4370	61	3.17	28.5	91	2.60	28.5
0	456	0.0393	4140	61	3.09	27.8	91	2.53	27.8
0	431	0.0416	3910	61	3.00	27.0	91	2.45	27.0
0	405	0.0442	3680	61	2.91	26.2	91	2.38	26.2
0	380	0.0472	3450	61	2.82	25.3	91	2.31	25.4
0	355	0.0506	3220	61	2.72	24.5	91	2.23	24.5
0	329	0.0544	2990	61	2.62	23.6	91	2.15	23.6
0	304	0.0590	2760	61	2.52	22.7	91	2.06	22.7
0	279	0.0643	2530	61	2.41	21.7	91	1.97	21.7
0	253	0.0708	2300	37	2.95	20.7	61	2.30	20.7
0	228	0.0786	2070	37	2.80	19.6	61	2.18	19.6
0	203	0.0885	1840	37	2.64	18.5	61	2.06	18.5
0	177	0.101	1610	37	2.47	17.3	61	1.92	17.3
0	152	0.118	1380	37	2.29	16.0	61	1.78	16.0
0	127	0.142	1150	37	2.09	14.6	61	1.63	14.6
	107	0.167	972	19	2.68	13.4	37	1.93	13.5
	85	0.211	771	19	2.39	11.9	37	1.71	12.0
	67.4	0.266	611	19	2.13	10.6	37	1.52	10.7
	53.5	0.334	485	19	1.89	9.46	37	1.36	9.50
	42.4	0.423	385	19	1.69	8.43	37	1.21	8.46
	33.6	0.533	305	7	2.47	7.42	19	1.50	7.51
	26.7	0.673	242	7	2.20	6.61	19	1.34	6.68
	21.2	0.849	192	7	1.96	5.88	19	1.19	5.95
	16.8	1.07	152	7	1.75	5.24	19	1.06	5.30
	13.3	1.35	121	7	1.56	4.67	19	0.944	4.72
	10.5	1.70	95.7	7	1.39	4.16	19	0.841	4.20
	8.37	2.14	75.9	7	1.23	3.70	19	0.749	3.74

= per cent conductivity, R_{25} = resistance of 100 per cent conductivity cable at
m table), R_t = resistance of cable of conductivity C at any temperature t° C.,

$$R_t = R_{25}\left[\frac{100}{C} + 0.00385\ (t - 25)\right].$$

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SOLID COPPER WIRE

British Standard Wire Gage; English Units

100 Per Cent Conductivity; Density 8.89 at 20° C.

Gage No.	Diameter in mils	Cross-section		Ohms per 1000 feet, 15.6° C. or 60° F.*	Pounds p 1000 fee
		Circular mils	Square inches		
7-0	500	250,000	0.1964	0.04077	736.8
6-0	464	215,300	0.1691	0.04734	653.7
5-0	432	186,600	0.1466	0.05461	564.9
4-0	400	160,000	0.1257	0.06370	484.3
3-0	372	138,400	0.1087	0.07365	418.9
2-0	348	121,100	0.09512	0.08416	366.6
0	324	105,000	0.08245	0.09709	317.8
1	300	90,000	0.07069	0.1132	272.4
2	276	76,180	0.05983	0.1338	230.6
3	252	63,500	0.04988	0.1605	192.2
4	232	53,820	0.04227	0.1894	162.9
5	212	44,940	0.03530	0.2268	136.0
6	192	36,860	0.02895	0.2765	111.6
7	176	30,980	0.02433	0.3290	93.76
8	160	25,600	0.02011	0.3981	77.49
9	144	20,740	0.01629	0.4915	62.77
10	128	16,380	0.01287	0.6221	49.59
11	116	13,460	0.01057	0.7574	40.73
12	104	10,820	0.008495	0.9423	32.74
13	92	8,464	0.006648	1.204	25.62
14	80	6,400	0.005027	1.592	19.37
15	72	5,184	0.004072	1.966	15.69
16	64	4,096	0.003217	2.488	12.40
17	56	3,136	0.002463	3.250	9.483
18	48	2,304	0.001810	4.424	6.971
19	40	1,600	0.001257	6.370	4.843
20	36	1,296	0.001018	7.864	3.923
22	28	784.0	0.0006158	13.00	2.373
24	22	484.0	0.0003801	21.06	1.465
26	18	324.0	0.0002545	31.46	0.9807
28	14.8	219.0	0.0001720	46.54	0.6639
30	12.4	153.8	0.0001208	66.28	0.4664
32	10.8	116.6	0.00009161	87.38	0.3537
34	9.2	84.64	0.00006648	120.4	0.2561
36	7.6	57.76	0.00004536	176.5	0.1748
38	6.0	36.00	0.00002827	283.1	0.1089
40	4.8	23.04	0.00001810	442.4	0.06974
42	4.0	16.00	0.00001257	637.0	0.04843
44	3.2	10.24	0.000008042	995.3	0.03100
50	1.0	1.000	0.0000007854	10,190	0.00397

*Let C = per cent conductivity, R_{60} = resistance of 100 per cent conductivity wire at 60° F. (from table), R_t = resistance of wire of conductivity C at any temperature t° F., then

$$R_t = R_{60}\left[\frac{100}{C} + 0.00223\,(t - 60)\right].$$

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SOLID COPPER WIRE

"Millimeter Gage"; Metric Units

r Cent Conductivity; Density 8.89 at 20° C.

Cross-section in sq. mm.	Ohms per kilometer, 20° C.	Kilograms per kilometer
78.54	0.2195	698.2
63.62	0.2710	565.6
50.27	0.3430	446.9
38.48	0.4480	342.1
28.27	0.6098	251.4
19.64	0.8781	174.6
15.90	1.084	141.4
12.57	1.372	111.7
9.621	1.792	85.53
7.069	2.439	62.84
4.909	3.512	43.64
3.142	5.488	27.93
2.545	6.775	22.62
2.011	8.575	17.87
1.539	11.20	13.69
1.131	15.24	10.05
0.7854	21.95	6.982
0.6362	27.10	5.656
0.5027	34.30	4.469
0.3848	44.80	3.421
0.2827	60.98	2.514
0.1964	87.81	1.746
0.1590	108.4	1.414
0.1257	137.2	1.117
0.09621	179.2	0.8553
0.07069	243.9	0.6284
0.04909	351.2	0.4364
0.03142	548.8	0.2793
0.01767	975.6	0.1571
0.007854	2195	0.06982
0.001964	8781	0.01746

nductivity,
of 100 per cent conductivity wire at 20° C. (from table),
of wire of conductivity C at any temperature t° C.,

$$R_t = R_{20}\left[\frac{100}{C} + 0.00393\,(t - 20)\right].$$

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SOLID COPPER WIRE; OHMS PER UNIT WEIGHT

A. W. G. or B. & S. Gage; English and Metric Units

100 Per Cent Conductivity; Density 8.89 at 20° C.

Gage No.	Ohms per pound			Ohms per kilogram		
	0° C. 32° F.	20° C. 68° F.	50° C. 122° F.	0° C.	20° C.	50° C.
0000	0.00007051	0.00007652	0.00008554	0.0001554	0.0001687	0.0001886
000	0.0001121	0.0001217	0.0001360	0.0002472	0.0002682	0.0002998
00	0.0001783	0.0001935	0.0002163	0.0003930	0.0004265	0.0004768
0	0.0002835	0.0003076	0.0003439	0.0006249	0.0006782	0.0007581
1	0.0004507	0.0004891	0.0005468	0.0009936	0.001078	0.001205
2	0.0007166	0.0007778	0.0008695	0.001580	0.001715	0.001917
3	0.001140	0.001237	0.001383	0.002512	0.002726	0.003048
4	0.001812	0.001966	0.002198	0.003995	0.004335	0.004846
5	0.002881	0.003127	0.003495	0.006352	0.006893	0.007704
6	0.004581	0.004972	0.005558	0.01010	0.01096	0.01225
7	0.007284	0.007906	0.008838	0.01606	0.01743	0.01948
8	0.01158	0.01257	0.01405	0.02553	0.02771	0.03097
9	0.01842	0.01999	0.02234	0.04060	0.04407	0.04926
10	0.02928	0.03178	0.03553	0.06456	0.07006	0.07831
11	0.04656	0.05053	0.05649	0.1026	0.1114	0.1245
12	0.07404	0.08035	0.08983	0.1632	0.1771	0.1980
13	0.1177	0.1278	0.1428	0.2595	0.2817	0.3149
14	0.1872	0.2032	0.2271	0.4127	0.4479	0.5007
15	0.2976	0.3230	0.3611	0.6562	0.7121	0.7961
16	0.4733	0.5136	0.5742	1.043	1.132	1.266
17	0.7525	0.8167	0.9130	1.659	1.800	2.013
18	1.197	1.299	1.452	2.638	2.863	3.201
19	1.903	2.065	2.308	4.194	4.552	5.089
20	3.025	3.283	3.670	6.670	7.238	8.092
21	4.810	5.221	5.836	10.60	11.51	12.87
22	7.649	8.302	9.280	16.86	18.30	20.46
23	12.16	13.20	14.76	26.81	29.10	32.53
24	19.34	20.99	23.46	42.63	46.27	51.73
25	30.75	33.37	37.31	67.79	73.57	82.25
26	48.89	53.06	59.32	107.8	117.0	131.8
27	77.74	84.37	94.32	171.4	186.0	207.9
28	123.6	134.2	150.0	272.5	295.8	330.6
29	196.6	213.3	238.5	433.3	470.3	525.7
30	312.5	339.2	379.2	689.0	747.8	836.0
31	497.0	539.3	602.9	1,096	1,189	1,329
32	790.2	857.6	958.7	1,742	1,891	2,114
33	1,256	1,364	1,524	2,770	3,006	3,361
34	1,998	2,168	2,424	4,404	4,780	5,344
35	3,177	3,448	3,854	7,003	7,602	8,497
36	5,051	5,482	6,128	11,140	12,080	13,510
38	12,770	13,860	15,490	28,150	30,560	34,160
40	32,290	35,040	39,170	71,180	77,260	86,360

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SOLID COPPER WIRE; WEIGHT PER OHM
A. W. G. or B. & S. Gage; English and Metric Units
100 Per Cent Conductivity; Density 8.89. at 20° C.

ns per ohm		Feet per ohm		Pounds per ohm		Grams per ohm	
	50° C.	20° C. 68° F.	50° C. 122° F.	20° C. 68° F.	50° C. 122° F.	20° C.	50° C.
	5563	20,400	18,250	13,070	11,690	5,928,000	5,302,000
	4412	16,180	14,470	8,219	7,352	3,728,000	3,335,000
	3499	12,830	11,480	5,169	4,624	2,344,000	2,097,000
	2774	10,180	9,103	3,251	2,908	1,474,000	1,319,000
	2200	8,070	7,219	2,044	1,829	927,300	829,500
	1745	6,400	5,725	1,286	1,150	583,200	521,700
	1384	5,075	4,540	808.6	723.3	366,800	328,100
	1097	4,025	3,600	508.5	454.9	230,700	206,300
	870.2	3,192	2,855	319.8	286.1	145,100	129,800
	690.1	2,531	2,264	201.1	179.9	91,230	81,610
	547.3	2,007	1,796	126.5	113.2	57,380	51,330
	434.0	1,592	1,424	79.56	71.16	36,090	32,280
	344.2	1,262	1,129	50.03	44.75	22,690	20,300
	273.0	1,001	895.6	31.47	28.15	14,270	12,770
	216.5	794.0	710.2	19.79	17.70	8,976	8,030
	171.7	629.6	563.2	12.44	11.13	5,645	5,050
	136.1	499.3	446.7	7.827	7.001	3,550	3,176
	108.0	396.0	354.2	4.922	4.403	2,233	1,997
	85.62	314.0	280.9	3.096	2.769	1,404	1,256
	67.90	249.0	222.8	1.947	1.742	883.1	790.0
	53.85	197.5	176.7	1.224	1.095	555.3	496.8
	42.70	156.6	140.1	0.7701	0.6888	349.3	312.4
	33.86	124.2	111.1	0.4843	0.4332	219.7	196.5
	26.86	98.49	88.11	0.3046	0.2725	138.2	123.6
	21.30	78.11	69.87	0.1915	0.1713	86.89	77.72
	16.89	61.95	55.41	0.1205	0.1078	54.64	48.88
	13.39	49.12	43.94	0.07576	0.06777	34.36	30.74
	10.62	38.96	34.85	0.04765	0.04262	21.61	19.33
	8.424	30.90	27.64	0.02997	0.02680	13.59	12.16
	6.680	24.50	21.92	0.01884	0.01686	8.548	7.647
	5.298	19.43	17.38	0.01185	0.01060	5.376	4.809
	4.201	15.41	13.78	0.007454	0.006668	3.381	3.022
	3.332	12.22	10.93	0.004688	0.004193	2.126	1.902
	2.642	9.691	8.669	0.002948	0.002637	1.337	1.196
	2.095	7.685	6.875	0.001854	0.001659	0.8410	0.7523
	1.662	6.094	5.452	0.001166	0.001043	0.5289	0.4731
	1.318	4.833	4.323	0.0007333	0.0006560	0.3326	0.2976
	1.045	3.833	3.429	0.0004612	0.0004126	0.2092	0.1871
	0.8839	3.040	2.719	0.0002900	0.0002595	0.1316	0.1177
	0.7012	2.410	2.156	0.0001824	0.0001632	0.08275	0.07402
	0.6304	1.516	1.356	0.00007216	0.00006454	0.03273	0.02927
	0.5000	0.9534	0.8529	0.00002854	0.00002553	0.01294	0.01158

SOLID ALUMINUM WIRE

A. W. G. or B. & S. Gage; English Units

61 Per Cent Conductivity; Density 2.70

Gage No.	Diameter in mils	Cross-section		Resistance at 20° C. or 68° F.*		Weight in pounds		Feet per pound
		Circular mils	Square inches	Ohms per 1000 feet	Ohms per mile	per 1000 feet	per mile	
0000	460.0	211,600	0.1662	0.0804	0.424	195	1027	5 1
000	409.6	167,800	0.1318	0.101	0.535	154	815	6.4
00	364.8	133,100	0.1045	0.128	0.675	122	646	8 1
0	324.9	105,500	0.08289	0.161	0.851	97.0	512	10 1
1	289.3	83,690	0.06573	0.203	1.073	76.9	406	13 0
2	257.6	66,370	0.05213	0.256	1.353	61.0	322	16.4
3	229.4	52,630	0.04134	0.323	1.706	48.4	255	20.7
4	204.3	41,740	0.03278	0.408	2.15	38.4	203	26 0
5	181.9	33,100	0.02600	0.514	2.71	30.4	160.7	32 9
6	162.0	26,250	0.02062	0.648	3.42	24.1	127.4	41.4
7	144.3	20,820	0.01635	0.817	4.31	19.1	101.0	52.3
8	128.5	16,510	0.01297	1.03	5.44	15.2	80.2	65.9
10	101.9	10,380	0.008155	1.64	8.65	9.55	50.4	104.8
12	80.81	6,530	0.005129	2.61	13.76	6.00	31.7	166.6
14	64.08	4,107	0.003225	4.14	21.9	3.78	19.93	265
15	57.07	3.257	0.002558	5.22	27.6	2.99	15.81	334
16	50.82	2,583	0.002029	6.59	34.8	2.37	12.54	421
17	45.26	2,048	0.001609	8.31	43.8	1.88	9.94	531
18	40.30	1,624	0.001276	10.5	55.3	1.49	7.89	670
19	35.89	1,288	0.001012	13.2	69.7	1.18	6.25	845
20	31.96	1,022	0.0008023	16.7	87.9	0.939	4.96	1,066
21	28.46	810.1	0.0006363	21.0	110.9	0.745	3.93	1,343
22	25.35	642.4	0.0005046	26.5	139.8	0.591	3.12	1,693
23	22.57	509.5	0.0004002	33.4	176.3	0.468	2.47	2,135
24	20.10	404.0	0.0003173	42.1	222	0.371	1.961	2,690
25	17.90	320.4	0.0002517	53.1	280	0.295	1.556	3,390
26	15.94	254.1	0.0001996	67.0	353	0.234	1.233	4,270
27	14.20	201.5	0.0001583	84.4	446	0.185	0.978	5,400
28	12.64	159.8	0.0001255	106	562	0.147	0.776	6,810
29	11.26	126.7	0.00009953	134	709	0.117	0.615	8,580
30	10.03	100.5	0.00007894	169	894	0.0924	0.488	10,820
31	8.928	79.70	0.00006260	213	1127	0.0733	0.387	13,640
32	7.950	63.21	0.00004964	269	1421	0.0581	0.307	17,210
33	7.080	50.13	0.00003937	339	1792	0.0461	0.243	21,700
34	6.305	39.75	0.00003122	428	2260	0.0365	0.1929	27,400
35	5.615	31.52	0.00002476	540	2850	0.0290	0.1530	34,500
36	5.000	25.00	0.00001964	681	3590	0.0230	0.1214	43,500
38	3.965	15.72	0.00001235	1080	5710	0.0145	0.0763	69,200
40	3.145	9.888	0.000007766	1720	9080	0.0091	0.0480	110,000

*Let C = per cent conductivity, R_{20} = resistance of 61 per cent conductivity wire at 20° C. (from table), R_t = resistance of wire of conductivity C at any temperature t° C., then

$$R_t = \frac{61\ R_{20}}{C}\left[1 + 0.004\,(t - 20)\right]$$

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ALUMINUM CABLES

commercial sizes of stranded aluminum cables, made by the Aluminum any of America, are not circular mil or A. W. G. sizes, but are of such sections as to give the same conductivity as even circular mil and A. W. G. of copper cables of 97 per cent conductivity. In the following table the our and the seventh columns are taken from a pamphlet entitled "Instruc- for Installation and Maintenance of Aluminum Electrical Conductors" by the Aluminum Company of America, in 1914.

W. G. gage or circular mils		Usual number of strands	Diameter of bare cable, inches	Resistance at 25° C. or 77° F.*		Weight in pounds	
per (97 cent) valent	Aluminum 61 per cent			Ohms per 1000 feet	Ohms per mile	per 1000 feet	per mile
00,000	1,590,000	61	1 7/16	0.0111	0.0588	1462	7719
50,000	1,515,000	61	1 3/32	0.0118	0.0619	1393	7355
00,000	1,431,000	61	1 23/64	0.0124	0.0653	1317	6954
50,000	1,351,500	61	1 21/64	0.0131	0.0691	1243	6563
00,000	1,272,000	61	1 9/32	0.0139	0.0734	1171	6189
50,000	1,192,500	37	1 1/4	0.0148	0.0783	1098	5797
00,000	1,113,000	37	1 13/64	0.0159	0.0839	1025	5412
50,000	1,033,500	37	1 5/32	0.0171	0.0903	950	5016
00,000	954,000	37	1 7/64	0.0186	0.0978	877	4631
50,000	874,500	37	1 1/16	0.0202	0.1068	805	4250
00,000	795,000	37	1 1/64	0.0223	0.1174	732	3865
50,000	715,500	37	31/32	0.0247	0.1305	658	3474
00,000	636,000	37	29/32	0.0278	0.1468	585	3089
50,000	556,500	19	55/64	0.0318	0.1677	512	2703
00,000	477,000	19	25/32	0.0371	0.1958	439	2318
50,000	397,500	19	23/32	0.0444	0.2351	365	1927
0000	336,420	7	21/32	0.0525	0.277	310.2	1638
000	266,800	7	3 7/64	0.0662	0.350	245.7	1297
00	211,950	7	23/64	0.0836	0.441	195	1030
0	167,800	7	15/32	0.105	0.557	155	818.4
1	133,220	7	13/32	0.133	0.702	122.6	647.3
2	105,530	7	23/64	0.167	0.885	97.2	513.2
3	83,640	7	21/64	0.211	1.116	77	406.6
4	66,370	7	19/64	0.267	1.407	61.2	323.1
5	52,630	7	17/64	0.336	1.774	48.5	256.1
6	41,740	7	15/64	0.423	2.237	38.5	203.3

* These resistances are taken equal to those given on page 1969 divided by 0.97.

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SOLID ALUMINUM WIRE

A. W. G. or B. & S. Gage in Metric Units

61 Per Cent Conductivity; Density 2.70; Temperature 20° C. or 68° F.*

Gage No.	Diameter in mm.	Cross-section in sq. mm.	Ohms per kilometer	Kilograms per kilometer
0000	11.68	107.2	0.264	289
000	10.40	85.03	0.333	230
00	9.266	67.43	0.419	182
0	8.252	53.48	0.529	144
1	7.348	42.41	0.667	114
2	6.544	33.63	0.841	90 8
3	5.827	26.67	1.06	72.0
4	5.189	21.15	1.34	57.1
5	4.621	16.77	1.69	45.3
6	4.115	13.30	2.13	35.9
7	3.665	10.55	2.68	28.5
8	3.264	8.366	3.38	22.6
10	2.588	5.261	5.38	14.2
12	2.053	3.309	8.55	8.93
14	1.628	2.081	13.6	5.62
15	1.450	1.650	17.1	4.46
16	1.291	1.309	21.6	3.53
17	1.150	1.038	27.3	2.80
18	1.024	0.8231	34.4	2.22
19	0.9116	0.6527	43.3	1.76
20	0.8118	0.5176	54.6	1.40
21	0.7230	0.4105	68.9	1.11
22	0.6438	0.3255	86.9	0.879
23	0.5733	0.2582	110	0.697
24	0.5106	0.2047	138	0.553
25	0.4547	0.1624	174	0.438
26	0.4049	0.1288	220	0.348
27	0.3606	0.1021	277	0.276
28	0.3211	0.08098	349	0.219
29	0.2859	0.06422	440	0.173
30	0.2546	0.05093	555	0.138
31	0.2268	0.04039	700	0.109
32	0.2019	0.03203	883	0.0865
33	0.1798	0.02540	1110	0.0686
34	0.1601	0.02014	1400	0.0544
35	0.1426	0.01597	1770	0.0431
36	0.1270	0.01267	2230	0.0342
38	0.1007	0.007967	3550	0.0215
40	0.07987	0.005010	5640	0.0135

* Let C = per cent conductivity, R_{20} = resistance of 61 per cent conductivity wire 20° C. (from table), R_t = resistance of wire of conductivity C at any temperature t° then

$$R_t = \frac{61\ R_{20}}{C}[1 + 0.004\ (t - 20)].$$

The temperature coefficient is approximate only.

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SOLID STEEL WIRE

American Steel Wire Gage; English Units

12.5 Per Cent Conductivity; Density 7.78

iameter	Cross-section		Resistance at 20° C. or 68° F.°		Weight in pounds		Feet per pound
Mils	Circular mils	Square inches	Ohms per 1000 feet	Ohms per mile	per 1000 feet	per mile	
500.0	250,000	0.1964	0.332	1.752	662.5	3499	1.51
490.0	240,100	0.1886	0.346	1.825	636.3	3360	1.57
468.8	219,800	0.1726	0.378	1.993	582.4	3075	1.72
460.0	211,600	0.1662	0.392	2.07	560.8	2961	1.78
437.5	191,400	0.1503	0.433	2.29	507.2	2678	1.97
430.0	184,900	0.1452	0.449	2.37	490.0	2587	2.04
406.3	165,000	0.1296	0.503	2.65	436.8	2306	2.28
393.8	155,100	0.1218	0.535	2.82	411.9	2175	2.42
375.0	140,600	0.1104	0.590	3.12	372.6	1967	2.68
362.5	131,400	0.1032	0.631	3.33	348.2	1839	2.87
343.8	118,200	0.09280	0.702	3.71	313.1	1653	3.19
131.0	109,600	0.08605	0.757	4.00	290.3	1533	3.44
112.5	97,660	0.07670	0.850	4.49	258.8	1366	3.86
06.5	93,940	0.07378	0.883	4.66	249.0	1315	4.02
83.0	80,090	0.06290	1.036	5.47	212.2	1121	4.71
81.3	79,100	0.06213	1.049	5.54	209.6	1107	4.77
12.5	68,910	0.05412	1.204	6.36	182.6	964.1	5.48
0.0	62,500	0.04909	1.328	7.01	165.6	874.5	6.04
3.7	59,490	0.04665	1.397	7.38	157.4	831.0	6.35
5.3	50,760	0.03987	1.635	8.63	134.5	710.2	7.43
4.8	47,850	0.03758	1.734	9.15	126.8	669.5	7.89
.0	42,850	0.03365	1.936	10.22	113.6	599.5	8.81
.0	36,860	0.02895	2.25	11.88	97.7	515.8	10.23
5	35,160	0.02761	2.36	12.46	93.2	491.9	10.73
0	31,330	0.02461	2.65	13.98	83.0	438.4	12.04
0	26,240	0.02061	3.16	16.69	69.6	367.2	14.38
3	24,410	0.01917	3.40	17.95	64.7	341.6	15.46
3	21,990	0.01727	3.77	19.92	58.3	307.8	17.16
)	18,200	0.01431	4.55	24.0	48.3	255.0	20.70
'	15,630	0.01227	5.31	28.0	41.4	218.6	24.15

onductivity,
of 12.5 per cent conductivity wire at 20° C. (from table),
of wire of any conductivity C at any temperature t° C,

$$R_t = \frac{12.5 R_{20}}{C}[1 + 0.006\,(t - 20)].$$

ficient is approximate only.

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SOLID STEEL WIRE — *Continued*

American Steel Wire Gage; English Units

12.5 Per Cent Conductivity; Density 7.78

Am. Steel Wire Gage No.	Diameter		Cross-section		Resistance at 20° C. or 68° F.*		Weight in pounds		Feet per pound
	In.	Mils	Circular mils	Square inches	Ohms per 1000 feet	Ohms per mile	per 1000 feet	per mile	
11		120.5	14,520	0.00140	5.71	30.2	38.5	203.2	
12		105.5	11,130	0.00874	7.45	39.4	29.5	155.7	
	9/32	93.8	8,789	0.00690	9.44	49.8	23.3	123.0	
13		91.5	8,372	0.00658	9.91	52.3	22.1	117.2	
14		80.0	6,400	0.00503	12.96	68.5	17.0	89.55	
15		72.0	5,184	0.00407	16.01	84.5	13.7	72.53	
16		62.5	3906	0.00307	21.2	112.1	10.4	54.66	
	1/16	62.5	3906	0.00307	21.2	112.1	10.4	54.66	
17		54.0	2916	0.00229	28.5	150.2	7.73	40.80	
18		47.5	2256	0.00177	36.8	194.2	5.98	31.57	
19		41.0	1681	0.00132	49.4	261	4.45	23.52	
20		34.8	1211	0.00095	68.5	362	3.21	16.95	
21		31.8	1008	0.00079	82.3	435	2.67	14.11	
	1/32	31.3	977	0.00076	85.0	449	2.59	13.66	
22		28.6	818	0.00064	101.4	536	2.17	11.45	
23		25.8	666	0.00052	124.6	658	1.76	9.31	
24		23.0	529	0.00042	156.8	828	1.40	7.40	
25		20.4	416	0.00033	199.4	1053	1.10	5.82	
26		18.1	328	0.00026	253	1337	0.87	4.58	
27		17.3	299	0.00024	277	1464	0.79	4.19	
28		16.2	262	0.00021	316	1669	0.70	3.67	
29		15.0	225	0.00018	369	1947	0.60	3.15	
30		14.0	196	0.00015	424	2240	0.52	2.74	
31		13.2	174	0.00014	476	2510	0.46	2.44	
32		12.8	164	0.00013	506	2670	0.43	2.30	
33		11.8	139	0.00011	596	3150	0.37	1.95	
34		10.4	108	0.00008	767	4050	0.29	1.51	
35		9.5	90	0.00007	919	4850	0.24	1.26	
36		9.0	81	0.00006	1023	5410	0.21	1.13	

*Let C = per cent conductivity,
R_{20} = resistance of 12.5 per cent conductivity wire at 20° C. (from table),
R_t = resistance of wire of any conductivity C at any temperature t° C.,
then

$$R_t = \frac{12.5\,R_{20}}{C}[1 + 0.006\,(t - 20)].$$

The temperature coefficient is approximate only.

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per-clad Steel Wire. — This wire consists of a steel core and a con- coat of copper permanently welded thereto. It is used chiefly for long ransmission and telephone wire. It is made in several grades, which in the relative amounts of steel and copper. The grades are designated e corresponding conductivity expressed as per cents of Matthiessen's ard; e.g., 40 per cent grade has a conductivity of 40 per cent.

COPPER-CLAD STEEL WIRE

A. W. G. or B. & S. Gage; English Units

40 Per Cent Conductivity; Density 8.26

Diameter in mils	Cross-section		Resistance at 23.9° C. or 75° F.		Weight in pounds		Feet per pound
	Circular mils	Square inches	Ohms per 1000 feet	Ohms per mile	per 1000 feet	per mile	
460.0	211,600	0.1662	0.123	0.649	595	3140	1.68
409.6	167,800	0.1318	0.154	0.813	471	2490	2.12
364.8	133,100	0.1045	0.195	1.03	374	1970	2.67
324.9	105,500	0.08289	0.246	1.30	297	1570	3.37
289.3	83,690	0.06573	0.310	1.64	235	1240	4.26
257.6	66,370	0.05213	0.390	2.06	186	982	5.38
229.4	52,630	0.04134	0.492	2.60	148	781	6.76
204.3	41,740	0.03278	0.622	3.28	117	618	8.55
181.9	33,100	0.02600	0.782	4.13	92.9	491	10.76
162.0	26,250	0.02062	0.987	5.21	73.7	389	13.57
144.3	20,820	0.01635	1.25	6.60	58.5	309	17.09
128.5	16,510	0.01297	1.57	8.29	46.4	245	21.6
114.4	13,090	0.01028	1.98	10.5	36.8	194	27.2
101.9	10,380	0.008155	2.50	13.2	29.2	154	34.2
90.74	8,234	0.006467	3.15	16.6	23.1	122	43.3
80.81	6,530	0.005129	3.97	21.0	18.3	96.6	54.6
71.96	5,178	0.004067	5.00	26.4	14.6	77.1	68.5
64.08	4,107	0.003225	6.31	33.3	11.5	60.7	87.0

re C = per cent conductivity,
R_{40} = resistance of 40 per cent conductivity wire at 23.9° C. (from table),
R_t = resistance of wire of conductivity C at temperature t° C.,

$$R_t = \frac{40\,R_{40}}{C}\,[1 + 0.00432\,(t - 23.9)].$$

e temperature coefficient is approximate only.

loy Wires of High Tensile Strength. — Copper alloys having a low uctivity, but having a tensile strength from 50 per cent to 100 per cent ter than that of copper are sometimes used where strength or hardness primary requisite, as in long spans of small wires or for trolley wires. The eport Brass Co. make a wire known as "phono-electric wire" which has nductivity of 25 per cent and a tensile strength ranging from 68,000 nds per square inch for No. 0000 B. & S. gauge to 85,000 pounds per square inch for No. 18 B. & S. gage.

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Trolley Wire. — Trolley wires of two different sections are in use in t United States. The sections shown in Fig. 1 are known as the "Americ Standard" and the sections shown in Fig. 2 as the "Figure 8" sections.

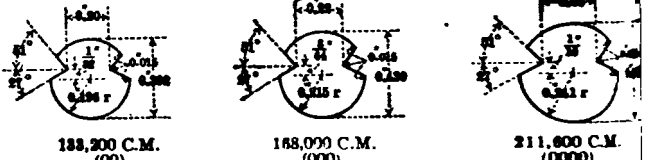


Fig. 1. American Standard Trolley-wire Sections

American Society for Testing Materials recommend that the sizes be specifi in circular mils, and not as gage numbers; the sizes shown in the figure ca in the area of the cross-section from the gage numbers given in parentheses less than 5 parts in 1000.

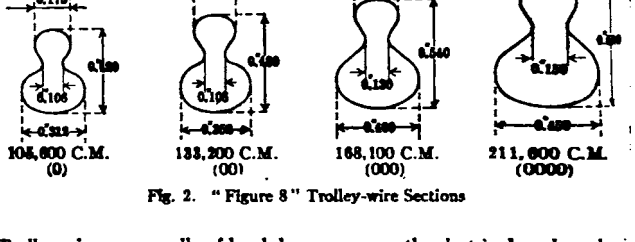


Fig. 2. "Figure 8" Trolley-wire Sections

Trolley wires are usually of hard-drawn copper; the electrical and mechani properties are the same as for round hard-drawn wire of the same cross-sect Copper alloys, such as phono-electric wire (*see above*), are sometimes used trolley wires.

FACTORS AFFECTING DIMENSIONS, WEIGHT AND RESIS ANCE OF STRANDED WIRES. — Individual stranded wires or cables a of four different types, namely: (a) bunched wire; (b) wire braids; (c) co centric-lay cables and (d) rope-lay cables.

Bunched Wires. — Bunched wires are used especially for those extra flexi cables known as cords, wherein the individual wires are so small that concentr stranding is not necessary to keep them together. The wires are assembl parallel and then generally given a slight twist. Sometimes they are ke together by being wound with soft cotton thread which also serves to preve adhesion between the insulation and wires.

Wire Braids. — In the flat form, wire braids are used for potential leads, et in lighting cables, where a flexible flat conductor is necessary. Tubular w braids are also frequently formed over the insulation of cables in order afford mechanical protection. Cables for naval or military purposes and f automobile work are frequently thus protected.

Concentric-lay Cables. — A concentric-lay cable is a stranded conduct composed of a central core surrounded by one or more layers of helically la

s. A rope-lay cable is a stranded wire made up in the same manner by stranded wires instead of individual solid wires for the core and layers. cores of concentric-lay cables may be composed of one, two, three or four of equal diameter. A five or six wire core would not be symmetrical seven wires would themselves constitute a core and a layer.

Number of Wires in Concentric-lay Cables. — The following table all the possible concentric-lay cables with eight or less layers of equal wires and formulæ for calculating the number of wires with any number yers.

NUMBER OF WIRES IN CONCENTRIC-LAY CABLES

(All wires of same diameter)

Number of yers over core	Number of wires in core			
	1	2	3	4
0	1	2	3	4
1	7	10	12	14
2	19	24	27	30
3	37	44	48	52
4	61	70	75	80
5	91	102	108	114
6	127	140	147	154
7	169	184	192	200
8	217	234	243	252
n	$3n^2+3n+1$	$3n^2+5n+2$	$3n^2+6n+3$	$3n^2+7n+4$

e number of wires per layer increases by six for each successive layer when ore has one wire, the first layer over the core having six. With cores having than one wire, the increment per layer is not constant.

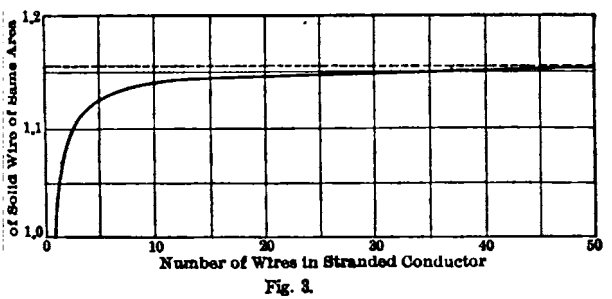


Fig. 3.

Diameter of Concentric-lay Cables. — The diameter of the circumscribing circle of any of the above cables is equal to $(2n + b)$ times the diameter ch wire, where n is the number of layers over the core and b has the following s: 1 wire in core, $b = 1$; 2 wires in core, $b = 2$; 3 wires in core, $b = 2.155$; es in core, $b = 2.414$.

e relation between the number of component wires and the diameter of the is shown in Fig. 3.

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COMMERCIAL STRANDED CONDUCTORS

Area of conductor C. M.	Number of wires in the stranded conductor								
	7	19	37	7×7 =49	61	91	127	169	217
	Diameter, in inches, of each wire in the cable								
2,000,000	0.5345	0.3244	0.2325	0.202	0.181	0.1482	0.1255	0.1086	0.096
1,750,000	0.5000	0.3035	0.2175	0.189	0.169	0.1387	0.1174	0.1020	0.090
1,500,000	0.4629	0.2810	0.2013	0.175	0.157	0.1285	0.1087	0.0940	0.083
1,250,000	0.4226	0.2565	0.1838	0.1507	0.143	0.1174	0.0992	0.0860	0.076
1,000,000	0.3779	0.2294	0.1644	0.1429	0.1285	0.1048	0.0887	0.0769	0.068
950,000	0.3684	0.2236	0.1602	0.1392	0.1247	0.1021	0.0864	0.0749	0.066
900,000	0.3585	0.2176	0.1559	0.1355	0.1214	0.0995	0.0841	0.0729	0.064
850,000	0.3484	0.2115	0.1515	0.1317	0.1180	0.0966	0.0818	0.0709	0.062
800,000	0.3380	0.2050	0.1470	0.1278	0.1145	0.0937	0.0793	0.0687	0.060
750,000	0.3273	0.1986	0.1423	0.1237	0.1108	0.0907	0.0769	0.0666	0.058
700,000	0.3163	0.1919	0.1375	0.1195	0.1071	0.0887	0.0742	0.0643	0.056
650,000	0.3047	0.1849	0.1325	0.1152	0.1032	0.0845	0.0715	0.0620	0.054
600,000	0.2927	0.1776	0.1273	0.1107	0.0991	0.0812	0.0687	0.0595	0.052
550,000	0.2803	0.1701	0.1219	0.1060	0.0949	0.0777	0.0658	0.0571	0.050
500,000	0.2673	0.1622	0.1162	0.1010	0.0905	0.0741	0.0628	0.0543	0.048
450,000	0.2535	0.1538	0.1103	0.0958	0.0858	0.0703	0.0595	0.0516	0.045
400,000	0.2390	0.1457	0.1039	0.0904	0.0809	0.0663	0.0561	0.0486	0.043
350,000	0.2236	0.1357	0.0972	0.0845	0.0757	0.0620	0.0526	0.0455	0.040
300,000	0.2070	0.1256	0.0903	0.0783	0.0701	0.0574	0.0486	0.0421	0.037
250,000	0.1889	0.1147	0.0824	0.0714	0.0640	0.0524	0.0443	0.0384	0.034
Size A. W. G.									
0000	0.1739	0.1055	0.0756	0.0657	0.0589	.....	.....	.....	.....
000	0.1548	0.0940	0.0674	0.0586	0.0525	.....	.....	.....	.....
00	0.1379	0.0837	0.0600	0.0521	0.0467	.....	.....	.....	.....
0	0.1228	0.0745	0.0534	0.0464	0.0416	.....	.....	.....	.....
1	0.1094	0.0664	0.0475	0.0413	.....	.....	.....	.....	.....
2	0.0974	0.0591	0.0424	0.0369	.....	.....	.....	.....	.....
3	0.0867	0.0525	0.0377	0.0327	.....	.....	.....	.....	.....
4	0.0772	0.0468	0.0335	0.0291	.....	.....	.....	.....	.....
5	0.0688	0.0418	0.0299	0.0260	.....	.....	.....	.....	.....
6	0.0612	0.0372	0.0266	0.0231	.....	.....	.....	.....	.....
7	0.0545	0.0331	0.0237	0.0206	.....	.....	.....	.....	.....
8	0.0484	0.0294	0.0211	0.0184					
9	0.0432	0.0263	0.0188	0.0164	.....	.....	.....	.....	.....
10	0.0386	0.0233	0.0168	.....	.....	.....	.....	.....	.....
12	0.0306	0.0185	0.0133	.....	.....	.....	.....	.....	.....
14	0.0242	0.0148	0.0105	.....	.....	.....	.....	.....	.....

Weights in lb. per 1000 ft. of all bare copper cables are computed by multiplying the circular mils by 0.00309.

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e-lay Cables. — As already noted, a rope-lay cable is made up in the way as a concentric-lay cable except that stranded wires are used for re and layers instead of individual solid wires. Rope strands are used ge conductors which would be too stiff if stranded concentrically. The las for regular concentric-lay cables may be readily modified to apply to ty cables, as each stranded wire bears the same relation to the rope as ndividual solid wire does to the concentric-lay cable. The following table the principal forms of rope-lay cables.

WIRES IN ROPE-LAY CABLES

Number of strands*	Total number of wires — Wires per strand*				
	7	19	37	61	91
1	7	19	37	61	91
7	49	133	259	427	637
19	133	361	703	1159	1,729
37	259	703	1369	2257	3,367
61	427	1159	2257	3721	5,551
91	637	1729	3367	5551	8,281
127	889	2413	4699	7747	11,557
$3(n^2+n)+1$	$21(n^2+n)+7$	$57(n^2+n)+19$	$111(n^2+n)+37$	$183(n^2+n)+61$	$273(n^2+n)+91$

ly "strand" is here meant the stranded wires of which the rope is built up.
e number of wires in a rope-lay cable is frequently designated by a product; 7 X 19 indicates a conductor made up of 7 strands, each strand containing 19

mp-core Cables. — Cables with **hemp** cores have caused serious le and are not being recommended. (D. B. Rushmore, *G. E. Review*, 1912.)

ameters of Component Wires in Commercial Stranded Conductors. e table on p. 1875 gives the diameters of the component wires in the types anded conductors ordinarily used.

fect of Lay on Resistance and Weight. — In the tables given on pp. 1969, and 1978, for stranded cables, the values given for "ohms per unit length" 'weight per unit length" are 2 per cent greater than for a solid rod of section equal to the total cross-section of the wires of the cable. This ment of 2 per cent means that the values are correct for cables having a lay n 15.7. For any other lay, equal to 1 in n, resistance or mass may be calcu- by increasing the above tabulated values by

$$\left(\frac{484}{n^2} - 2\right) \text{ per cent.}$$

neral Formulas for Properties of Cables in Terms of the Properties e Constituent Wires. — The following table gives the principal formulas ncentric-lay cable having a core of one wire.

= total area in circular mils of the component wires measured at right angles to their axes, when laid out straight.
= diameter of cable over-all, in inches.
= diameter of each of the component wires, in inches.
= diameter of core, in inches.

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d_p = pitch diameter, in inches, of any layer (= mean diameter of the made by any layer).
e = elongation, per cent, at which the wires (other than the core) brea
l = number of wires in any layer having pitch diameter d_p.
N = total number of wires except where the core is of special size, in case N is the number of wires exclusive of the core.
n = number of layers of wire over the core.
P = pitch of any layer of wires = distance in inches measured alo axis of the cable for one complete turn of the helix formed by a of this layer.
p = pitch-factor of any layer of wires = ratio of the actual length of to the corresponding axial length of the cable.
R = ratio of wire area to the total area of the circle circumscribing th side of the conductor.
s = stress in pounds per square inch in the core when the elongation
t = tensile strength of each outer wire, in pounds per square inch.
T = tensile strength of conductor, in pounds.
W = weight of conductor, in pounds per foot.
w = weight of each wire of the cable, in pounds per foot.
w_c = weight of the core of the cable, in pounds per foot.

PROPERTIES OF CONCENTRIC-LAY CABLES

		Regular; $d_c = d$	Special; $d_c \neq$
I.	Number of wires in terms of number of layers (and core diameter).	$N = 3(n^2+n)+1$ (including core)	$N = 3\left(n\frac{d_c}{d}+$ (excluding
II.	Diameter of cable in terms of diameter of wires and number of layers.	$D = d(1+2n)$	$D = d_c + 2nd$
III.	Diameter of cable in terms of total area and number of wires.	$D = 10^{-3}\sqrt{\frac{1}{3}\left(4-\frac{1}{N}\right)}\cdot\sqrt{A}$	
IV.	Ratio of wire area to area of circle circumscribing the outside of cable.	$R = \frac{3(n^2+n)+1}{(2n+1)^2}$	
V.	Weight of cable in terms of weight of wire, number of layers and pitch factors.	$W = w$ $(1+6p_6+12p_{12}+$ etc.)	$W = w_c +$ $(1+6p_6+12p_{12}+$
VI.	Strength of cable in terms of strength of the component wires and the pitch factors.	$T = \frac{\pi}{4}d^2$ $\left[s+t\left(\frac{6}{p_6}+\frac{12}{p_{12}}+\text{etc.}\right)\right]$	$T = \frac{\pi}{4}\left[sd_c^2+$ $d^2t\left(\frac{6}{p_6}+\frac{12}{p_{12}}+\text{etc.}\right.$

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PROPERTIES OF CONCENTRIC-LAY CABLES — *Continued*

	Regular; $d_o = d$	Special; $d_o \neq d$
Minimum pitch in terms of wire diameter and core diameter.	$\frac{3\pi d_p}{\sqrt{(n+3)(n-3)}} = 10.1$ times pitch diameter	$\frac{\pi d p l d}{\sqrt{(\pi d_p)^2 - (ld)^2}}$
Diameter of wires in terms of total conductor area and number of wires.	$d = \frac{1}{1000}\sqrt{\frac{A}{N}}$	

ENGTH, ELASTICITY AND EXPANSION COEFFICIENT OF

. — The strength and elasticity of a wire of any material depends to erable extent upon the method of manufacture, heat treatment, etc. ile strength of soft copper is between 25,000 and 35,000 pounds per ch, as against 60,000 pounds per square inch for hard-drawn copper. ue to the greater relative thickness of the hard "skin" and com- y soft "core" of small hard-drawn copper wires as compared with es, the tensile strength, in pounds per square inch, of a small hard- pper wire is greater than the tensile strength of a large hard-drawn r example, a No. 0000 B. & S. hard-drawn copper wire has a tensile of about 50,000 pounds per square inch as against approximately unds per square inch for a No. 18. A similar but smaller variation soft-drawn wires. The tensile strength of steel wire depends to a very nt upon the composition of the steel.

llowing table gives, for a No. 0 A. W. G. wire, representative values rious quantities stated. These values do not hold, except to a rough ation, for other sizes of wire. For further information see articles on *Aluminum*, etc., and the section on *Specifications* below.

NGTH, ELASTICITY AND COEFFICIENT OF EXPANSION
Of a No. 0 A. W. G. or B. & S. Wire

Kind of wire	Tensile strength, lb. per sq. in.	Elastic limit, lb. per sq. in.*	Modulus of elasticity, lb.-in. units	Coefficient of linear expansion per °F.	Coefficient of linear expansion per °C.
oft-drawn	36,000	.....	.....	9.6×10^{-6}	17×10^{-6}
ard-drawn	54,500	30,000	16×10^{6}	9.6×10^{-6}	17×10^{-6}
n, soft-drawn	16,000	.....	.....	12.8×10^{-6}	23×10^{-6}
n, hard-drawn	25,000	25,000	9×10^{6}	12.8×10^{-6}	23×10^{-6}
nd steel, 40% grade	60,000	51,000	22×10^{6}	6.7×10^{-6}	12×10^{-6}
ctric	75,800	55,000	18×10^{6}	8.3×10^{-6}	14.9×10^{-6}
linary	68,000	40,000	24×10^{6} to 30×10^{6}	7.0×10^{-6}	12.6×10^{-6}
rmens-Martin	90,000	45,000		7.0×10^{-6}	12.6×10^{-6}
h strength	150,000	82,000		7.0×10^{-6}	12.6×10^{-6}
ra high strength	225,000	135,000		7.0×10^{-6}	12.6×10^{-6}

is no elastic limit for soft annealed copper and the elastic limits of hard- er and aluminum are doubtful.

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The tensile strength in pounds for solid wires from 1/16 inch to 1/2 inch diameter are given in the following table.

BREAKING LOAD FOR SOLID WIRES IN POUNDS PER WI

Gage No. A.W.G. or B. & S.	Diameter		Hard-drawn copper (Am. Soc. for Test. Mat.)*	Hard-drawn aluminum (23,000 to 33,300 lb. per sq. in.)	Copper-clad steel, 40 per cent grade	Steel (100,0 lb. per sq. in.
	Inches	Mils				
	1/2	500	9310	4520	11,400	19,6
0000		460	8140	3829	10,000	16,6
	7/16	437	7500	3460	9,250	15,5
000		410	6720	3030	8,300	13,8
	3/8	375	5800	2540	7,150	11,9
00		365	5540	2400	6,850	11,4
0		325	4520	1910	5,700	9,4
	5/16	312	4220	1770	5,400	8,9
1		289	3680	1530	4,800	7,9
2		258	3000	1240	4,000	6,5
	1/4	250	2830	1170	3,780	6,2
3		229	2420	1000	3,200	5,2
4		204	1950	810	2,600	4,2
	5/16	187	1680	693	2,300	3,8
5		182	1570	655	2,200	3,6
6		162	1270	532	1,800	2,9
7		144	1020	432	1,450	2,3
8		129	822	351	1,200	1,9
	1/8	125	780	335	1,150	1,8
9		114	660	287	975	1,5
10		102	528	234	800	1,2
11		91	423	191	650	1,0
12		81	337	155	510	8
13		72	268	126	410	6
14		64	213	103	330	5
	1/16	62	203	98	310	5

* Tensile strength in pounds per square inch ranging from 49,000 for No. 0000 66,200 for No. 14; see below.

† For wires having a tensile strength of S pounds per square inch, multiply $S/100{,}000$. The tensile strength of steel varies from 60,000 to 225,000 pounds square inch.

Strength, Elasticity and Expansion Coefficient of Cables.—The following is a summary of the results of tests made on stranded copper wires at the Massachusetts Institute of Technology in 1912. Each figure is the average of a number of individual tests. In determining the modulus of elasticity each cable was given a preliminary stretch before readings were taken.

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MECHANICAL PROPERTIES OF BARE COPPER CABLES

Size of cable A. W. G. or cir. mils	Number of wires in cable	Pitch of layers, inches: First layer	Pitch of layers, inches: Second layer	Modulus, lb.-in. units	Elastic limit, lb. per sq. in.	Tensile strength, lb. per sq. in.
0	7	4.5	...	16.6×10^6	22,000	53,500
300,000	19	7	5	16.4×10^6	21,300	59,800
300,000	19	9	4.5	16.3×10^6	25,000	56,000
300,000	19	9	9	16.5×10^6	24,000	52,600
300,000	19	4.5	3	13.6×10^6	25,300	53,800

OPERTIES OF COMPONENT WIRES OF ABOVE CABLES

Size of component wires, mils	Modulus, lb.-in. units	Elastic limit, lb. per sq. in.	Tensile strength, lb. per sq. in.
125	16.9×10^6	27,000	62,800
125	18.9×10^6	27,000	61,900
125	16.6×10^6	26,000	61,800
125	17.5×10^6	26,000	59,300

by B. Welbourne (Jour. I.E.E., 1917, Vol. indicate that the elastic modulus of copper ries with the number of strands, as shown ompanying table.

Strands	Modulus, lb.-in. units
7	20.0×10^6
19	17.5×10^6
37	15.5×10^6
61	14.0×10^6
91	12.5×10^6

Cable for Catenary Construction. — A of 22×10^6 pound-inch units is representative ry steel messenger cable.

llowing tables are compiled from tables by the General Electric Co. (*Bulletin* High" and "Extra high" strength steel ly be used where absolutely necessary, as, nt of its stiffness, it requires special me- astenings.

STEEL CABLE FOR CATENARY SUSPENSION

alvanized Siemens-Martin Steel Strand, 90,000 Pounds Per Square Inch.

Tensile strength, pounds	Elastic limit, pounds	Elongation, per cent	Lay, inches
3,060	1,830	6 to 9	3
4,860	2,910	6 to 9	3½
6,800	4,080	5 to 8	4
9,000	5,300	5 to 8	4½
11,000	6,600	5 to 8	4½
19,000	11,400	4 to 6	5

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STEEL CABLE FOR CATENARY SUSPENSION — (*Continued*)

Extra-galvanized High-strength Crucible Steel Strand				
Diameter, inches	Tensile strength, pounds	Elastic limit, pounds	Elongation, per cent	Lay, inches
¼	5,100	3,315	3 to 5	3½
5/16	8,100	5,265	3 to 5	4
⅜	11,500	7,475	3 to 5	4½
7/16	15,000	9,500	3 to 5	5
½	18,000	11,700	3 to 5	5
⅝	25,000	16,250	2 to 4	5½

Extra-galvanized Extra-high-strength Plow Steel Strand.				
Diameter, inches	Tensile strength, pounds	Elastic limit pounds	Elongation, per cent	Lay, inches
¼	7,600	5,700	2½ to 4	4
5/16	12,100	9,075	2½ to 4	4½
⅜	17,250	12,930	2½ to 4	5
7/16	22,500	16,800	2½ to 4	5½
½	27,000	20,250	2½ to 4	6
⅝	42,000	31,500	1½ to 3	6½

COMPARISON OF COPPER AND ALUMINUM FOR EQUAL LENGTH AND EQUAL RESISTANCE. — (*See Aluminum.*)

ALUMINUM-STEEL CABLES. — Cables made of a central core of steel, solid or stranded, surrounded by one or more layers of aluminum wire are now finding great favor for aerial lines. Their great advantage is that they may be erected not only with less sag than aluminum but with from 60 to 70 per cent of that of hard-drawn copper.

The modulus of elasticity and temperature coefficient of expansion depend upon the relative cross-section of aluminum and steel. The anchor clamps hold both the aluminum and steel, so that at low temperatures the load is divided between the two metals. As the temperature rises, the aluminum expands faster than the steel and the load gradually shifts over to the steel which in turn stretches more to keep pace with the expanded length of aluminum so that there is no relative motion between the two metals. Eventually the steel carries the total load, and the expansion follows the coefficient for steel only.

Let H_a = fraction of area covered by aluminum,
H_s = fraction of area covered by steel,
M_a = modulus of elasticity of aluminum (9,000,000),
M_s = modulus of elasticity of steel (30,000,000),
M = modulus of elasticity of aluminum-steel cable,
G_a = coefficient of expansion of aluminum (0.0000128),
G_s = coefficient of expansion of steel (0.0000064),
G = coefficient of expansion of cable.

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$$M = M_a H_a + M_s H_s = (9 \times H_a + 30 H_s) 10^6,$$

$$G = \left\{ \frac{1}{1 + \frac{M_a H_a}{M_s H_s}} \right\} G_s - \left\{ \frac{1}{1 + \frac{M_a H_a}{M_s H_s}} - 1 \right\} G_a$$

$$= 0.0000064 \left\{ \frac{1}{1 + 0.3 \frac{H_a}{H_s}} \right\} - 0.0000128 \left\{ \frac{1}{1 + 0.3 \frac{H_a}{H_s}} - 1 \right\}.$$

RENT-CARRYING CAPACITY OF BARE WIRES. — (*See also* * *Rheostats; Wires, Resistance.*) Let d = diameter of conductor in inches, nissible temperature rise in ° C. above surrounding medium (air, earth, or r = resistance of conductor in ohms per mil-foot at final temperature, ent per conductor in amperes. Assuming that the rate of heat radia- unit length of wire is proportional to the difference of temperature the conductor and the surrounding medium and also proportional to ıce of the conductor, then for solid conductors

$$I = K \sqrt{\frac{T d^3}{r}},$$

tranded conductors

$$1.2\, K \sqrt{\frac{T d^3}{r}},$$

is a constant, which depends upon the condition of the surface of the upon the amount of heat convection due to air currents. Values of ant K for air given by different authorities vary from 800 to 1000, r referring to still air and the latter to open air.

S OF BARE WIRES AND CABLES. — The usual tests on bare gaging diameter, measuring tensile strength, elongation, modulus, ıit and electrical conductivity.

; **Diameter.** — (*See also section on Specifications, below.*) The best ge for measuring wire diameters is that shown

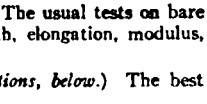


Fig. 4.

The wire is placed between the measuring ınd the screw adjusted until a click occurs. ber of large divisions exposed on the axis is l by 100; the number of small divisions ex- the axis is multiplied by 25; and the sum of items added to the number indicated on the revolving scale. The ıe the diameter of the wire in mils.

Strength, Elongation, Modulus and Elastic Limit. — The essen- es of a wire-testing machine are a means of applying a measurable ce to the wire, and a means of taking up the elongation. Accordingly, testing machine consists of two pairs of jaws for gripping the wire, one connected to a balance lever and the other pair to a power-driven n which draws it in the direction of the axis of the wire. A typical s shown diagrammatically in Fig. 5, where A the two pairs of jaws between which the wire ed. The machine is operated by setting in e mechanism which makes the jaw A move the direction indicated. The operator then counterpoise C by hand, in the direction in-

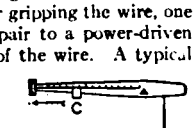


Fig. 5.

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A. C. S. R.				Copper of equivalent resistance	Usual stranding		Elastic limit, pounds	Ultimate strength pounds	Ohms per 1000 feet (61 per cent)	Diameter, inches	Weight-pounds Per 1000 feet			Per cent of total weight	
B. & S. gage No.	Aluminum area				Aluminum	Steel					Total	Al.	Steel	Per cent Al.	Per cent steel
	Circular mils	Square inches	Square millimeters												
.....	605,000	.5656	364.9	380,500	54×.1059	7×.1059	14,675	21,270	.0286	.953	780.0	568.0	212.0	72.8	27.2
.....	500,000	.3927	253.3	314,500	30×.1291	19×.0775	17,140	23,750	.0347	.904	777.0	469.0	308.0	60.4	39.6
.....	336,400	.2642	170.5	No. 4/0	30×.1059	7×.1059	11,715	16,200	.0515	.741	528.0	316.0	212.0	59.8	40.2
.....	266,800	.2094	135.1	No. 3/0	6×.2108	7×.0705	6,470	9,385	.0648	.633	343.0	250.0	93.0	72.8	27.1
No. 4/0	211,600	.1662	107.2	No. 2/0	6×.1880	1×.1880	5,940	8,435	.0816	.564	295.0	199.0	96.0	67.6	32.4
No. 3/0	167,805	.1318	85.03	No. 1/0	6×.1670	1×.1670	4,690	6,660	.1026	.501	232.5	157.0	75.5	67.6	32.4
No. 2/0	133,079	.1045	67.42	No. 1	6×.1490	1×.1490	3,730	5,300	.1294	.447	185.0	125.0	60.0	67.6	32.4
No. 1/0	105,534	.0829	53.48	No. 2	6×.1327	1×.1327	2,960	4,200	.1639	.398	147.0	99.5	47.5	67.6	32.4
No. 1	83,694	.0657	42.39	No. 3	6×.1182	1×.1182	2,355	3,340	.2070	.355	117.0	79.0	38.0	67.6	32.4
No. 2	66,373	.0521	33.61	No. 4	6×.1052	1×.1052	1,860	2,660	.2610	.316	92.4	62.5	29.9	67.6	32.4
No. 3	52,634	.0413	26.65	No. 5	6×.0938	1×.0938	1,480	2,100	.3291	.281	73.4	49.7	23.7	67.6	32.4
No. 4	41,742	.0328	21.16	No. 6	6×.0834	1×.0834	1,170	1,665	.4150	.250	58.0	39.3	18.7	67.6	32.4
No. 5	33,102	.0260	16.77	No. 7	6×.0743	1×.0743	930	1,315	.5217	.223	46.0	31.0	15.0	67.6	32.4
No. 6	26,250	.0206	13.29	No. 8	6×.0661	1×.0661	735	1,045	.6577	.198	36.4	24.6	11.8	67.6	32.4
No. 7	20,816	.0163	10.52	No. 9	6×.0586	1×.0586	575	840	.8295	.176	28.8	19.3	9.2	67.6	32.4
No. 8	16,509	.0130	8.39	No. 10	6×.0529	1×.0529	460	661	1.0458	.158	23.0	15.6	7.4	67.6	32.4

so as to keep the beam balanced. This operation is continued until : breaks, when the elongation of the sample is measured by the travel jaw *A* and its breaking strength by the weight indicated on the beam at the counterpoise *C*.

leasurement of Strain. — The amount by which the wire is stretched ired by means of an extensometer which consists of a pair of clamps to wire at points a definite distance apart, and a magnifying scale for ng the increase of distance between amps as the wire stretches. The rain curve obtained by plotting igations thus measured against sses measured by the machine de- bove is not a true one, as there is an abnormal elongation due to the ning of the wire, as shown by *OA* in Fig. 6. The standard of overcoming this, is described n 8 of the A.S.T.M. *Specification -drawn Copper Wire.*

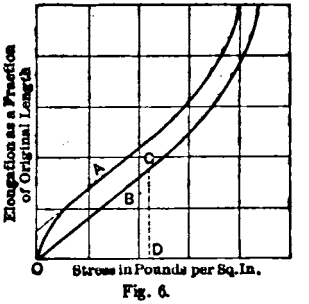


Fig. 6.

lodulus of Elasticity. — The of elasticity is obtained from e of the straight part of the cor- urve. In Fig. 6 the modulus of elasticity is OD/CD pound-inch

lastic Limit. — The true elastic limit can be obtained only by applying of increasing loads, releasing the load (leaving, however, a sufficient eep the wire straight) and measuring the elongation between successive The load at which a permanent elongation begins is the elastic limit.

ictivity. — In order to maintain a wire at a uniform and known tem- it must be short. Unless the wire is very small the test sample will have a very low resistance, and an ordinary Wheatstone bridge will fficiently accurate to measure it. This difficulty is avoided by using a either the Kelvin, Hoop, Willyoung or Reeves type (*see Bridges for Measurements; Resistance and Conductance*).

IFICATIONS FOR COPPER WIRE AND CABLE. — The fol- ecifications for bare copper wire and cable are those prepared by the Society for Testing Materials, 1915 (hard-drawn copper), and 1915 annealed copper), and 1916 (copper cable). See also the article on *ions and Contracts*, and the section on *Specifications* in the article on *l Cables, Insulated*.

IFICATION FOR SOFT OR ANNEALED COPPER WIRE.

General. — The copper shall be of such quality and purity that, awn and annealed, it shall have the properties and characteristics quired.

This specification covers untinned, drawn and annealed round wire.

(*a*) The wire must be free from all imperfections not consistent with commercial practice.

(*b*) Necessary brazes in soft or annealed wire must be made in e with the best commercial practice.

Shipment; Coils, Spools and Reels. — (*a*) Wire may be shipped in reels as agreed upon by the purchaser and manufacturer. In Table I ere are stated the maximum and minimum weights of wire of the stated

sizes which may be shipped in any one package, whether coil, reel or spool. In the case of wire larger than 0.010 inch in diameter, the maximum and minimum package weights are net, and in the case of wire 0.010 inch and less in diameter the maximum package weights are gross, and the minimum package weights are net. The table also states the limiting dimensions of the coils, reels or spools on which wire may be shipped. The length and diameter stated for reels and spools are to be measured over-all and are maximum sizes; reels or spools smaller than these may be used provided the minimum weights called for are carried by the reel or spool. In the table, there are also stated the diameters of the draw-block on which the final drawing of the wire is to be made, when the wire is shipped in coils; it being understood that the wire is not to be reeled after final drawing. This provision is made to insure that coils of wire of any given gage, when supplied by different manufacturers, will be of the same general dimensions.

Wire 0.204 inch in diameter and larger may be shipped in larger packages when agreed upon.

(*b*) The wire shall be protected against damage in ordinary handling and shipping.

TABLE I

Diameters, inches	Package weights, pounds		Diam. of draw-block, inches	Dimensions of reels and spools, inches		
	Max.	Min.		Max. diam.	Max. length	Diam. of barrel for wire
0.460 to 0.360	520	290	24	32	21	1½ to 2
0.359 to 0.258	430	290	24	32	21	1½ to 2
0.257 to 0.129	290	140	22	24	12	1½ to 2
0.128 to 0.102	230	95	22	24	12	⅝ to 1
0.101 to 0.083	230	75	22	24	12	⅝ to 1
0.082 to 0.081	200	75	16	24	12	⅝ to 1
0.080 to 0.064	200	50	16	24	12	⅝ to 1
0.063 to 0.051	120	50	16	24	10	⅝ to 1
0.050 to 0.041	100	50	16	24	10	⅝ to 1
0.040 to 0.032	50	20	8	24	8	⅝ to 1
0.031 to 0.020	25	15	8	10	6½	⅝ to 1
0.019 to 0.011	10	5	8	5½	4	⅝ to 1
0.010 to 0.008	5	2½	8	4	4	⅝ to 1
0.007 to 0.0056	2½	1	6	2½	4	⅝ to 1
0.005	1½	⅝	6	2½	4	⅝ to 1
0.004	1½	⅝	6	2½	4	⅝ to 1
0.003	1	¼	6	2½	4	⅝ to 1

5. **Specific Gravity.** — For the purpose of calculating weights, cross sections, etc., the specific gravity of copper shall be taken as 8.89.

6. **Size and Gaging.** — (*a*) Size shall be expressed as the diameter of the wire in decimal fractions of an inch.

(*b*) Wire shall be accurate in diameter; permissible variations from nominal diameter shall be:

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r wire 0.010 inch in diameter and larger, 1 per cent over or under.
r wire less than 0.010 inch in diameter, 0.1 mil (0.0001 inch) over or under.

Each coil shall be gaged at three places, one near each end and one approxi-ly at the middle; from spools, approximately twelve feet shall be reeled he wire shall be gaged in six places between the second and twelfth foot the end. The coils or spools will be rejected if the average of the measure-s obtained is not within the limits specified in (*b*).

7. **Tensile Strength and Elongation.** — Wire shall be so drawn and aled that its tensile strength shall not be greater and its elongation not than the values stated in Table II. Tensile tests shall be made upon samples, and the elongation shall be determined as the permanent increase ngth, due to the breaking of the wire in tension, measured between bench cs placed upon the wire originally 10 inches apart. The fracture shall be een the bench marks and not closer than 1 inch to either bench mark. If, testing a sample from any coil, reel or spool of wire, the results are found e below the stated value in elongation or above the stated value in tensile ngth, tests upon two additional samples shall be made, and the average of three tests shall determine acceptance or rejection of the coil. For wire se nominal diameter is between listed sizes, the requirements shall be those ie next larger size included in the table.

TABLE II. — ANNEALED COPPER WIRE

Diameter, inches	Tensile strength, lb. per sq. in.	Elongation in 10 in., per cent
0.460–0.290	36,000	35
0.289–0.103	37,000	30
0.102–0.021	38,500	25
0.020–0.003	40,000	20

8. **Resistivity.** — Electric resistivity shall be determined upon fair mples by resistance measurements at a temperature of 20° C. (68° F.) and it ll not exceed 891.58 pounds per mile-ohm (0.15614 ohm per meter-gram).

9. **Testing and Inspection.** — All testing and inspection shall be made the place of manufacture. The manufacturer shall afford the inspector resenting the purchaser all reasonable facilities to satisfy him that the material forms to the requirements of these specifications.

SPECIFICATION FOR HARD-DRAWN COPPER WIRE

1. **General.** — The material shall be copper of such quality and purity that, en drawn hard, it shall have the properties and characteristics herein required.

2. These specifications cover hard-drawn round wire, grooved trolley wire, l figure-eight trolley wire, as hereinafter described.

3. (*a*) The wire, in all shapes, must be free from all imperfections not sistent with the best commercial practice.

(*b*) Necessary brazes in hard-drawn wire must be made in accordance with st commercial practice, and tests upon a section of wire containing a braze ist show at least 95 per cent of the tensile strength of the unbrazed wire. ongation tests are not to be made upon test sections including brazes.

4. **Shipment.** — (*a*) Package sizes for round wire and for cable shall

be agreed upon in the placing of individual orders; standard packages of grooved trolley wire shall be shipped upon reels holding about 2500 pounds each.

(*b*) The wire shall be protected against damage in ordinary handling and shipping.

5. **Specific Gravity.** — For the purpose of calculating weights, cross-sections, etc., the specific gravity of copper shall be taken as 8.89 at 20° C.

6. **Testing and Inspection.** — All testing and inspection shall be made at the place of manufacture. The manufacturer shall afford the inspector representing the purchaser all reasonable facilities to enable him to satisfy himself that the material conforms to the requirements of these specifications.

Hard Drawn Round Wire

7. **Dimensions and Permissible Variations.** — (*a*) Size shall be expressed as the diameter of the wire in decimal fractions of an inch, using not more than three places of decimals; i.e., in mils.

(*b*) Wire is expected to be accurate in diameter; permissible variations from nominal diameter shall be:

For wire 0.100 inch in diameter and larger, one per cent over or under;
For wire less than 0.100 inch in diameter, one mil over or under.

(*c*) Each coil is to be gaged at three places, one near each end, and one approximately at the middle; the coil may be rejected if, two points being within the accepted limits, the third point is off gage more than 2 per cent in the case of wire 0.064 inch in diameter and larger, or more than 3 per cent in the case of wire less than 0.064 inch in diameter.

8. **Physical Test.** — Wire shall be so drawn that its tensile strength and elongation shall be at least equal to the value stated in Table I. Tensile tests shall be made upon fair samples, and the elongation of wire larger in diameter than 0.204 inch shall be determined as the permanent increase in length due to the breaking of the wire in tension, measured between bench marks placed upon the wire originally 10 inches apart. The elongation of wire 0.204 inch in diameter and smaller shall be determined by measurements made between the jaws of the testing machine. The zero length shall be the distance between the jaws when a load equal to 10 per cent of the required ultimate breaking strength shall have been applied, and the final length shall be the distance between the jaws at the time of rupture. The zero length shall be as near 60 inches as possible. The fracture shall be between the bench marks in the case of wire larger than 0.204 inch in diameter and between the jaws in the case of smaller wire, and not closer than 1 inch to either bench mark or jaw. If, upon testing a sample from any coil of wire, the results are found to be below the values stated in the table, tests upon two additional samples shall be made and the average of the three tests shall determine acceptance or rejection of the coil. For wire whose nominal diameter is between listed sizes, the requirements shall be those of the next larger size included in Table I.

9. **Electric Resistivity.** — Electric resistivity shall be determined upon fair samples by resistance measurements at a temperature of 20° C. (68° F.

The wire shall not exceed the following limits:

For diameters 0.460 inch to 0.325 inch, 900.77 pounds per mile-ohm at 20° C.
For diameters 0.324 inch to 0.040 inch, 910.15 pounds per mile-ohm at 20° C.

Grooved Trolley Wire

10. **Sections.** — Standard sections shall be known as the "American Standard" grooved trolley-wire sections, the shape and dimensions of which are as shown in Fig. 1, above.

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TABLE I.—HARD-DRAWN COPPER WIRE

prox. age No., & S.	Diameter, inches	Area, circular mils	Tensile strength, lb. per sq. in.	Elongation, per cent
				in 10 in.
000	0.460	211,600	49,000	3.75
00	0.410	168,100	51,000	3.25
00	0.365	133,225	52,800	2.80
0	0.325	105,625	54,500	2.40
1	0.289	83,520	56,100	2.17
2	0.258	66,565	57,600	1.98
3	0.229	52,440	59,000	1.79
				in 60 in.
4	0.204	41,615	60,100	1.24
5	0.182	33,125	61,200	1.18
	0.165	27,225	62,000	1.14
6	0.162	26,245	62,100	1.14
7	0.144	20,735	63,000	1.09
	0.134	17,956	63,400	1.07
8	0.128	16,385	63,700	1.06
9	0.114	12,995	64,300	1.02
	0.104	10,815	64,800	1.00
10	0.102	10,404	64,900	1.00
	0.092	8,464	65,400	0.97
11	0.091	8,281	65,400	0.97
12	0.081	6,561	65,700	0.95
	0.080	6,400	65,700	0.94
13	0.072	5,184	65,900	0.92
	0.065	4,225	66,200	0.91
14	0.064	4,096	66,200	0.90
15	0.057	3,249	66,400	0.89
	0.051	2,601	66,600	0.87
16	0.045	2,025	66,800	0.86
18	0.040	1,600	67,000	0.85

11. **Dimensions and Permissible Variations.** — (*a*) Size shall l
ressed as the area of cross-section in circular mils, the standard sizes beir
follows:

211,600 circular mils, weighing 3386 pounds per mile.
168,100 circular mils, weighing 2690 pounds per mile.
133,200 circular mils, weighing 2132 pounds per mile.

(*b*) Grooved trolley wire may vary 4 per cent over or under in weight p
it length from standard, as determined from the nominal cross-section.

12. **Physical Tests.** — The physical tests shall be made in the san
anner as those upon round wire. The tensile strength of grooved wi
all be at least 95 per cent of that required for round wire of the same sc
onal area; the elongation shall be the same as that required for round wire
e same sectional area.

13. **Electric Resistivity.** — The requirements for electric resistivit
hall be the same as those for round wire of the same sectional area.

Figure-eight Trolley Wire

14. **Sections.** — Standard sections of figure-eight trolley wire shall be shown in Fig. 2, above.

15. **Requirements.** — The requirements for weight, physical properties and electric resistivity of figure-eight trolley wire shall be the same as for the same sizes of grooved trolley wire.

SPECIFICATION FOR BARE CONCENTRIC-LAY COPPER CABLE: HARD, MEDIUM-HARD, OR SOFT

1. (*a*) **Products Covered.** — These specifications cover bare concentric-lay cables made from round copper wires laid helically around a central core in one or more layers. The central core shall be made of wire having the same quality and temper as the concentric layers, unless otherwise especially provided for in separate specifications governing the individual case.

(*b*) **Classes.** — The purpose for which the several classes of concentric-lay cables are generally used are as follows:

Class *A*, for bare, weatherproof, slow-burning, and slow-burning weatherproof cable for aerial use;

Class *B*, for various insulated cable, such as rubber, paper, varnished cloth, etc.

Class *C*, for cable where greater flexibility is required than in Class *B*.

2. **Requirements of Wires.** — The copper wires entering into the construction of standard concentric-lay cable shall, before stranding, meet all the requirements of that one of the Standard Specifications of the American Society for Testing Materials for Hard-Drawn, Medium Hard-Drawn, or Soft or Annealed Copper Wire (Serial Designations: *B* 1, *B* 2, or *B* 3), which apply.

3. **Brazes.** — Brazes may be made in the wire when finished and ready for cabling. Such brazes shall be made in accordance with the best commercial practice. No brazes in cable made from hard, or medium hard-drawn copper wire may be closer together than 50 feet.

4. **Pitch and Lay.** — The pitch of standard cable shall not be less than 12 nor more than 16 diameters of the cable, and the lay may be right or left handed, unless one direction of lay is specified by the purchaser.

5. **Testing.** — Tests for the physical and electrical properties of the wire composing the cables may be made before, but not after stranding. Experience indicates that the tensile strength of concentric-lay copper cable of standard pitch is at least 90 per cent of the total strength required of the wires forming the cable.

6. **Weights and Area.** — For the purpose of calculating weights, cross-sections, etc., the specific gravity of copper shall be taken as 8.89 at 20° C. The resistance and mass of a stranded conductor are greater than in a solid conductor of the same cross-sectional area, depending on the lay (that is, the pitch of the twist of the wires). Two per cent shall be taken as the standard increment of resistance and of mass. In cases where the lay is definitely known, the increment shall be calculated and not assumed.

7. **Variation in Area.** — The area of cross-section of the completed cable shall not be more than 2 per cent below the area specified, as determined by weight.

8. **Construction.** — The area of cross-section, number and diameter of wires, in standard cable Classes *A*, *B* and *C*, shall be as specified in Table 1.

TABLE I

Area of Cross-section Circular mils.	Approximate A. W. G. or B. & S. gage sizes	Class A		Class B		Class C	
		Number of wires	Diameter of wires mils.	Number of wires	Diameter of wires mils.	Number of wires	Diameter of wires mils
1,000,000	.....	91	148.2	127	125.5	169	108.8
900,000	.....	91	144.5	127	122.3	169	106.6
800,000	.....	91	140.6	127	119.1	169	103.8
700,000	.....	91	136.6	127	115.7	169	100.8
600,000	.....	91	132.6	127	112.2	169	97.8
500,000	.....	61	156.8	91	128.4	127	108.8
400,000	.....	61	151.5	91	124.0	127	105.6
300,000	.....	61	146.0	91	119.5	127	101.2
250,000	.....	61	143.2	91	117.2	127	99.2
200,000	.....	61	140.3	91	114.8	127	97.2
100,000	.....	61	134.3	91	109.9	127	93.1
000,000	.....	61	128.0	61	128.0	91	104.8
950,000	.....	61	124.8	61	124.8	91	102.2
900,000	.....	61	121.5	61	121.5	91	99.4
850,000	.....	61	118.0	61	118.0	91	96.6
800,000	.....	61	114.5	61	114.5	91	93.8
750,000	.....	61	110.9	61	110.9	91	90.8
700,000	.....	61	107.1	61	107.1	91	87.7
650,000	.....	61	103.2	61	103.2	91	84.5
600,000	.....	37	127.3	61	99.2	91	81.2
550,000	.....	37	121.9	61	95.0	91	77.7
500,000	.....	37	116.2	37	116.2	61	90.5
450,000	.....	37	110.3	37	110.3	61	85.9
400,000	.....	19	145.1	37	104.0	61	81.0
350,000	.....	19	135.7	37	97.3	61	75.7
300,000	.....	19	135.7	37	90.0	61	70.1
250,000	.....	19	114.7	37	82.2	61	64.0
212,000	4/0	7-19	173.9-105.5	19	105.5	37-61	75.6-58
168,000	3/0	7-19	155.0- 94.0	19	94.0	37-61	67.3-52
133,000	2/0	7	138.0	19	83.7	37	60.0
106,000	1/0	7	122.8	19	74.5	37	53.4
85,750	1	7	109.3	19	66.4	37	47.6
66,400	2	7	97.4	7	97.4	19	59.1
52,600	3	7	86.7	7	86.7	19	52.6
41,700	4	7	77.2	7	77.2	19	46.9
33,100	5	7	68.8	7	68.8	19	41.7
26,300	6	7	61.2	7	61.2	19	37.2
20,800	7	7	54.5	7	54.5	19	33.1
16,500	8	7	48.6	7	48.6	19	29.5

Note. — Class A cable, sizes 4/0 and 3/0, is usually 7-strand when b and 19-strand when weatherproof, etc.

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9. (*a*) **Packing and Shipping.** — Packing sizes for cable shall be agreed upon in the placing of individual orders.

(*b*) The cable shall be protected against damage in ordinary handling and transportation.

10. (*a*) **Inspection.** — All testing and inspection, both of individual wires entering into the construction of the cable, and of the completed cable, shall be made at the place of manufacture. Tests on individual wires shall be made on samples taken before cabling, and not on wires removed from the completed cable.

(*b*) The manufacturer shall afford the inspector representing the purchaser all reasonable facilities to satisfy him that the material conforms to the requirements of these specifications.

INSTALLATION OF BARE WIRES AND CABLES. — For the installation of wires and cables in buildings see article on *Wiring of Buildings for Light and Power*. Below is given a brief description of modern practice in erecting bare wires and cables on pole or tower lines. For the construction of the latter see articles on *Distribution Lines; Transmission Lines*. Catenary construction is described in the article on *Trolley Systems, Overhead*.

Simple Span Construction with Pin Insulators. — Starting at an anchored pole, a rope about twice the length of the span is put over the cross arm and the wire pulled up by means of it. The rope is then put over the cross arm of the next pole and the wire drawn up in the same way. This is repeated from pole to pole until the reel, which remains at the starting point, is exhausted. The pulling may be done by men, horses, automobile, or locomotive. Care should be taken to prevent the wire unwinding too rapidly from the reel and the end of the wire must be prevented from slipping away.

The wire is placed on the insulators by means of a block and tackle attached either to the arm above or to a temporary boom. The next step is to draw the wires to the proper tension. Commencing at the first pole after the anchor, the wire is gripped by a clamp attached to a rope which is pulled until the wire is drawn to the sag indicated by a table or curve showing the proper sag for different temperatures and spans (*Spans, Wire*). The sag is gauged by sighting from pole to pole, using a gauge or sight on each pole, and drawing the wire until the bottom of the span is tangential to the sight line.

Tying to Insulator. — (*See also Insulators for Overhead Lines.*) The wires are tied to their insulators by small wires, usually of the same metal, as shown in Fig. 7. The two ends of the tie wire (not visible in Fig. 7) are twisted together for three or four turns. The tie wire must be held quite taut while it is being installed.

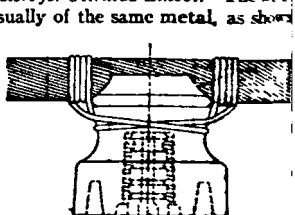


Fig. 7.

Simple Span Construction with Suspension Insulators. — Where suspension insulators are used, the wire, instead of being initially placed over the cross arms, is temporarily suspended therefrom on snatch blocks provided with wooden rollers. Prior to running the cables, linemen are sent ahead to attach the snatch blocks to the arms of the towers. The cables are then strung loosely through the snatch blocks, in much the same way as they are strung over the cross arms in the construction described above. The cables are anchored to the first pole and the necessary tension applied to the cable between the first and second towers, a dynamometer being used to indicate when the required stress point has been reached. The cable is then anchored

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second tower and the operation repeated for the different spans until ble length is exhausted. The cable is then transferred to the insulator , and the anchorages removed except at the ends.

Clamping to Insulator. — The usual type of insulator clamp (Fig. 8) s of a curved, malleable-iron wire seat nine inches long, a saddle which fits over e and a pair of hook bolts to hold the wire between the saddle and wire seat. The at is supported from the insulator through el joint. Copper wire or cable is laid in e seat, the saddle placed on it and the hook laced in position. In the case of alumi- ire a 1/16-inch aluminum sleeve should be around the wire in the clamp. The lamp is then attached to the insulator by a bolt and socket or pin joint.

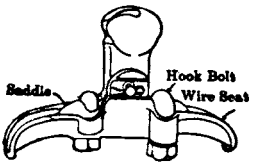


Fig. 8.

ting Conductors. — The following methods are used:

Western Union Joint. — The two ends of the wire are brought to- o that they lap from 3 to 8 inches, depending upon the size. Then ig half-way between the two ends, each wire is wound around the other a tight helix. With hard-drawn copper, excessive stress is avoided by he helix a long pitch for the first turn or two and then gradually reducing h until a tight helix is obtained.

uld appear from tests on galvanized-iron wire by C. T. Rashman (*E. W., l. 56, p. 1187*), that in order to make the joint as strong as the wire, l have the form shown in Fig. 9 which may be described as consisting k of five turns and five end turns at each end.

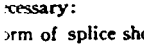


Fig. 9.

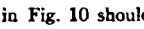

Fig. 10.


Fig. 11.

ler to obtain five turns in the neck, the following length of neck was :cessary:

Size wire, B.W.G.	Length of neck, inches
14	3-½
12	3-¾
10	4
8	6
6	7

orm of splice shown in Fig. 10 should be

Dovetailing Strands. — The cables are l for say three or four feet, dovetailed or d, and the strands individually wound ie unopened part of the cable. The joint soldered or not, as desired.

Aluminum Tube Joint. — Aluminum con- of sizes up to about one-half inch diam- usually jointed by inserting the two e by side into a flat aluminum tube, which given 3 or 4 twists as shown in Fig. 11 by means of a special kind of led connectors.

Pressed Aluminum Joint. — Aluminum conductors larger than one- in diameter are more often jointed by dovetailing the strands, or by cal clamps such as the Dossert connector (*see below*), or by inserting the to a cast aluminum sleeve which is squeezed hydraulically until the ors and sleeve flow into a solid homogeneous mass.

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Dossert Joint and Connector. — The Dossert joint, shown in Fig. 1 consists of a compression sleeve which is slipped over the conductor, a screw



Fig. 12.

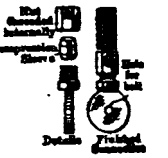


Fig. 13.

the lug proper and a nut threaded with a taper thread. The sleeve contains the conductor is thrust into the lug, with the nut over it. The nut is the tightened until the reaction of the tapered surface and the sleeve gives rise a pressure of several thousand pounds per square inch, thereby making go electrical contact.

The Dossert connector or terminal is similar in construction, and is shown Fig. 13.

BIBLIOGRAPHY. — (*See also bibliographies in the articles on Aluminum Copper; Steel; Wires and Cables, Insulated.*) American Society for Testi Materials, *Standard Specifications* (various); Fowle, F. F., *Electrical Proper of Compound Wires*, El. W., 1910, Vol. 56, pp. 1471, 1521; El. W., 1911, Vol. p. 108; Huber-Stockar. E., *Aluminum for Electric Conductors*, Int. El Congress, Turin, 1911 (contains a bibliography); Kennelly, A. E., Wright, C. and Van Bylevelt, J. S., *The Convection of Heat from Small Copper Wires*, Tra A.I.E.E., 1909, Vol. 28, p. 363 (contains a bibliography); Wolff, F. A. a Dellinger, J. H., *Electrical Conductivity of Commercial Copper*, Bureau of Stan ards Circ. No. 148.

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ES AND CABLES, INSULATED. — (*See also Aluminum; Capac- Charging Current; Copper; Distribution Lines; Electrolysis; Inductance ductive Reactance; Insulating Materials; Resistance; Skin Effect; Stand- the A.I.E.E.; Transmission Lines; Wires and Cables, Bare; Wires, nce; Wiring of Buildings.*)

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MINOLOGY. — The terminology employed in referring to wires and as been in a very confused state, the same term being used with several t meanings. The following terminology is quoted from the *Standards .I.E.E.*

. — A slender rod or filament of drawn metal.

efinition restricts the term to what would ordinarily be understood by the term ire." In the definition the word "slender" is used in the sense that the length in comparison with the diameter. If a wire is covered with insulation, it is called an insulated wire. While primarily the term "wire" refers to the metal, less when the context shows that the wire is insulated the term "wire" will stood to include the insulation.

uctor. —A wire, or combination of wires not insulated from one another, for carrying a single electric current.

rm "conductor" is not to include a combination of conductors insulated from her, which would be suitable for carrying several different electric currents. conductors (such as bus-bars) are, of course, conductors, but are not considered e terminology here given.

ded Conductor. — A conductor composed of a group of wires or any tion of groups of wires.

ires in a stranded conductor are usually twisted or braided together.

d. — One of the wires or groups of wires of any stranded conductor.

ajority of American copper wire manufacturers have used the word "strand" ate a group of bare wires twisted together.

. — (1) A stranded conductor (single-conductor cable; or (2) a combi- f conductors insulated from one another (multiple-conductor cable).

mponent conductors of the second kind of cable may be either solid or stranded, kind of cable may or may not have a common insulating covering. The first able is a single conductor, while the second kind is a group of several conductors. "cable" is applied by some manufacturers to a solid wire heavily insulated covered; this usage arises from the manner of the insulation, but such a con- not included under this definition of "cable." The term "cable" is a general

one and in practice it is usually applied only to the larger sizes. A small cable is call "stranded wire" or a "cord," both of which are defined below. Cables may be bar insulated, and the latter may be armored with lead or steel wires or bands.

Stranded Wire. — A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a fila is subdivided into several smaller filaments or strands and is used as a single wire, called a "stranded wire." There is no sharp dividing line of size between a "stran wire" and a "cable." If used as a wire, for example, in winding inductance coi magnets, it is called a stranded wire and not a cable. If it is substantially insulated, called a "cord," defined below.

Cord. — A small cable, very flexible and substantially insulated to withst wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable." likewise no sharp dividing line in respect to the character of insulation between a "co and a "stranded wire."

Concentric Strand. — A strand composed of a central core surrounded one or more layers of helically laid wires or groups of wires.

Concentric-lay Cable. — A single-conductor cable composed of a con core surrounded by one or more layers of helically laid wires.

Rope-lay Cable. — A single-conductor cable composed of a central c surrounded by one or more layers of helically laid groups of wires.

This kind of cable differs from the preceding in that the main strands are the selves stranded.

N-Conductor Cable. — A combination of N conductors insulated from another.

It is not intended that the name as here given be actually used. One would speak of a "3-conductor cable" and a "12-conductor cable," etc. In referring to general case, one may speak of a "multiple-conductor cable" (as in definition gi above.)

N-Conductor Concentric Cable. — A cable composed of an insula central conducting core with (N-1) tubular stranded conductors laid over concentrically and separated by layers of insulation.

This kind of cable usually has only 2 or 3 conductors. Such cables are used in con ing alternating currents. The remarks on the expression "N-Conductor" given in preceding definition apply here also.

Duplex Cable. — Two insulated single-conductor cables twisted together

They may or may not have a common insulating covering.

Twin Cable. — Two insulated single-conductor cables laid parallel, having common covering.

Twin Wire. — Two small insulated conductors laid parallel, having a com mon covering.

Triplex Cable. — Three insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

Twisted Pair. — Two small insulated conductors twisted together without common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so th the combination is a special case of a "cord."

Sector Cable. — A sector cable is a multiple-conductor cable in which th

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section of each conductor is substantially a sector, an ellipse, or a figure ediate between them.

or cables are used in order to obtain decreased overall diameter and thus permit e of larger conductors in a cable of given diameter.

und Conductor. — A round conductor is either a solid or stranded con- r of which the cross-section is substantially circular.

it Conductor. — A split conductor is a conductor which is divided into ır more parts, separated from one another by insulation which is thin ared with the insulation around the conductor.

term split conductor usually designates a conductor in two parts or splits, which e either concentric or external to one another.

:tor of Assurance. — The factor of assurance of wire or cable insulation ratio of the voltage at which it is tested to that at which it is used.

ulation Resistance. — The insulation resistance of an insulated conductor electrical resistance offered by its insulation, to an impressed voltage ıg to produce a leakage of current through it.

tular Mil. — A circular mil is a unit of area equal to $\frac{\pi}{4}$ (=0.7854 . . .)

quare mil. The cross-sectional area of a circle in circular mils is there- equal to the square of its diameter in mils. A circular inch is equal to a ın circular mils.

y. — The lay of any helical element of a cable is the axial length of a turn : helix of that element.

ong the helical elements of a cable may be each strand in a concentric-lay cable, or nsulated conductor in a multiple conductor cable.

rection of Lay. — The direction of lay is the lateral direction in which rands of a cable run over the top of the cable as they recede from an observer ng along the axis of the cable.

)NSTRUCTION OF INSULATED WIRES AND CABLES. — on the manufacture and properties of insulating materials will be found e articles on *Cambric, Varnished; Gutta-percha; Paper, Impregnated; Rub- Insulating Materials, Miscellaneous.* Data on the conductor itself will be l in the articles on *Copper; Aluminum; Wires and Cables, Bare.*

nductors. — Round copper wire, solid or stranded, is almost invariably for insulated wires and cables. Aluminum, requiring a larger cross-section ie same conductance per unit length, requires more insulating material for ame thickness of insulation. Aluminum cables, however, are sometimes ided with a weatherproof covering.

Stranding. — Conductors are stranded in order to make them more ıle. The cable can then be drawn into a conduit more readily, following ends of the conduit without injury during installation. In the case of cables, flexibility is required first in order to permit them to be put on ; second, to permit easy installation, and third to permit them to be bent ıd the walls of splicing chambers. Cords, elevator cables, mining machine r, etc., must have considerable flexibility in order to permit them to be ily shifted from place to place in service.

ır conduit work it is found unnecessary to strand conductors smaller than 6 A. W. G., although some contractors use stranded conductors as small as 12.

Sector-shaped Conductors. — Two, three and four conductor cables,

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with sector-shaped conductors are in successful use, the three-conductor ty being most common. It has been shown experimentally that if the conduct are properly shaped there will be lower dielectric stresses than in a round ductor cable of the same cross-section. The principal advantage of thi of cable, however, is the greater carrying capacity for a given outside diamet

Preparation of Conductors for Insulation. — Where rubber insula is used it is necessary to cover the conductor with a thin film of tin or with layer of soft cotton threads.

Tinning. — Copper and rubber when brought into contact react on one another chemically. It was formerly thought that this action was due the sulphur in the rubber compound combining with the copper and in t old days, it was common practice to place a layer of pure rubber next to t copper and the regular vulcanized compound over that. It was found, howev that pure rubber reacted with the copper even more vigorously than vulcani rubber containing free sulphur. The pure rubber broke down into a gl sticky mass. It was later found that tinning the copper afforded the neces protection as tin does not react with rubber.

Separators. — Small stranded conductors are usually covered with winding of soft cotton threads for the following purposes:

1. To protect the copper and rubber from mutual chemical action where coating of tin on the copper cannot be used.
2. To hold together a group of fine wires so that individual wires will stand up and penetrate the insulation during the manufacturing process.
3. To prevent adhesion between the rubber and copper in order that the cop may be easily bared for making connections.

A separator composed of a wind of soft cotton is used on cords of various ty for the first and second reasons. A similar cotton wind on small conductors, paper or dry muslin tape on large conductors is used on cables for car wiring the third reason given above.

Insulation. — The materials used for insulation are vulcanized rubber, gut percha, varnished cloth, impregnated paper, asbestos, cotton and silk thre enamel, etc.

Rubber Insulation. — There are two processes by which rubb compound is put on wire, the strip and the tube or seamless processes. By t former, the compound is first made into long narrow strips and then pres around the wire; by the latter, the wire is run through a die through which t compound is pressed on to the wire. Insulation made by the former proc shows a seam or ridge where the sides of the strip have united, unless a tape applied before vulcanization, while that made by the tube process is seamles

Rubber insulating compounds are prepared by mixing rubber gum with s phur, wax and fillers which may be mineral substances or rubber substitut Experience has shown that from 25 per cent to 30 per cent of rubber must used in order to obtain compounds which will resist oxidation when expose the air.

The various grades of rubber insulation on the market may be divided in three classes, known respectively as 30 per cent Hevea, Intermediate and C compounds. The majority of commercial 30 per cent Hevea compounds pro ably fall within the following limits of composition:

Ingredient	Percentage by weight
Rubber	30 to 32
Whiting	0 to 30
Zinc oxide	28 to 67

Ingredient	Percentage by weight
Litharge	1 to 12
Ozokerate	2 to 4
Sulphur	2 to 4

npounds of intermediate grade usually contain less than 30 per cent of . rubber mixed with reclaimed rubber, to make a total of at least 30 per cent ber gum. The other ingredients are similar to those used in 30 per cent . compounds.

e compounds contain a mixture of new and reclaimed rubber, mineral · or black hydrocarbon, sulphur and mineral fillers.

Gutta-Percha is applied to the wire in the same manner as rubber. It l only for deep-sea submarine cables.

Varnished Cloth. — The prepared cloth is applied to the conductor in m of tape wound on helically and reversed every two layers, with over- g joints staggered in successive layers. A thin layer of a non-hardening ; filler is applied between layers.

Impregnated Paper. — Strips of Manila paper are applied helically, ioroughly dried and impregnated with an oily compound.

Asbestos. — Asbestos is used for low-voltage wires to be used in very hot It is applied in the form of threads or tape, usually in several layers. more layers of varnished cloth are sometimes used to separate the groups stos tapes, and the whole is covered with a protecting braid.

Cotton and Silk. — Cotton or silk insulation consists of one to three of threads spun on to the wire.

Enamel. — This type of insulation is suitable only for wires under 10 diameter. Cellulose acetate is a common form of enamel. A solution lose acetate is applied to revolving coating rolls, which, in turn, deposit he moving wire. The quantity of solution placed on the wire must be d to a nicety. After receiving its coating of solution, the wire passes h an oven at the rate of several hundred feet per minute. The volatile is here driven off and the coating hardened, after which the process is d until the required number of coatings have been applied. This method an even distribution of the film over the whole surface of the wire (*R. g*).

rs. — Dry jute or paper is used as a filler between the insulated conductors iple-conductor cables, being placed directly in contact with the insulation. or asphalted jute is used as a filler between the sheath and armor of d cables.

ective Coverings. — Coverings of treated cotton, hemp, paper, rein- rubber, and lead are used to protect cables from mechanical injury and

Cotton Braid. — The most common covering for rubber-insulated tors is a cotton braid saturated with a compound consisting of asphaltic ls and waxy hydrocarbons (principally paraffine wax). The hydrocarbon ic is used to carry the asphaltic material into the fibers.

purpose of this saturation is to protect the cotton against natural deter- n.

melting point of saturating compound is from 118 to 124° F.

saturated cotton is covered with a finishing wax, the purpose of which is he interstices between threads and to afford a smooth surface which will : moisture and permit the wire to be drawn into a conduit with the least

friction. Finishing wax is usually composed of asphaltic material and high grade waxes, such as Carnauba and Montan wax, which are used to give it or lustre.

There are two important grades of finishing wax, one of which has a melting point between 156 and 166° F. and a higher grade which has a melting point between 180 and 190° F.

Weatherproofing. — Treated cotton braid is also put on uninsulated hard-drawn copper wire for overhead service, in order to protect the wire from destructive arcing due to accidental contact with tree branches and other foreign bodies.

Lead Sheath. — The only thoroughly waterproof cable covering yet devised is a lead sheath. It is put over the insulation by passing the cable through a die while hot lead is pressed hydraulically around it through an annular die, forming a continuous and close-fitting pipe. Were it not for electrolytic corrosion, it would be practically permanent. Unfortunately lead is very subject to electrolytic and even chemical corrosion. It is also rendered brittle and eventually breaks into pieces when exposed to vibration, this effect being due to crystallization. Pure lead is suitable for cables which are hard and compact. Other cables require a small quantity of tin to harden the lead. For a given thickness pure lead is cheaper, but for a given tensile strength a 3 per cent tin alloy is cheaper.

Antimony has been used instead of tin with very satisfactory results and material saving in cost, especially with telephone cable.

Armor Wire and Tape. — Submarine cables are usually covered with steel wire armor and cables to be buried direct in the ground are usually covered with galvanized steel tape armor. In either case the armor is covered with asphalted jute.

APPLICATIONS OF VARIOUS TYPES OF CABLES. — The type of insulation and protection to employ in any instance depends upon the purpose for which the conductor is to be used and the place in which it is to be installed.

Power Cables, that is, cables for the transmission or distribution of electric energy, may be installed in buildings, in cars, in underground conduits, on pole lines, or under water.

Wires and cables for buildings are usually rubber insulated and covered with a saturated braid. Varnished cambric is often used for the larger sizes.

Wires and cables for power houses are usually varnished cambric insulated with either a saturated or a flame-proof braid.

Wires and cables for underground conduit lines are almost invariably paper insulated, but rubber or varnished cambric are sometimes used.

Wires for mining machinery and for railway signals are invariably rubber insulated.

Submarine Power Cables are usually insulated with rubber, sometimes sheathed in lead and armored with wire or steel bands. In recent years, however, paper-insulated lead-sheathed and armored submarines have come into extensive use.

Communication Wires and Cables, that is, wires and cables for telephone and telegraph service, are rubber insulated where only two or three conductors are required. Cables composed of many pairs are generally insulated with dry paper and are known as dry-core cables.

Submarine telegraph cables are insulated either with gutta-percha or vulcanized rubber, the former if for deep-sea use. Such cables are protected by jute and steel wire armor.

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ulated Conductors for Instrument and Machine Windings. — Enam- ire or wire insulated with cotton or silk is used for the former, while hed cambric, mica and asbestos compounds are used for the latter.

ULATION THICKNESS. — The thickness of insulation required for ltage cables is merely that necessitated by inevitable irregularities of acture and roughness in handling. At voltages between 500 and 1000, lectric stress begins to have an influence and when 2000 volts are reached, lectric stress becomes the dominant factor. If certain assumptions are the thickness of insulation corresponding to a given dielectric stress e calculated, but these assumptions are only partially realized in e. These assumptions are:

hat the radial depth of the insulation or dielectric is the same at all i.e., that the cross-section of the cable is a perfect circle with the con- section (also a perfect circle) exactly in the center of the insulation. Due, r, to the crinkling of tape, the pressure of the braid, or other accidents ufacture, this is never the case. The eccentricity of the conductor with to the insulation may, however, be allowed for by adding to the theoreti- kness of insulation an additional thickness, known as the "error thick- r excess thickness.

hat the dielectric is perfectly homogeneous throughout. This is never l in practice. It is probable that even in the most carefully made on there is a minute amount of air and moisture, but sufficient to considerably any conclusions based on absolute homogeneity of the ic. In the case of impregnated paper, the lack of homogeneity results rtant departures from the following law.

hat when the electric stress, or potential gradient at any part of the dielec- eeds a certain value F_s known as its dielectric strength, that part of the ic becomes a partial conductor even though there is no actual rupture turing.

assumption is made only in the case of rubber insulation, and then en the electric stress is applied for a considerable time. The internal wn of the rubber appears to be due to the ionization of the air between ber and conductor, the rubber being oxidized, split internally, and show- er signs of disintegration. (See C. A. Adams, Trans. A.I.E.E., 1917, . pp. 514–517.)

retical Thickness of Insulation. — Let

otential gradient, in kilovolts per centimeter, at any point P in the dielectric at a distance x centimeters from the center of the wire, Fig. 1,

ilovolts between wire and sheath (or outside surface of insulation).

adius of wire, in centimeters,

utside radius of insulation, in centimeters,

ielectric strength of the insulation, in kilovolts per centimeter.

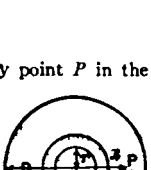


Fig. 1.

on the assumption of a perfectly homogeneous dielectric and perfect try between conductor and insulation,

$$F = \frac{E}{x \log_e \left(\frac{R}{r}\right)}.$$

, the potential gradient is the greatest at the surface of the conductor

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and decreases toward the outer surface of the insulation as shown in Fig. The potential gradient at the surface of the conductor is

$$F_{max} = \frac{E}{r \log_e \left(\frac{R}{r}\right)}.$$

For the same outside diameter of the insulation this stress at the surface va with the radius of the conductor as shown in Fig. 3, and has a minimum va theoretically when $r = R/2.72$, but actually when R/r is somewhat gre than 2.72.

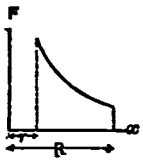


Fig. 2.

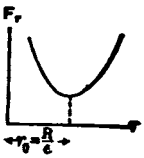


Fig. 3.

Consequently, if the breakdown of a cable is a progressive action, i.e., if insulation breaks down close to the wire and then the breakdown spreads through the insulation, it is evident, from Fig. 3, that if r is greater than R and the impressed voltage E is such as to produce a stress F_r at the sur of the conductor in excess of F_s, then as successive layers of the insulation br down, F_r at each new conducting surface thus formed will be greater than and the breakdown will rapidly extend to the sheath. If, however, r is than $R/2.72$, then a value of F_r in excess of F_s will break down only a suf layer of insulation to render the value of F_r at the new conducting surface formed just equal to F_s.

Therefore, on the basis of the assumptions noted in the preceding sec the maximum voltage which a cable can withstand is equal to

$$E_m = F_s r \log_e \left(\frac{R}{r}\right),$$

provided R/r is less than 2.72, but when R/r is greater than 2.72 the maxim voltage is

$$E_m = F_s r_0 \log_e \left(\frac{R}{r_0}\right) = \frac{RF_s}{2.72},$$

and is *independent of the radius of the conductor.*

If there are films or globules of air in the insulation the dielectric stress in th will be greater than in the surrounding insulation in the ratio of the dielectr constant of the insulation to that of the air. As the dielectric constants common insulating materials are between twice and five times that of air, th air will be stressed between two and five times as much as the insulation. air ionizes at a much lower stress than the dielectric strength of the insulatio the limiting working voltage of a cable may depend upon the effects of i ionization. In the case of rubber insulation the principal effect is oxidation ozone, but in the case of paper or varnished cambric the energy loss due ionization is the most serious matter.

Practical Determination of Insulation Thickness. — On account of th numerous assumptions which must be made in determining the necessa thickness of insulation from any simple theory, such as outlined above, a theor

little value in the generality of cases and reliance must be placed upon ence, as embodied in the standards of various associations.

RUBBER INSULATION

Thickness of Insulation in 64ths of an Inch

ting ure, its een es	Nat. Elec. Code * and A.I.E.E. Standard			A.I.E.E. Standard,† 30–40 per cent hevea	
	Size of wire, A. W. G. or B. & S. and Cir. Mils.	Insulation thickness, on each wire	Working pressure, volts, a-c.	Size of wire,	Insulation thickness
00	18–16	2	8,000	All	18
00	14–8	3	9,000	All	20
00	7–2	4	10,000	All	22
00	1–0000	5	11,000	All	24
00	225,000–500,000	6			
00	525,000–1,000,000	7			
00	1,100,000–2,000,000	8			
00	14–8	6			
00	7–2	7			
00	1–0000	8			
00	225,000–500,000	9			
00	525,000–1,000,000	10			
00	1,100,000–2,200,000	10			
00	14–8	8			
00	7–2	9			
00	1–2,000,000	10			
00	14–0000	10			
00	225,000–500,000	11			
00	525,000–2,000,000	12			
000	14–1,000,000	12			
000	1,100,000–2,000,000	14			
000	14–1,000,000	16			
000	1,100,000–2,000,000	18			

Railway Signal Association ‡ 666 volts or less			
Single conductor		Multi-conductor	
Size of wire, A. W. G. or B. & S.	Insulation thickness, 64ths inch	Size of wire, A. W. G. or B. & S.	Insulation thickness, 64ths inch
18–16	4	16	3
14–9	5	14–10	4
8–4	6	9–6	5
2–0	8	4	6

* The rubber to comply with the rubber specification of the National Board of e Underwriters, which assumes the use of 20 per cent of rubber gum.

† The A.I.E.E. Standards for 600 to 7000 volts are identical with the code xpt that they cover only 30 to 40 per cent hevea insulation and that for ltiple conductor cables of any voltage the thickness of insulation on each nductor shall be based on the highest r.m.s. voltage between the conductor d the outside of the insulation.

‡ The rubber insulation to comply with the specifications of the R.S.A., which lls for a very high-grade 30 per cent Para compound.

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VARNISHED CLOTH AND IMPREGNATED PAPER

Insulation Thickness

(Wall thickness for single-conductor cables and thickness between conductors for multiple-conductor cables.)

(*G. E. Co. Practice*)

Working pressure, volts between wires	Varnished cloth		Impregnated paper	
	Size, A. W. G. or B. & S. and Cir. Mils	Insulation thickness,* 64ths inch	Size, A. W. G. or B. & S. and Cir. Mils	Insulation thickness,* 64ths inch
600†	6–2	6	6–2	4
600	1–0000	8	1–0000	5
600	250,000–500,000	10	225,000–500,000	6
600	550,000 and over	12	550,000–1,000,000	7
1,000	6–2	4	12–2	5
1,000	1–0000	5	1–0000	6
1,000	250,000–500,000	6	.....	..
1,000	550,000–1,000,000	7	225,000–500,000	7
1,000	1,100,000 and over	8	550,000–2,000,000	8
2,000	6–0000	6	10–0000	7
2,000	250,000–500,000	7	225,000–500,000	8
2,000	550,000–2,000,000	8	550,000–2,000,000	9
3,000‡	All sizes	8	8 and larger	10
4,000	All sizes	10	8 and larger	12
5,000	All sizes	12	6 and larger	14
.....	.....	.....	6 and larger	16
7,000	All sizes	14	5 and larger	18
8,500	All sizes	16	.....	..
.....	.....	.....	5 and larger	20
11,500	All sizes	20	4 and larger	22
13,500	All sizes	24	.....	..
14,000	All sizes	24	4 and larger	24
15,000	All sizes	26	3 and larger	26
16,000	All sizes	26	.....	..
17,000	All sizes	28	3 and larger	28
18,000	All sizes	28	.....	..
19,000	All sizes	30	2 and larger	30

* Above working voltages are based on all conductors of the circuit being insulated. For d-c 600-volt railway single-conductor, leaded cables, use 1,000-volt class. For three-phase "Y"-connected circuits with grounded neutral and three-conductor cables, thickness of insulation between conductors and ground may only be 1/10 of that between conductors.

† For three-conductor cables only, use 1,000-volt class for single-conductors from 0 to 1,000 volts.

‡ For three-conductor cables use 5/64 in. for No. 6 to No. 0000, 6/64 in. for 250,000 to 500,000 cir. mils and 7/64 in. for larger sizes.

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PAPER INSULATED CABLE

ulation Thicknesses of Cables of Various Light and Power Companies

3 and 4 Conductor Cables

Name of company	Operating voltage	Size A. W. G. or Cir. Mil.	Insulation, Conductor	64ths inch Belt
go	33,000	350,000	19	7
ukee	26,400	#00	18	18
nore	26,000	#0000	18	10
n	25,000	.....	18	12
York Edison	24,000	350,000	17	8
it	23,000	#00	18	14
o	23,000	300,000	18	14
and	22,000	#2	20	20
go	22,000	350,000	19	7
urgh	22,000	250,000	18	10
ngeles	20,000	#0000	16	16
York Edison	15,000	350,000	14	14
ancisco	15,000	#0000	13	13
ukee	13,200	.....	14	14
ille	13,200	250,000	14	14
	13,200	133,000	12	10
ington	13,200	#0000	12	12
ore	13,000	#0000	16	4
o	12,000	500,000	13	6
ngeles	12,000	#0000	14	14
and	11,000	#0000	16	4
urgh	11,000	#0000	14	12
York Edison	8,000	350,000	10	10
ille	7,500	#8	8	8
ore	6,600	#0000	10	8
	6,600	250,000	8	8
ancisco	5,000	#0000	8	8
	4,800	200,000	10	10
and	4,600	#0000	8	8
ille	4,000	250,000	10	10
ore	4,000	#0	8	6
o	4,000	#0	6	5
ille	4,000	#0000	6	6
ngeles	2,500	#0000	6	6
ancisco	2,500	#0000	6	6
and	2,300	#0	6	4
urgh	2,300	#0000	8	6
ancisco	750	#0000	4	4

n, Silk and Enamel. — The thicknesses rated by various manufa
s "single," "double," and "triple" covered differ by several mils; s
on *Electromagnet Windings*. Enamel insulation will stand a workir
l of about 500 volts alternating per mil of thickness. Silk or cott
d about one-quarter as much.

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WEIGHT OF INSULATED WIRES AND CABLES. — So many ables enter into the weight of an insulated wire or cable, and there are so forms in use, that it is impossible to give comprehensive tables here reader is referred to the catalogues and circulars of the manufacturing com When such sources of data are not available the weight may be calculated the dimensions of the cable by finding the sum of the weights of the cond and the weights of the insulation, braid, tape, sheath, etc. The weight conductor may be found in the wire tables under *Wires and Cables, Bare.* weight of the insulation, braid, tape or sheath, may be found by calcu the cross-section of each of these materials and multiplying by the leng the cable and a factor proportional to the density of the material; see accompanying.

The cross-section of a tube having an internal diameter d and thick is $\pi t(d+t)$. When the diameter and thickness are in inches and the spe gravity of the material forming the tube is δ, then the weight in pounds per feet of tube is

$$W = 1362\,\delta(d+t).$$

The values of the specific gravity δ, the product $1362\,\delta$, and the weight per in., for the various materials used in the construction of cables are given in accompanying table. From this relation the weight per 1000 feet of any tub (circular cross-section) layer of insulation, braid tape or sheath may be read calculated. The formula is, therefore, directly applicable to single-con cables.

The weight of duplex or triplex cables is calculated as for a group of conductor cables, except with regard to the fillers. The cross-section filling material is most readily calculated by subtracting from the cross of the entire cable the cross-sections of the individual conductors and the insulation, sheath, etc. The weight of twin cables can also be readily f calculating the cross-section of the various parts in inches and multip the length and the proper density factor.

The weight of separators in pounds per 1000 feet is usually between

WEIGHTS OF CABLE INSULATION

Material	Specific gravity, δ	Pounds per cubic inch, $0.03613\,\delta$	$1362\,\delta$
Rubber compound, 30 per cent para:			
Organic base	1.2	0.0434	1635
Mineral base	1.5 to 2.0	0.054 to 0.072	2043 to 27
Varnished cloth	1.26	0.455	1720
Paper, impregnated	1.5	0.054	2043
Lead	11.4	0.411	15.530
Braid, untreated	1.11	0.0402	1515
Braid, saturated	1.33	0.0480	1809
Tarred jute, in cable	0.534	0.0193	728
Dry jute, in cable	0.267	0.00965	364
Dry hemp, in cable	0.267	0.00965	364
Gutta percha	1.0	0.0361	1361
Rubber filled tape	1.0	0.0361	1362

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es the mean diameter, expressed in inches, of the conductor and sepa-

weight of saturated braids per 1000 feet is from 12 to 30 times the diameter e insulation expressed in inches.
corresponding multiplier for 12 mil tape with ½ lap, is 24.

ULATION RESISTANCE. — The insulation resistance of a cable is r expressed in megohm-miles, sometimes erroneously called megohms ile. The total insulation resistance of a cable varies inversely as its e.g., a cable two miles long has half the resistance between conductor eath of a length of one mile of this cable. The formulas for insulation ce of various types of cables are given below.

le-conductor Cable. — In absolute units the insulation resistance of a of l centimeters of such a cable is

$$R' = \frac{\rho}{2\pi l} \log_e \frac{D}{d},$$

d = diameter of conductor, D = outside diameter of insulation, R = insula- istance, l = axial length, ρ = specific resistance. From the above formula ohm-miles are

$$R = k \log_{10} \frac{D}{d},$$

k = 0.43 × (specific resistance in millions of megohms per centimeter cube)

two diameters are d either in inches centimeters. The k for various types ation at 60° F., n electrification of nately one minute constant d-c. volt- iven in the accom- table. k varies ith the time of ation and with the ture.

Insulation	k at 60° F.	
	Limits	Usual values
Vulcanized rubber.	780 to 23,000	3000 to 6000
Gutta-percha.....	500 to 4,000	2500
Varnished cloth....	400 to 1,200	700
Impregnated paper.	1000 to 3,000	1500

ables on the following pages give the value of $\log_{10} \frac{D}{d}$ for various sizes of l thicknesses of insulation.

insulation resistance be measured with alternating current, it will o be much less than with direct current because of the dielectric loss.

and Three-conductor Cable in Lead Sheath. — The insulation e between the two conductors of a two-conductor cable is practically hat between each conductor separately and the sheath.
nsulation resistance of a three-conductor cable between any one con- nd the other two conductors and the sheath is approximately one-half between each conductor separately and the sheath. Simple formulas e resistances in terms of the dimensions of the cable are not available, arious parts of the coverings (insulation, fillers and braids) have differ- tivities.

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$\text{LOG}_{10} \frac{D}{d}$ FOR SOLID WIRES

Size wire, A. W. G. or B. & S.	d inches	Insulation thickness, 64ths of an inch						
		3	4	5	6	7	8	9
14	0.064	0.393	0.470	0.537	0.595	0.645	0.691	0.732
12	0.081	0.334	0.405	0.467	0.521	0.568	0.613	0.650
10	0.102	0.283	0.348	0.403	0.453	0.498	0.538	0.574
8	0.129	0.238	0.294	0.344	0.391	0.431	0.468	0.502
6	0.162	0.199	0.248	0.292	0.334	0.371	0.405	0.436
4	0.204	0.164	0.207	0.246	0.283	0.316	0.346	0.377
2	0.258	0.134	0.170	0.207	0.238	0.267	0.294	0.320
1	0.289	0.124	0.155	0.188	0.217	0.243	0.270	0.294
0	0.325	0.111	0.140	0.170	0.199	0.223	0.248	0.270
00	0.365	0.100	0.127	0.155	0.182	0.204	0.225	0.248
000	0.410	0.090	0.114	0.140	0.164	0.185	0.207	0.226
0000	0.460	0.079	0.104	0.127	0.149	0.170	0.188	0.207

Size wire, A. W. G. or B. & S.	d inches	Insulation thickness, 64ths of an inch						
		11	12	14	16	18	20	22
14	0.064	0.804	0.836	0.894	0.945	0.991	1.032	1.070
12	0.081	0.720	0.751	0.807	0.856	0.900	0.941	0.977
10	0.102	0.640	0.670	0.723	0.771	0.814	0.853	0.889
8	0.129	0.565	0.592	0.642	0.688	0.729	0.766	0.803
6	0.162	0.494	0.520	0.568	0.611	0.650	0.687	0.720
4	0.204	0.428	0.453	0.498	0.538	0.575	0.609	0.640
2	0.258	0.367	0.389	0.431	0.468	0.502	0.534	0.565
1	0.289	0.340	0.362	0.401	0.436	0.470	0.500	0.529
0	0.325	0.314	0.332	0.371	0.405	0.436	0.465	0.496
00	0.365	0.288	0.307	0.342	0.377	0.405	0.433	0.461
000	0.410	0.265	0.281	0.316	0.346	0.375	0.401	0.428
0000	0.460	0.243	0.260	0.290	0.320	0.346	0.373	0.398

d = diameter of wire; D = outside diameter of insulation.

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$\text{LOG}_{10} \frac{D}{d}$ FOR CABLES (STRANDED WIRES)

d inches	Insulation thickness, 64ths of an inch							
	3	4	5	6	7	8	9	10
0.073	0.360	0.433	0.497	0.553	0.602	0.646	0.686	0.724
0.092	0.307	0.373	0.431	0.483	0.529	0.571	0.607	0.643
0.116	0.258	0.318	0.369	0.418	0.461	0.498	0.534	0.568
0.146	0.215	0.267	0.316	0.360	0.398	0.433	0.470	0.497
0.184	.....	0.225	0.267	0.305	0.340	0.373	0.403	0.431
0.232	.....	0.188	0.223	0.258	0.288	0.316	0.344	0.371
0.292	.....	0.152	0.185	0.215	0.241	0.267	0.290	0.314
0.332	.....	0.140	0.167	0.196	0.220	0.243	0.267	0.288
0.373	.....	0.127	0.152	0.179	0.201	0.225	0.246	0.267
0.419	.....	.....	0.137	0.161	0.182	0.201	0.223	0.243
0.471	.....	.....	0.124	0.146	0.167	0.185	0.204	0.220
0.529	.....	.....	0.114	0.130	0.149	0.167	0.185	0.201
0.575	.....	.....	0.104	0.124	0.140	0.158	0.173	0.190
0.632	.....	.....	0.097	0.114	0.130	0.146	0.161	0.176
0.681	.....	.....	0.090	0.104	0.121	0.137	0.149	0.164
0.728	.....	.....	0.083	0.100	0.114	0.127	0.143	0.155
0.772	.....	.....	0.079	0.093	0.107	0.121	0.137	0.149
0.815	.....	.....	0.076	0.090	0.104	0.117	0.130	0.140
0.893	.....	.....	.....	0.086	0.097	0.111	0.121	0.130
0.964	.....	.....	.....	0.079	0.090	0.100	0.111	0.124
0.998	.....	.....	.....	0.074	0.085	0.097	0.107	0.118
1.031	.....	.....	.....	0.073	0.084	0.094	0.104	0.115
1.094	.....	.....	.....	0.069	0.079	0.089	0.099	0.109
1.153	.....	.....	.....	0.066	0.076	0.085	0.095	0.104
1.289	.....	.....	.....	0.059	0.068	0.077	0.086	0.094
1.413	.....	.....	.....	0.054	0.063	0.071	0.078	0.087
1.526	.....	.....	.....	0.050	0.058	0.066	0.073	0.081
1.632	.....	.....	.....	0.047	0.055	0.062	0.069	0.076

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$\text{LOG}_{10}\frac{D}{d}$ FOR CABLES (STRANDED WIRES)

Size wire, A.W.G. or B. & S. and C. M.	d inches	Insulation thickness, 64ths of an inch							
		11	12	14	16	18	20	22	
14	0.073	0.757	0.788	0.845	0.895	0.940	0.980	1.018	1.
12	0.092	0.676	0.705	0.760	0.809	0.852	0.892	0.928	0.
10	0.116	0.598	0.626	0.679	0.725	0.767	0.806	0.841	0.
8	0.146	0.525	0.553	0.602	0.645	0.686	0.723	0.757	0.
6	0.184	0.458	0.483	0.529	0.571	0.609	0.643	0.676	0.
4	0.232	0.394	0.418	0.461	0.498	0.534	0.567	0.598	0.
2	0.296	0.334	0.356	0.394	0.430	0.462	0.493	0.521	0.
1	0.332	0.310	0.328	0.365	0.398	0.431	0.459	0.487	0.
0	0.373	0.286	0.305	0.338	0.371	0.401	0.430	0.455	0.
00	0.419	0.260	0.276	0.310	0.340	0.369	0.396	0.422	0.
000	0.471	0.238	0.255	0.286	0.314	0.342	0.367	0.391	0.
0000	0.529	0.217	0.233	0.260	0.290	0.314	0.338	0.362	0.
250,000	0.575	0.204	0.217	0.246	0.272	0.297	0.320	0.342	0.
300,000	0.632	0.190	0.204	0.230	0.255	0.276	0.299	0.320	0.
350,000	0.681	0.176	0.190	0.215	0.238	0.262	0.283	0.303	0.
400,000	0.728	0.167	0.182	0.204	0.228	0.250	0.270	0.290	0.
450,000	0.772	0.161	0.173	0.196	0.217	0.238	0.258	0.276	0.
500,000	0.815	0.152	0.164	0.188	0.210	0.228	0.248	0.267	0.
600,000	0.833	0.143	0.152	0.173	0.193	0.212	0.230	0.248	0.
700,000	0.964	0.134	0.143	0.164	0.182	0.201	0.217	0.236	0.
750,000	0.998	0.129	0.138	0.158	0.176	0.196	0.211	0.228	0.
800,000	1.031	0.125	0.135	0.154	0.172	0.189	0.206	0.222	0.
900,000	1.094	0.118	0.128	0.146	0.163	0.180	0.196	0.212	0.
1,000,000	1.153	0.113	0.122	0.140	0.157	0.173	0.188	0.203	0.
1,250,000	1.289	0.103	0.111	0.127	0.142	0.157	0.172	0.186	0.
1,500,000	1.413	0.094	0.102	0.117	0.132	0.146	0.159	0.172	0.
1,750,000	1.526	0.088	0.096	0.110	0.123	0.136	0.149	0.162	0.
2,000,000	1.632	0.083	0.090	0.103	0.116	0.129	0.141	0.153	0.

CAPACITY AND CHARGING CURRENT. — See article on *Capa and Charging Current.*

INDUCTANCE, REACTANCE AND IMPEDANCE. — The formu for bare wires and cables (*see Inductance and Inductive Reactance*) are also plicable to lead-sheathed insulated cables, the insulation and sheath produc practically no effect on the self inductance.

Resistance and Impedance of Three-conductor Cables. — The follo ing table, published by the G. E. Co., is based upon 100 per cent conductiv copper at 75° F., with an allowance of 3 per cent for spiral path of the compos wires, 60 cycles per second, and standard thicknesses of varnished cam insulation.

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NCE AND IMPEDANCE OF THREE-CONDUCTOR COPPER CABLES

Resistance ohms of each conductor per mile R	Impedance of each conductor at 60 cycles, ohms per mile, z					
	Working voltage between wires					
	3000	5000	7000	10,000	15,000	20,000
0.850	0.858	0.859	0.863	0.867	0.872	0.884
0.674	0.692	0.696	0.700	0.706	0.712	0.724
0.535	0.545	0.547	0.552	0.558	0.565	0.580
0.424	0.436	0.439	0.444	0.452	0.460	0.478
0.336	0.352	0.352	0.357	0.365	0.374	0.396
0.267	0.280	0.283	0.288	0.296	0.306	0.332
0.227	0.245	0.245	0.252	0.261	0.272	0.299
0.188	0.210	0.210	0.217	0.227	0.241	0.270
0.161	0.187	0.187	0.194	0.204	0.217	0.250
0.141	0.166	0.166	0.174	0.185	0.199	0.234
0.127	0.148	0.148	0.156	0.167	0.182	0.221
0.113	0.137	0.137	0.144	0.156	0.172	0.212

e is $x = \sqrt{z^2 - r^2}$; the inductance is $L = x \div 2\pi f$ where f is the cles per second.

and Reactance of a Pair of Armored Single-conductor J. B. Whitehead (*Trans. A.I.E.E., 1909, Vol. 28, p. 737*), gives rmula for the self inductance of each of two parallel armored cables:

$$L = 0.161 \left\{ 2 \log_e \frac{D}{r} + \frac{1}{2} \right\} + 0.078\,(k - 1),$$

nrys per mile of each conductor,
ce between centers of conductors, any unit,
of each conductor, in same unit as D,
6, depending upon the permeability of the armor wires.

l paper concludes as follows: 1. Theoretically the reactance of single-conductor, iron-armored power cable may be from of unarmored cable, depending on the distance to return or increases with decreasing distance. 2. In cables as manuance is about 0.7 of the maximum theoretical value as calcue formula. 3. The effective resistance at 25 and 60 cycles times respectively the d-c. resistance for a current density 00 circular mils, and varies little with the distance between ie impedance for distances under 12 inches is about 3 times t 60 cycles and 1.7 to 2 times the d-c. resistance at 25 cycles. and the armor grounded at both ends the impedance is nd is largely of the nature of resistance. 5. The impedance or iron-armored cable with conductors located 0.873 inch ers and at the current density given above is about 5 per cles and 3 per cent greater at 25 cycles than the calculated is in effective resistance, due to eddy currents in the lead

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H. W. Fisher (*Trans. A.I.E.E., 1909, Vol. 28, p. 747*) says that the impedance of armored cables cannot be calculated with any degree of certainty owing to the effect of slight differences in the air gaps between armor wires. He finds that a single-conductor No. 0 B. & S. cable armored with two flat bands of steel (0.39×1.) may have a maximum effective resistance 8 times the direct resistance when the lead and armor are disconnected, and that under practical conditions of operation the ratio is about 3.5. With larger cables the ratio will be greater.

Unless the armor and lead of single-conductor cables are bonded together arcs may occur between them and under water they would be injured by alternating-current electrolysis. Single-conductor steel armored cables cannot be used with 60-cycle currents greater than 8 or 10 amperes because of the inductance and losses due to hysteresis and eddy currents.

CURRENT-CARRYING CAPACITY OF WIRES AND CABLES. The maximum permissible temperature rise of insulated conductors is limited by the effect of heat upon the insulation. The highest temperatures which may be safely attained continuously are given in the table below.

Insulation	Maximum permissible temperature centigrade	
	Low voltage	At E kv. between conductors
Impregnated paper...	85	$85-E$
Varnished cambric...	75	$75-E$
Rubber insulation....	60	$60-0.25E$

When rubber is heated, the usual order of events is as follows: Oxidation is accelerated if air is present, "devulcanization" commences, i.e., the rubber molecule breaks up without, however, liberating any sulphur; vulcanization proceeds until all the free sulphur has combined with the rubber or mineral matter. In the case of varnished cambric, both the insulation resistance and dielectric strength fall quite rapidly after the limiting temperature is attained. The same applies to impregnated paper in a less degree. Furthermore, at high voltages, the dielectric loss is often considerable, and if neglected in calculating carrying capacity, is likely to make one overlook possibilities of temperatures far in excess of those to be expected on the basis of I^2R losses alone. The A.I.E.E. rule for high voltage cables may be assumed to refer to temperatures calculated on the assumption that the only losses are ohmic losses in the conductor. Hence, if the A.I.E.E. temperatures are used, dielectric losses may be neglected and the carrying capacities derived from these temperatures may be used with safety. The A.I.E.E. rule is equivalent to assuming that the dielectric loss in watts per foot are equal to $12\frac{E}{R}$ (see below).

Where, however, cables of either very low or very high dielectric loss are used it may be advisable to calculate the carrying capacity, taking the dielectric loss into account, as in the former case a higher, and in the latter case, a lower carrying capacity will be obtained than when the A.I.E.E. rule is followed.

ormula for Carrying Capacity, Using A.I.E.E. Rule. — Where the cable truction or operating conditions are unusual, the carrying capacity may be ulated from the following formula.

$$I = 110\sqrt{\frac{T}{rR}},$$

re I = amperes,
T = permissible temperature rise, degrees centigrade,
r = electrical resistance per 1000 feet of each conductor in ohms (the factor 110 would become unity if r were expressed in ohms per inch),
R = heat resistance, from conductor to air, in degrees, centigrade rise per watt lost in each inch of conductor (see below).

ormula for Carrying Capacity, Using Actual Dielectric Loss. — When desired to take into account the dielectric loss, an approximation may be e by assuming the entire dielectric loss to occur at the surfaces of the con- ors. Then:

$$I = 110\sqrt{\frac{1}{r}\left(\frac{T}{R} - W\right)}.$$

re W = dielectric loss per inch of cable for each phase at the ultimate temp- ure. This is 1/6 of the dielectric loss in watts per foot of cable.

ample. — In the case of a No. 0000 paper insulated cable for 12,000 volt ice, with a dielectric loss of one watt per foot at 85° C., the carrying capacity be about 5 per cent less than if the dielectric loss were zero.

ormulas for Heat Resistance of Cables. — The heat resistance of single luctor cables may be calculated from the formula given below.

t D = overall diameter of cable, inches,
Q = ratio of the outer to the inner diameter of each layer of heat insulation,
K = heat resistivity of the material of each layer of heat insulation in degrees centigrade rise per watt per inch cube,
= 285 for rubber,
= 300 for varnished cambric,
= 300 for impregnated cotton,
= 465–485 for impregnated paper,
= 100 for asphalted jute,
= 300 for impregnated cotton braid.
H = heat resistivity from cable surface to room, in degrees centigrade per watt dissipated from each square inch of surface.
= 120 for impregnated braid,
= 120 for painted steel braid,
= 180 for lead bright,
= 155 for lead dull.

hen,

$$R = 0.318\frac{H}{D} + 0.367\,\Sigma K \log_{10} Q.$$

corresponding formula for multiple conductor cables has been developed by and is quoted by Powell, *Trans. A.I.E.E., 1916, Vol. 35-2, p. 1035.* The ; resistances of triplex paper, lead cables are given below, based upon Mie's ula and the following heat resistivities,

$$K = 475 \quad \text{and} \quad H = 155.$$

hese tables give the heat resistance from each conductor to air and are used h values of r for one conductor to get the carrying capacity of each conductor.

HEAT RESISTANCE OF THREE-CONDUCTOR CABLES

Each Conductor to Outside of Sheath

Thickness of Belt Insulation = ½ × Thickness of Conductor Insulation

Size of conductor or A. W. G. or circular inch	Heat resistances, degrees centigrade rise, per watt dissipated, per inch length of cable							
	6×3	8×4	10×5	12×6	14×7	16×7	18×9	20 X
6	253	257	259	263	266	269	272	27
4	230	235	237	242	244	249	252	25
2	206	210	216	220	230	228	235	23
1	194	200	204	210	212	217	220	22
0	182	190	192	198	202	208	211	21
00	174	178	183	187	194	197	201	20
000	159	166	172	178	183	187	191	19
0000	151	157	162	168	172	178	183	18
0.25	144	150	155	161	164	170	174	17
0.30	137	142	148	154	158	163	168	17
0.35	131	136	142	145	153	157	161	16
0.40	125	131	136	140	146	150	155	16
0.45	120	127	132	137	143	147	151	15
0.50	117	123	128	133	139	142	147	15

HEAT RESISTANCE OF THREE-CONDUCTOR CABLES

Each Conductor to Outside of Sheath

Thickness of Belt Insulation = Thickness of Conductor Insulation

Size of conductor or A. W. G. or circular inch	Heat resistances, degrees centigrade rise, per watt dissipated, per inch length of cable							
	6×6	8×8	10×10	12×12	14×14	16×16	18×18	20 ×
6	266	272	277	284	287	291	296	3
4	242	250	255	261	260	271	275	
2	217	225	232	238	240	249	254	2
1	204	213	219	225	231	237	242	
0	252	102	206	215	221	228	232	2
00	184	190	194	204	211	215	221	2
000	171	179	186	193	198	205	210	2
0000	160	166	176	183	188	195	200	2
0.25	153	160	168	175	181	187	192	1
0.30	145	152	160	166	172	180	185	1
0.35	138	145	154	159	167	173	178	1
0.40	132	140	147	153	161	167	172	1
0.45	128	136	143	150	156	163	167	1
0.50	124	131	138	145	152	157	162	167

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ıe cable is in a duct, the heat resistance of the duct should be taken into it. For a single duct, this is usually from 1 to 20 degrees C. per watt lost h inch of duct. Clark and Shanklin, *Trans. A.I.E.E., 1920*, give the e heat resistance from the conductors in a cable, to the earth, as 69° C. tt lost in each inch of duct, or 207° C. per watt lost in each inch of each ıtor of a triplex cable. R.W. Atkinson, *Jour. A.I.E.E., Sept., 1920*, gives per watt-inch as a safe average figure for a conduit containing up to 16 surrounded by earth with a normal amount of moisture.

OR "A" TO REDUCE CARRYING CAPACITY PER CABLE WHEN EVERAL EQUALLY LOADED CABLES FILL A DUCT LINE

ıer of ducts ıontally or ıtically	Number of ducts vertically or horizontally							
	1	2	3	4	5	6	7	8
1	1	0.86	0.81	0.79	0.77	0.76	0.76	0.75
2	0.86	0.71	0.64	0.61	0.59	0.58	0.57	0.56
3	0.81	0.64	0.58	0.54	0.52	0.50	0.49	0.48
4	0.79	0.61	0.54	0.50	0.47	0.46	0.44	0.43
5	0.77	0.59	0.52	0.47	0.45	0.43	0.42	0.40
6	0.76	0.58	0.50	0.46	0.43	0.41	0.39	0.38
7	0.76	0.57	0.49	0.44	0.42	0.39	0.38	0.36
8	0.75	0.56	0.48	0.43	0.40	0.38	0.36	0.35
9	0.74	0.55	0.47	0.42	0.39	0.37	0.36	
10	0.74	0.55	0.46	0.42	0.39	0.37		
11	0.74	0.54	0.46	0.41	0.38			
12	0.73	0.54	0.46	0.41	0.38			

in a group of ducts 3×6 each of the 18 cables could carry only 0.5 of ent which could be carried by one cable alone.

RYING CAPACITY PER CONDUCTOR OF MULTIPLE CONDUCTOR CABLES

ırrying Capacity of Single Conductor Having Same Total Thickness of Insulation between Conductor and Air.)

Number of conductors	Type of cable	Multiply carrying capacity for single conductor cable by
2	Flat (twin)	0.87
2	Round (duplex)	0.80
2	Concentric *	0.75
3	Round (triplex)	0.72
3	Modified sector	0.75
4	Round	0.67

* Also D-shaped cables.

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CARRYING CAPACITIES, IN AMPERES, ALLOWED BY THE REGULATIONS OF THE NATIONAL BOARD OF FIRE UNDERWRITERS FOR INTERIOR COPPER CONDUCTORS.

(For Aluminum 84 Per cent of These Currents is Allowed)

Single Conductor Cables or Each Conductor of Multiple Conductor Cables

A. W. G.	Area in circular mils	Table A. Rubber insulation	Table B. Varnished cloth	Table C. Other insulation
18	1,624	3	.....	5
16	2,583	6	.....	10
14	4,107	15	(18)	20
12	6,530	20	(25)	25
10	10,380	25	(30)	30
8	16,510	35	(40)	50
6	26,250	50	60	70
5	33,100	55	65	80
4	41,740	70	85	90
3	52,630	80	95	100
2	66,370	90	110	125
1	83,690	100	120	150
0	105,500	125	150	200
00	133,100	150	180	225
000	167,800	175	210	275
	200,000	200	240	300
0000	211,600	225	270	325
	250,000	250	300	350
	300,000	275	330	400
	400,000	325	390	500
	500,000	400	480	600
	600,000	450	540	680
	700,000	500	600	760
	800,000	550	660	840
	900,000	600	720	920
	1,000,000	650	780	1000
	1,100,000	690	830	1080
	1,200,000	730	880	1150
	1,300,000	770	920	1220
	1,400,000	810	970	1290
	1,500,000	850	1020	1360
	1,600,000	890	1070	1430
	1,700,000	930	1120	1490
	1,800,000	970	1160	1550
	1,900,000	1010	1210	1610
	2,000,000	1050	1260	1670

Varnished cloth smaller than No. 6 may be used by special permission only.

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IMUM CONTINUOUS CARRYING CAPACITIES IN OPEN AIR, AMPERES

Assuming A.I.E.E. Ultimate Temperatures and 40° C. Air Temp.

Single Conductor Cables

ize	Rubber			Varnished cambric			Paper		
	Braid		Lead	Braid		Lead	Lead		
W. G. or cular	0–600 V.	7000 V.	13500 V.	0–600 V	7000 V.	13500 V.	0–600 V.	7000 V.	13500 V.
14	20	.....	.....	.....	.....	.....	30		
12	25	.....	.....	.....	.....	.....	35		
10	30	.....	.....	.....	.....	.....	50		
8	45	.....	.....	.....	.....	.....	65		
6	60	60	55	75	75	60	85	75	65
4	85	80	70	105	100	80	120	100	90
2	110	110	100	140	130	110	160	140	120
1	130	130	115	165	160	130	185	160	140
0	155	150	130	190	185	150	215	180	165
00	180	180	160	225	210	180	250	220	195
000	210	205	180	265	255	205	290	250	225
000	250	240	210	310	290	240	335	295	260
.25	280	265	240	345	320	270	380	330	290
.35	350	320	300	430	400	335	470	410	365
.50	450	410	330	540	505	435	600	520	460
.75	600	555	500	720	660	560	790	670	590
.00	720	670	600	880	795	670	970	820	725

This table is based on the following heat resistivities:

Material	C° per watt per inch cube
Rubber	285
Varnished cambric	300
Impregnated paper	475
Saturated braid	300
	C° per watt per square inch
Lead (to air)	155
Braid (to air)	120

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Cables Buried Underground, Under Water, etc. — A cable buried in earth will carry 25 per cent more current with a given rise in temperature than it will when run in a dry duct, depending upon the character of the soil. If immersed in water it will carry about 50 per cent more.

Current-carrying Capacity of Lead Sheath. — The carrying capacity of a lead sheath is given approximately by the following formula:

$$C = 128 \sqrt{dp\,(d-p)T},$$

where

d = outside diameter of sheath in inches,
p = thickness of sheath in inches,
T = temperature rise, ° C.

Rise of Temperature with Time. — Fig. 5 shows the rise of temperature with time for a single conductor, 0.5 square inch in cross-section, carrying 750 amperes. Curves I to VI are from a paper by C. Beaver (*Jour. I.E.E., 1911*) and curve VII from Del Mar's *Electric Power Conductors*.

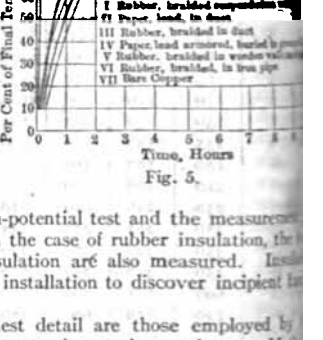


Fig. 5.

TESTS AND INSPECTION OF INSULATED WIRES AND CABLES. — (*See also section on Specifications, below.*) Wires and cables are submitted to factory tests to ascertain whether they meet specified requirements. For the tests on the conductors themselves, see the article on *Wires and Cables, Bare*. The usual factory tests of insulation are the high-potential test and the measurement of insulation resistance and capacity. In the case of rubber insulation, the tensile strength and elasticity of the insulation are also measured. Insulated wires and cables are also tested after installation to discover incipient faults and to locate existing faults.

The tests described below in greatest detail are those employed by the majority of American cable manufacturers and operating engineers. Methods of measuring insulation resistance are described in the article on *Resistance and Conductance*, and methods of measuring capacity and inductance in the articles on *Capacity* and *Inductance*.

A.I.E.E. Rules for Tests. — Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

The outer surface of the insulation of complete insulated wires and cables shall be grounded while being electrically tested. If the insulation is not provided with a conducting covering and if the covering is not liable to injury by water, the ground shall be obtained by immersing the insulated wire or cable for at least twelve hours and testing at the end of that period while immersed. If the outer covering is susceptible to injury by immersion, the insulated conductor shall be tested before the application of such covering.

Dry core paper-insulated lead-covered cables, such as telephone and telegraph cables, for use in water, shall be tested after at least twelve hours' immersion.

In the case of multiple-conductor cables, without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

High-voltage Tests. — High-voltage tests are intended to detect weak spots in the insulation and to determine whether its dielectric strength is such

r enabling it to withstand the voltage to which it is likely to be subjected ice, with a suitable factor of assurance.

-voltage tests shall be made at the factory by applying an alternating between the conductor and sheath or water. The initially applied must not be greater than the working and the rate of increase shall be ap- ely uniform and not over 100 per cent nds.

in the case of communication cables s insulated with code rubber com- e duration of the test voltage shall onsecutive minutes. Code wires are one minute.

ultiple-conductor cable is designed ne operating voltage between con- d sheath or water as between con- h conductor shall be tested against onductors connected together and h or water. If the cable is designed ating voltage between conductors different from that between con- test between conductors and the ter shall be made separately and l on the normal operating voltage ductors and sheath or water as the accompanying table.

s based upon the minimum thick- ition specified by engineers and panies. The following tables d where the insulation thickness

HIGH-VOLTAGE TESTS FOR VARNISHED CAMBRIC OR IMPREGNATED PAPER INSULATED CABLES, MINIMUM VALUES A.I.E.E. STANDARD

Operating kilovolts	Test kilovolts
Below 0.5*	2.5
0.5	3
1	4
2	6.5
3	9
4	11.5
5	14
7.5	19.5
10	25
Over 10	2½ times operating pressure

*Minimum thickness shall be 1/16 inch.

ating current is used for cable rica, the use of direct current is vor in Europe. The source of current is usually a mechanical oltages as high as 150 kilovolts have been attained. It is s method that it enables a very high voltage to be applied the insulation. (J. Delon.)

esistance Test. — The purposes of the insulation resistance tain whether the high-voltage test has caused a break-down, to ss of the insulation and to reveal lack of uniformity in manu- it is accordingly made after the high-voltage test, by measuring nt after a one-minute electrification, with a continuous e.m.f. o volts, the conductor being maintained negative to the sheath case of multiple conductor cables, the insulation resistance is ach conductor to the other conductors in multiple with the

sts of Rubber. — The test piece should be carefully pre- cisions and irregularities. The best way to obtain a test l conductor is to wet a sharp knife and run it tangentially ts to cut off a strip of rubber of segmental cross-section. In nductors, the best plan is probably to remove the insulation, nd cut off a piece of uniform width by means of a special a pair of parallel knife blades attached to a common frame. ections of rubber which occur on the inside of insulation

POTENTIAL TESTS FOR VARNISHED-CLOTH INSULATION

Potentials in Kilovolts

(G. E. Co. Bulletin 4787)

Size wire, A. W. G. or B. & S. and circular mils	Thickness of insulation, 64ths inch	At factory	After installation		
		5 min.	5 min.	30 min.	60 min.
6–2	4	2.5	2	1.6	1.3
1–0000	5	2.5	2	1.6	1.3
250,000–500,000	6	2.5	2	1.6	1.3
550,000–1,000,000	7	2.5	2	1.6	1.3
1,100,000 and over	8	2.5	2	1.6	1.3
6–0000	6	5.0	4	3.2	2.6
250,000–500,000	7	5.0	4	3.2	2.6
550,000–2,000,000	8	5.0	4	3.2	2.6
All sizes	9	7.5	6	4.8	3.8
All sizes	10	10.0	8	6.4	5.1
All sizes	12	12.5	10	8.0	6.4
All sizes	14	15.0	12	9.6	7.7
All sizes	16	17.5	14	11.2	9.0
All sizes	18	20.0	16	12 8	10.2
All sizes	18	22.5	18	14.4	11.5
All sizes	20	25.0	20	16.0	12.8
All sizes	22	27.5	22	17.6	14.1
All sizes	24	30.0	24	19.2	15.4
All sizes	24	32.5	26	20.8	16.6
All sizes	26	35.0	28	22.4	17.9
All sizes	26	37.5	30	24.0	19.2
All sizes	28	40.0	32	25.6	20.5
All sizes	28	42.5	34	27.2	21.7
All sizes	30	45.0	36	28.8	23.0
All sizes	30	47.5	38	30.4	24.3
All sizes	32	50.0	40	32.0	25.5
All sizes	32	52.5	42	33.6	26.8
All sizes	34	55.0	44	35.2	28.1
All sizes	34	57.0	46	36.8	29.4
All sizes	36	60.0	48	38.4	30.7
All sizes	36	62.5	50	40.0	31.9

Tests on three-conductor cables for circuits with grounded neutral, in propo
on to thickness of insulation: Example, three-phase, 12,000-volt circuit "Y"
eutral grounded, insulation on each conductor 5/64 inch (total between condu
ors 5/32 inch), outer belt 5/64 inch (total 9/64 inch); test pressure at factory for
inutes, between conductors 30,000 volts each conductor to earth 22,500 volt
or mechanical reasons, thickness of insulation on individual conductors
hree-conductor cables 3000 volts and less is made somewhat greater tha
quired by working pressure on some sizes.

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POTENTIAL TESTS FOR PAPER INSULATION

Potentials in Kilovolts

(G. E. Co. Bulletin 4787)

Size wire, W. G. or B. & S. and circular mils	Thickness of insulation, 64ths inch	At factory	After installation		
		5 min.	5 min.	30 min.	60 min.
14–2	4	2.0	1.6	1.3	1
1–0000	5	2.0	1.6	1.3	1
5,000–500,000	6	2.0	1.6	1.3	1
1,000–1,000,000	7	2.0	1.6	1.3	1
12–2	5	2.5	2	1.6	1.3
1–0000	6	2.5	2	1.6	1.3
5,000–500,000	7	2.5	2	1.6	1.3
0,000–2,000,000	8	2.5	2	1.6	1.3
10–0000	7	5.0	4	3.2	2.5
5,000–500,000	8	5.0	4	3.2	2.5
0,000–2,000,000	9	5.0	4	3.2	2.5
8 and larger	10	7.5	6	4.8	3.8
8 and larger	12	10.0	8	6.4	5.1
6 and larger	14	12.5	10	8.0	6.4
6 and larger	16	15.0	12	9.6	7.7
5 and larger	18	17.5	14	11.2	9.0
5 and larger	20	22.5	18	14.4	11.5
4 and larger	22	27.5	22	17.6	14.1
4 and larger	24	32.5	26	20.8	16.6
3 and larger	26	37.5	30	24.0	19.2
3 and larger	28	42.5	34	27.2	21.7
2 and larger	30	47.5	38	30.4	24.3
2 and larger	32	52.5	42	33.6	26.8
1 and larger	34	57.0	46	36.8	29.4
0 and larger	36	62.5	50	40.0	31.9

ests on three-phase cables for grounded neutral in proportion to thick-s of insulation: Example, three-phase 13,000-volt circuit "Y," neutral nded, insulation on each conductor 5/16 inch (total between conductors inch), outer belt 9/32 inch (total 9/32 inch); test pressure at factory for five nutes, between conductors 32,500 volts, each conductor to earth 17,500 ts.

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HIGH-VOLTAGE TESTS FOR RUBBER COVERED WIRES AND CABLES

(a) National Electric Code, One Minute Test

Size	Working voltage					
	600	1500	2500	3500	5000	
14 to 8 A. W. G.	1500	6000	8000	10,000	12,500	17,5
6 to 2	2000	7000	9000	10,000	12,500	17,5
1 to 0000	2500	8000	10000	10,000	12,500	17,5
225,000 to 500,000 cir. mils	3000	9000	10000	11,250	12,500	17,5
600,000 and over cir. mils	3500	10000	10000	12,500	12,500	17,5

(b) A.I.E.E. Standards, Five Minutes Test

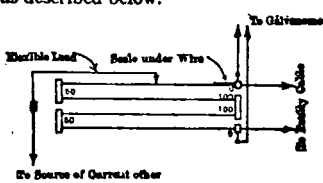
One kilovolt per 64th inch insulation thickness up to 19/64 in. Above 19/64 10 kilovolts plus 1.5 kv. per 64th inch up to 29/64. Where thickness is 29/64 or over, rule applies only to conductors as big as No. 6 A.W.G. The A.I.E.E. allows lower test voltage for working voltages up to 600 v. a-c. In this case the rule is as follows:

14-8 A.W.G.	3.0 kv.
7-0000	3.5
250,000 and larger	4.0

stripped from stranded conductors are neglected in computing the cross-section area.

In order to measure its tensile strength the sample of rubber is held in a sort of grip and stretched in a machine similar to that used for wire (*see Bureau of Standards Bulletin No. 37*). It is usual to reduce the results thus obtained to pounds per square inch.

Tests after Installation. — A high-potential-test with the voltages given above in the tables is usually applied to the full length of cable immediately after installation and at regular intervals to detect incipient faults. Double line voltage is frequently used for the periodic tests. Grounds or crosses of relatively low resistance may be detected by bridge methods or by exploration as described below.



Arrangement of Bridge

Fig. 6.

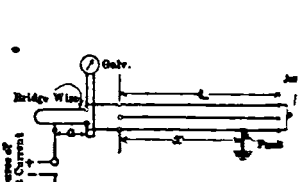


Fig. 7.

Some engineers make periodic insulation-resistance tests and plot the results as a curve. If the curve manifests any decided downward tendencies the cause is immediately sought for. The methods of making these tests are given below.

Testing for Faults by Murray Bridge Methods. — The bridge used in the Murray loop tests is shown diagrammatically in Fig. 6. It consists essentially of a resistance wire graduated into two equal scales each reading from 0 to 100, the zero points being at the ends of the wire. A galvanometer

onnected across the zero points and a flexible lead connected to the positerminal of a source of direct current is put in sliding contact with the . The negative terminal of the direct-current source is grounded.

ne Conductor Grounded. — When one conductor of a multiple-conductor e is grounded, the bridge is connected as shown in Fig. 7, a jumper being ed between the faulty conductor and one of the others. The sliding con- is moved along the bridge wire until the galvanometer deflection becomes . Let a = distance of sliding contact, on bridge scale, to the terminal of br dge connected to faulty wire, as a percentage of the length of half the ge wire, and L = length of cable; then if x is the distance from the bridge to fault,

$$x = \frac{aL}{100}.$$

wo Conductors Crossed. — When one conductor of a three-conductor cable ossed with another, the bridge is connected as shown in Fig. 8, a jumper

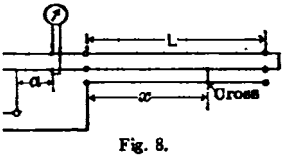


Fig. 8.

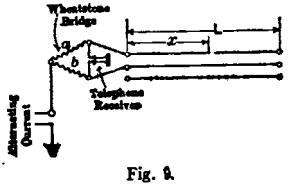


Fig. 9.

g again used, although connected differently. Zero reading is obtained on galvanometer as before, and, using the same notation,

$$x = \frac{aL}{100}.$$

ne Conductor Open. — When one conductor is open, the bridge is connected hown in Fig. 9, a telephone receiver being substituted for the galvanometer, alternating current for the direct current. The sliding contact is moved g the bridge until silence is obtained in the telephone.

et a = distance from sliding contact to the terminal of bridge connected to n conductor,

= distance from sliding contact to the terminal of bridge connected to whole ductor: then,

$$x = \frac{b}{a} L.$$

Ayrton's Method to Detect Crosses. — In Fig. 10, a, b and r repre- three arms of a Wheatstone bridge, the fourth arm being the conductor N, ch is in contact with a second conductor M of the same cable at the point Ground the conductor N at the far end and let x and y be the resistances

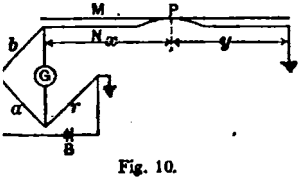


Fig. 10.

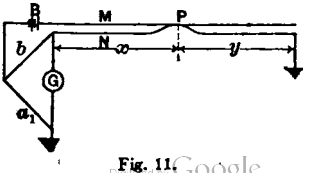


Fig. 11.

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of the grounded conductor from the bridge to P and from P to the ground respectively. Let a, b and r be the resistances of the other three arms of the bridge. Make $a = b$, and adjust the variable resistance r until the galvanometer shows no deflection; then

$$x + y = r,$$

neglecting the resistance of the ground.

Then connect battery to M instead of to earth as shown in Fig. 11, and adjust a to a value a_1 such that the galvanometer shows no deflection. Then $a_1 = b$, or

$$\frac{x}{x+y} = \frac{b}{b+a_1}.$$

But from first arrangement $x + y = r$, whence

$$x = \frac{br}{b+a_1}.$$

From the resistance of the conductor per foot, the distance to the point P is then immediately determined.

Varley Loop Test for Grounds. — Grounds may be located by the arrangement shown in Fig. 12. Loop the bad wire at the distant end with a good one of equal resistance. Call the resistance of the good wire c and the resistance to the fault on the bad wire x. Adjust the rheostat until the galvanometer balances. Then

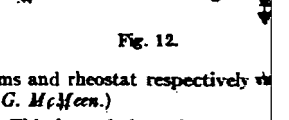


Fig. 12.

$$x = \frac{2bc - ar}{a+b},$$

a, b and r being the values of the bridge arms and rheostat respectively when the galvanometer shows no deflection. (*S. G. McMeen.*)

Varley Loop Test for Crosses. — This is made by substituting the crossed wires for the earth path of Fig. 12, using one good wire as before.

Cable Tests by Exploring Coil. — Grounds on wires in cables may be located by the use of a telephone receiver connected to an exploring coil. To do this, connect a source of interrupted current to one end of the wire in trouble, the other terminal of the source being grounded. Remove from the wire in trouble all the grounds other than the fault. Then move along the cable a coil such as one spool of an 80-ohm telephone ringer (*see Telephony*) across whose terminals a receiver is connected. Hold the exploring coil with its iron core at right angles to the cable. A tone from the interrupter should be heard when the exploring coil is between the fault and the source of sound, but not when it is beyond the fault. (*S. G. McMeen.*)

Listening Tests on Telephone Lines. — A long telephone line will be noisy if one of its wires is grounded, open or crossed with a third wire, whether the latter be grounded or clear. To determine where the fault is, listen on the line while assistants short-circuit it at different places. The fault is beyond the short-circuit if the short-circuit makes the line quiet (*S. G. McMeen.*)

SPECIFICATIONS. — (*See also article on Wires and Cables, Bare.*) The following forms are recommended for insulated wire and cable specifications. The general idea is for the purchaser to have printed or mimeographed forms and to fill them in according to specific requirements. These tabular specifications are supplemented by general specifications for workmanship and material which should be included when bids are sought or orders given. This arrange

t minimizes the chance of accidental omission on the part of the purchaser manufacturer and saves the bidder time in reading long specifications.

ems to be Covered in Detail Specification. —
ification No.,
,
e briefly the service for which the conductor is intended,
ıber of separately insulated conductors,
erial of conductors,
e of stranding (parallel, concentric or rope),
ıber of strands per conductor,
ıber of wires per strand (if rope strand),
l area of conductor or A.W.G. No.,
luctor shall *not* be tinned (omit the word "not" as required),
e of separator, if any,
lation material, each conductor,
belt,
mum thickness of insulation, each conductor,
belt,
, material,
ber of tapes, each conductor,
over each layer,
over-all,
ure wire (if any), size,
insulation,
location,
ngs, material,
number,
thickness, inches,
, material,
number on each conductor,
number over-all,
rs (if required), material,
number,
arrangement,
als (if required), material,
g under sheath,
h material,
ness of sheath,
g between sheath and armor, material,
thickness, measured after armoring,
r, material, wire or band,
over armor,
mum over-all diameter (if limit is necessary),
h, maximum,
minimum,
ber to be supplied in coils or on reels,

orkmanship and materials shall conform with stated general specifications as the following:

NERAL WIRE AND CABLE SPECIFICATIONS. — Purchasers re desirous of obtaining wires or cables of adequate design and good con-ion, use specifications which describe the major details of construction to lowed and tests to be applied.

merly every customer who purchased on specification wrote his own ications, but this led to endless difficulty with the manufacturers who had ke special compounds or follow special rules for each customer. In recent

years various engineering societies have adopted standard specifications wh are now largely used.

American Institute of Electrical Engineers. — (*a*) *Standards of the A.I.E.E.* which cover definitions of terms, methods of test, insulation thickness for va grade rubber insulation, test voltages, etc.

(*b*) Marine Code, which covers merchant ship wiring.

American Railway Association. — Signal wire specifications.

American Railway Engineering Association. — General wire specifications

American Society for Testing Materials. — Specifications for bare copper wi and cables. Tentative specifications for rubber-insulated conductors.

Association of Railway Electrical Engineers. — Specifications for practica all types of wires and cables used by railways. (Now becoming obsolete)

Joint Rubber Insulation Committee (superseded in 1921 by A.S.T.M.). — Spe fication for 30 per cent hevea rubber insulation.

National Board of Fire Underwriters. — Specification for wires and cables to used in buildings.

National Electric Light Association. — Specifications for paper-insulat lead-covered underground cable.

Rubber-insulated Wire and Cable. — Most of the characteristics of ru ber compounds are so good from the point of view of electrical insulati that the efforts of purchasers are mostly concentrated on obtaining life, or p manency.

There are three recognized standard specifications for rubber insulation, t National Electrical Code specification which is the least severe, the Joint Rub Insulation Committee specification which has severe chemical requirem and the American Railway Engineering Association (Signal Division), specifi tion which specifies a formula and requires rigid inspection during manufact The idea of chemical clauses is that by specifying close limits upon the follo analytical results (obtained by a standard method of analysis), the use of permanent substances will be prevented.

Analytical results upon which limits are placed	Deleterious substances whose use is prevented by limits upon analytical results
Total sulphur	Reclaimed rubber
Alcoholic potash extract	Rubber substitutes
Chloroform extract	Tars
Mineral matter	Carbon, cellulose, etc.
Saponifiable acetone extract	Unextracted high resin rubbers
Unsaponifiable acetone extract	Deresinated rubber

The chemical requirements are supplemented by mechanical and electri requirements, the former for the purpose of checking vulcanization and th latter to ensure proper insulating qualities.

Paper Cable. — The principal characteristic which is insisted upon for l voltage paper insulated cables is good condition of the paper in regard to mechan cal strength, in order that the cable may not be injured during installatio When cables are installed they often have to be bent to a very short radius, an unless the paper is in very good condition, it will crack, usually on the outsi of the bend. If the paper is wrinkled, scorched or improperly lapped, it wi break open when it is installed.

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rchasers, therefore, require that a high grade of manila rope paper be used hat it be free from wrinkles, tears and scorches.

the case of high-voltage cables, in addition to the requirements for low- ge cable, it is usual to put a limit upon the dielectric losses in order to e the cable having ample carrying capacity.

'ere bending tests, followed by high voltage tests, are often specified to up defects in the paper, and lack of uniformity in drying or impregnating ealed by the megohms test.

rnished Cambric Cable. — Most of the specifications for varnished ric cables are not very severe, except in requiring a smooth application of ipe and proper overlap.

lectric loss requirements are not applied to varnished cambric cables, ome recent specifications call for certain characteristics of the varnished itself, which make it necessary to use only the highest grade of cloth. specifications call for soaking the cambric in petroleum at a high tempera- o make sure that it does not become tacky as a result of reaction with the ler" compound.

STALLATION OF INSULATED WIRES AND CABLES. — For stallation of wires and cables in buildings see articles on *Wiring of Buildings ght and Power; Wiring of Buildings for Miscellaneous Devices*. Below is a brief description of modern practice in installing insulated wires and on messenger wires and in underground conduit systems. For the con- ion of the pole lines carrying the messenger wire see articles on *Poles rhead Lines; Towers, Transmission*. For the construction of conduit sys- ee article on *Conduits and Conduit Lines*. See also the articles on *Distri- Lines* and *Transmission Lines*.

ssenger Construction. — The messenger wire is erected in the same man- an ordinary line wire; see article on *Transmission Lines*. A "leading- ire is stretched from the bottom of one pole to the messenger wire on the g pole, forming an incline on which to pull up the cable. A pulling rope fastened to the end of the cable by means of a cable grip and carried ide of the messenger to the point where the cable is to reach, thence through ch-block down to the terminal pole to a second block at the bottom and to a capstan, winch, locomotive or whatever is to be used for pulling. temporary rollers should be provided on the poles over which the rope r the rope should be suspended from the messenger by wire hooks. The s then slowly drawn up the inclined wire and along the messenger, attach- nporary carriers to the cable as it is paid out and hooking them over the ger to carry the weight of the cable. Linemen must be stationed on each pass these carriers around the messenger clamp or insulator. The final sion of the cable may be accomplished in either of the following ways: nen the end of the cable arrives at the beginning of the last span, the n on each pole replaces the temporary carriers by permanent hangers, g them regularly along the cable, so that when the last span is pulled, all ngers will be in place. (2) When the cable has been pulled all the way, an rides along the messenger wire in a carriage replacing each temporary by a hanger. This plan is preferable as the hangers may be attached ightly to the messenger wire, and are less likely to slip on the cable.

allation of Cables in Ducts. — The conduit system having been con- d, it must be prepared for the reception of the cable by being cleaned rodded as described in the article on *Conduits and Conduit Lines*.

nere are several ducts available, the choice of the particular duct to be hould be governed by the following considerations: 1. Avoiding un-

necessary crossings of cable in the splicing chambers, substations, etc.; 3. Avoiding the obstructing of empty ducts; 3. Keeping the cables cool; and 4. Keeping d-c. cables away from others. The following statement in the catalogue of the A. S. & W. Co. is pertinent with regard to keeping the cables cool. "Usually the coolest and best heat-radiating ducts are those located at the lower corners of the system, next are those nearest to the outside of the system and lastly the middle and top ducts which not only take up heat from the lower cables, but must dissipate heat through adjoining ducts. Attention to these points when planning a new system may prove very profitable in the end."

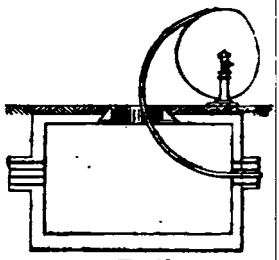


Fig. 13.

The next step is to set the cable reel on the shaft of a pair of wheels of slightly greater diameter than the reel itself or on jacks and raise it slightly above the ground, taking care to locate it as shown in Fig. 13, so that the cable will unreel into the manhole without making a reverse bend.

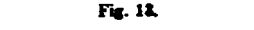


Fig. 14.

The pulling rope having been left in the duct after rodding, the cable is unreeled sufficiently to bring its end close to the mouth of the latter and a wire pulling grip (Fig. 14) is drawn over its end. The end of the grip is hooked to the rope and the rope pulled from the other end. Fig. 15 shows an arrangement of pulleys for guiding the pulling rope. The pulling may be done by capstan, winch, motor truck, horse or by hand, depending upon the size and amount of cable to be pulled, and upon local conditions. The cable should be carefully guided into the duct so as to avoid sharp bends and abrasions, and a small quantity of grease may with advantage be spread over the cable as it enters the duct. R. J. Robb (*Journ. I.E.E., 1911, Vol. 47, p. 350*) says that 112 pounds of petroleum jelly is required per mile of cable. It is also necessary to cover the edges of the duct with pieces of lead to prevent abrasion of the cable as it passes into the mouth of the duct.

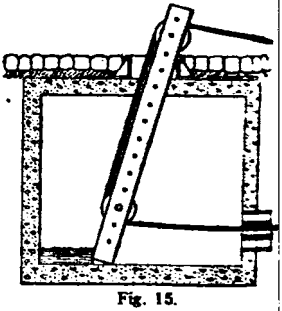


Fig. 15.

Protection of Cables in Splicing Chambers. — (*See also article on Conduits and Conduit Lines.*) Wherever there are several large cables in a splicing chamber, there is always danger that a burn-out of one cable will involve some or all of the remainder. Hence it is usual to protect such cables by means of one or more of the following methods:

1. Concrete shelves,
2. Open-face conduits,
3. Cement coating with ⅛-inch rope bond,
4. Asbestos tape saturated with silicate of soda,
5. Asbestos tape covered with soft steel-tape armor,
6. Asbestos rope,
7. Split tile duct.

Methods Nos. 1 and 2 are applicable only to chambers containing few cables

3 has given good results in many cases, but the cement is liable to crack fall away from the cable unless carefully bonded. On the other hand, the ion of a burn-out is plainly indicated by the cement covering being blown No. 4 combined with No. 5 is very generally used and gives very satis- ry results. No. 6 is but little used. No. 7 is very satisfactory, but is dumsy, and cannot be used where there are many cables in the chambers. ie necessity for such protection (according to the Committee on Under- nd Construction of the N. E. L. A., 1911) is equally great with low-tension s as with high-tension cables, for, while a breakdown of the insulation of h-tension cable is often attended with a violent explosion and the genera- of a very high temperature, the duration of the trouble is limited to one ro seconds; whereas in the case of a short circuit on a low-tension cable, it continue to burn with a considerable flame for several minutes, which d be quite long enough to damage adjacent unprotected cables.

the case of direct-current feeders for electric railways, where the return ounded, the danger of burn-outs spreading is much greater than with the ated lighting systems referred to in the N. E. L. A. report. This sub- is treated at greater length in the author's *Electric Power Conductors*, which the following is quoted: "If it is necessary to put direct- and alter- g-current cables in the same duct line, it is well to isolate the direct-current s as much as possible in the splicing chambers. The racks on which direct- nt cables are supported should not be in metallic contact with other racks. owever, this is unavoidable, the cables should not lay directly on the racks, n insulating pads or blocks."

isting Insulated Conductors. — (*See also article on Wires and Cables,*) Having selected the corresponding cable ends, they should be inspected echanical defects along the entire exposed length and bushings placed them at the ducts so that the sheath will not be cut by the edges of the uits. The cables should then be bent until the ends overlap, the bends g of ample radius throughout, and the position of the cable such that the , when completed, will not have to bear any elastic stress or weight.

Drying Out Cable Ends. — In the case of paper- or cambric-insulated s, the ends should be examined for moisture before they are finally cut t and if any exists or is suspected, heat should be applied to the sheath, aning at the duct end and slowly working to the open end. This is lly done with a gasoline torch but sometimes by pouring on hot insulating pound.

Overlap. — This operation having been completed, the cable ends are o as to leave an overlap, depending upon the method of joining the conduc- (*see below*) and upon the number of separately insulated conductors in the e. If the cable has but a single conductor, and a butt joint is to be used, overlap should be merely sufficient to allow for cutting off the ends, whereas interlaced joint is contemplated, the overlap should be greater by about 4 times the diameter of the conductor.

Removal of Sheath. — The next operation is to cut off a sufficient th of lead sheath to permit the joint to be made. This length may be ed from the size of the sleeve to be used (*see below*). The operation is ormed with a chipping knife and hammer, or with a special tool designed the purpose, and the greatest care should be exercised to avoid cutting the lation to the slightest degree. It is usual to make a cut around the sheath gradually increase its depth until the lead is cut through. The lead must be cut lengthwise from the circular cut to the end, injury to the insulation g avoided by holding the knife tangent thereto. The lead may then be ed off with a pair of pliers and loose particles carefully removed. In the

case of high-tension cables the ends of the lead should then be turned up slightly to a bell-mouth shape by means of a fibre wedge.

Putting on Lead Sheath. — Before jointing the conductors, the lead sleeve should be slipped over one of the cable ends and pushed out of the way. The ends of the sleeve and the corresponding surfaces of the sheath should have been previously scraped for a length of about a couple of inches along the outside and the cleaned surfaces smeared with stearine.

Removal of Insulation. — The next step is to cut back the insulation for a length between ¼ and ½ inch greater than half the length of the connector to be used, and taper the remainder uniformly for a distance of 1 to 1½ inches using a small sharp knife. In the case of multiple-conductor cables having a belt, the belt must be cut back sufficiently to expose all the joints, the greatest care being exercised to avoid cutting the inner insulation in doing so. The paper tapes should be tied with string to prevent unwrapping. The surface of each taper should be covered temporarily with a strip of dry cloth.

Jointing the Conductors. — The next process is to prepare the conductor or conductors for jointing. The most usual type of joint is made by butting the ends of the conductors and enclosing them in a cylindrical copper connector. The conductors are first cleaned with gasoline and then tinned by pouring molten solder over them, using stearine for flux. All burrs should be removed with a file and the ends smoothed so that they will butt together perfectly. The connector is then put over one conductor end and the other end slipped in until the two ends butt. Solder is then poured over the joint until it is thoroughly saturated, when the surplus is wiped off so as to leave no sharp projections.

Connectors. — The connector should have a cross-section not less than that of the conductor and a length about four times the diameter of the conductor. From points ¼ inch back from each end, it should be pencilled down to the rounded edges at the ends, and it should be split the entire length. It should be finished so as to eliminate all sharp points and edges. The opening should not be over 3/64 inch in width.

Jointing Stranded Conductors. — While the connector joint is by far the most common, stranded conductors may be joined by cutting the wires alternately long and short, and fitting the two conductor ends into one another. The joint is then bound with small wire. Stranded conductors are sometimes joined by cutting the wires of successive layers alternately long and short, and telescoping the ends into one another.

Insulation of Joint. — The next step is to insulate the joint. The depression at each end of the copper sleeve should be filled flush with impregnated 4-strand cotton twine, which should be thoroughly impregnated with compound. The usual process is to cover the joint with a tape of similar material to the remainder of the cable insulation, although this method is not universal. If oiled paper or varnished cambric, the tape should be cut on the bias. Narrow strips of impregnated tape should first be wrapped back and forth in the space between the two ends of the original paper insulation until it is built up to the level of this insulation. Compound should be applied on each layer. Wider tape is then wound on until a thickness about 40 per cent greater than that of the cable insulation is reached.

In the case of three-conductor high-tension cables the wrapping should commence at a point on the covered conductor 3 inches from the outer belt and extend to a corresponding point at the other end. The wrapping is then continued back and forth, stopping each successive layer ¼ inch short of the end of the preceding layer. In applying the tape, each turn should be drawn tight

ould overlap the preceding turn by two-thirds of its width. the tape should be applied tightly and evenly. In the case nsion should be such as to stretch it to about half its width. nust be taken to have everything perfectly clean and dry.

t." — Where cotton or linen tape is used, each layer must ouring hot compound over it until all the moisture is expelled oing is thoroughly saturated. Before applying the com- nould assure himself that it is *not* hot enough to ignite a d in it; otherwise the tape is likely to be charred. This e entering the splicing chamber, as the accidental ignition l is dangerous in such a confined space.

— Where rubber tape containing sulphur is used, it should ed by the application of heat from a spirit lamp, care being heat evenly and to avoid burning the insulation. This mplete in about one minute with conductors up to one-half

or Three-conductor Cables. — In the case of three-con- all the conductors are joined and insulated as described, a liameter is inserted between them at the center of the joint er. A band of tape is then wrapped around all three con- ameter that the whole will slide nicely into the lead sleeve, . Instead of this, a band of tape may be built around each nter of the splice.

ting Tubes. f insulating n insulating nductors be- oring it over atter is com- to get the y during sol- large enough

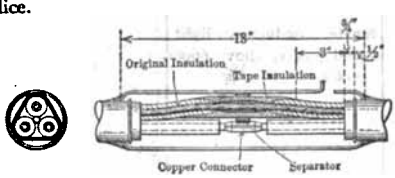


Fig. 16.

the insulation. Such tubes are made of prepared paper, micanite. The jointed conductor should first be wound to the level of the original insulation, "boiled out" as de- then the sleeve slipped on. A further "boiling out" with mpletes the job. In the case of belted multiple-conductor to the insulating tube over each conductor a large tube er the belt before splicing the conductors.

Baffles. — Baffles of micanite, bakelite, etc., are now com- en conductors of triplex cables. They replace part of the n around each conductor and the whole of the belt. The mmonwealth Edison Co. splices are of this type.

ves. — The joint having been insulated, the lead sleeve t symmetrically over it, and the ends beaten down into sheath, taking care to make the sleeve concentric with the

sheath are then joined by pouring solder over the ends from g the joint with a cloth. This process should be continued tight joints are obtained, the under side being examined for of a hand mirror.

is well wiped on, two small holes should be made in the top pound poured in one hole until it appears at the other. If ars the compound should be poured in one hole and allowed

to escape from the other until this defect ceases. The joint should be allowed to cool for about an hour, and if then the compound has settled should be added until the sleeve is full. The sleeve is then closed by small patches of lead over the holes. When the joint has thoroughly and solidified, it may be pushed gently into its permanent place.

The following data on lead sleeves are given by the Standard Underground Cable Co.

DATA ON LEAD SLEEVES

	Outside diam. of cable, mils	Inside diam. of sleeve, inches	Length of sleeve, inches	Gals. of compound per joint
Single-conductor, light and power, up to 6600 volts.	Up to 550	1	8	0.05
	551–950	1½	10	0.1
	951–1350	2	12	0.2
	1351–1750	2½	12	0.3
	1751–2150	3	14	0.5
	2151–2550	3½	14	0.6
Single conductor, light and power, above 6600 volts.	Up to 550	1	10	0.05
	551–950	1½	12	0.1
	951–1350	2	14	0.2
	1351–1750	2½	16	0.4
	1751–2150	3	18	0.6
	2151–2550	3½	18	0.8
Multi-conductor, light and power, all voltages.	Up to 800	1½	14	0.2
	801–1200	2	16	0.25
	1201–1600	2½	16	0.35
	1601–2000	3	18	0.6
	2001–2400	3½	18	0.8
	2401–2800	4	18	1.0
	2801–3200	4½	20	1.4

Compounds for Filling Lead Sleeves. — Various compounds have been used for filling the sleeves, such as conduline, G. E. No. 227 compound, E. P. Trotter's "B–7," ozite, etc. The Commonwealth Edison Co. of Chicago uses a compound developed by the engineers of the company. It is poured at a temperature of 150° C.

A good compound should have a high melting point, adhesiveness, high dielectric strength, low coefficient of contraction and should not be brittle at ordinary temperatures.

Stamping the Joint. — After the joint is completed the jointer should stamp his initials at each end of the sleeve.

Taped Joints. — Where the cable has no lead sheath, but is merely braided, it is usual to finish the joint with friction tape.

Shielded Splice. — A joint used for 25,000-volt cables is described by Torchio, Elec. W., 1916, Vol. 67, p. 873. The conductors are wrapped with oil-saturated paper-tape, and over the three conductors is provided an outer jacket pierced with holes to allow a free circulation of oil. Over the jacket is

gauze sleeve and around it a heavy lamp wick. The gauze protects t sharp potential gradients and the wick retains the insulating oil within lice. When the joint is completed, it is subjected to a vacuum of 27–29 and then filled with liquid petrolatum.

minals. — Conductors may be soldered to lugs or terminals or they may mped mechanically by means of a Dossert or similar connector.
he former case the insulation is cut from the end of the conductor, which n brightened by scraping or sandpapering and smeared with soldering The conductor is then tinned by plunging into molten solder. The lug also be tinned internally and heated so that it will hold some solder in olten state. The conductor, also heated above the melting point of solder, i pushed into the lug and the latter cooled by the application of wet waste. cool the shreds and globules of solder are filed off and the surfaces ened with sandpaper. Some jointers prefer to hold the lug in the molten until it attains the same temperature as the latter. In this case, if the s been previously treated with flux, its outside as well as its inside surface e tinned and it will make better contact with its accompanying lug or al. If, however, the copper or brass surface is desired for appearances, r be preserved by coating the outside of the lug in a light oil of high flash. before dipping it into the solder.
either case it is advisable to wrap the end insulation in a rag previously ; out in cold water to prevent it being melted or charred.

nding Sheaths. — The conductors of high-tension cables induce electro-charges on the sheaths, often raising the latter to dangerously high poten- It is, therefore, customary to ground the sheaths of cables at suitable in order to carry off the "static," as these induced charges are called. heaths of low-tension cables do not have to be grounded to drain off static icity. The sheaths of direct-current railway feeders which are used in nction with a grounded return system should, however, be grounded to gative return system, except when the tracks have insulated sections for atic block signals, in order to afford a low-resistance path for a short- t current. Unless this is done, the escaping current will return through es paths, inflicting damage without attaining sufficient strength to trip ation circuit breakers.

RN-OUTS OR PUNCTURING OF INSULATION. — Cable burn- may be caused by mechanical injury, exposure to excessive heat or cold, mulative heating, by chemical deterioration, or by transient high-voltage omena.

rn-outs Due to Mechanical Injury. — Paper insulation differs from r and varnished cambric in depending upon the integrity of the lead sheath i incloses it. Hence in the case of paper-insulated conductors, a puncture e lead sheath will sooner or later result in a burn-out even though it may a week or longer for the moisture to penetrate the insulation sufficiently complish this. (*Burch, Trans. A.I.E.E., 1903, Vol. 22, p. 433.*)
chanical injury often occurs in the process of installing underground cables. ght projection in a duct will cut a groove in the lead sheath, thereby reduc- s effective thickness and rendering it liable to crack open. The bending ble in splicing chambers may crack the insulation, especially if tightly d paper insulation is used A loosely insulated cable is also liable to injury use bending will flatten the cable, compress the insulation in one direction flare it out in the other, causing voids or air spaces between the layers, h under the influence of high voltages will cause electric discharges, heating e and consequent chemical action. Mechanical injury after installation

may be due to settlement of the conduit line, to careless stepping upon the cable to vibration setting up crystallization of the lead sheath, etc.

Exposure to alternate heat and cold leads to expansion and contraction which may introduce mechanical stresses into the insulation and thereby injure it. Excessive heat (120 to 150° F.), such as would result from direct exposure to summer sunlight, is likely to dangerously reduce the insulating qualities of varnished cambric and to a less extent that of impregnated paper. A higher degree of heat (200° F.), such as would occur in the proximity of steam pipes has the effect of making rubber insulation become brittle.

Chemical deterioration may be due to electrolysis (q.v.) or merely to ordinary chemical reaction between the sheath and the material in contact with it, the former cause being the more common.

Burn-outs Due to Static Discharges. — Failure of high-tension rubber insulated conductors is sometimes due to electrostatic discharges from the charged conductor to its supports, the irregular potential gradient giving rise to local static discharges with consequent formation of ozone and oxidation of the rubber.

Burn-outs Due to Imperfect Manufacture or Splicing. — Insulated conductors also burn out because of defects of manufacture or of splicing. The former class of defects is happily rare, but dirt, moisture and jagged edges of metal are frequently responsible for the failure of joints, especially on high-tension cables.

Transient High Voltage and Currents. — "Surges," i.e., transient high voltages and heavy currents, are sometimes responsible for very serious cable failures, such as described in *Trans. A.I.E.E., Vol. 24, p. 297*. To determine the origin and cause of high-voltage disturbances, so as to be able to guard against their recurrence, the most important thing seems to be to very carefully observe and record all the details of the phenomena, even those which appear unessential. The existence of static (i.e., high-voltage discharges of small currents) on switchboards, lines, etc., and the existence of voltages and currents different from those which may be expected require special attention. Either of these is sufficient to raise the suspicion of some dangerous fault in the system or some dangerous arrangement of apparatus, which requires considerable. The severity of the phenomena depends almost entirely upon the power momentarily available in the system and very rapidly increases with the size of the generating stations (*C. P. Steinmetz*).

After considering the likelihood and severity of such potential disturbances P. Junkersfeld and E. Schweitzer reached the following conclusions with respect to their influence upon the use of high-tension cables.

1. Where local and commercial conditions justify, pressures as high as 25 000 volts can be satisfactorily used even for systems aggregating as much as a hundred miles of cable. No single line of such a system would be much longer than twenty miles. If higher voltages are needed to meet operating requirements and can be justified commercially, special construction will be necessary to overcome limitations in paper, rubber or varnished-cabric insulation, and also in the standard forms of underground conduit or subways used in this country.

2. On comparatively short lengths, underground or under water, as a part of a long overhead transmission line, cables operating at 40,000 volts can be used.

3. Potential rises of 50 per cent and 100 per cent are not uncommon in large underground cable systems, although this fact may not always be manifested due to the high factor of safety in the insulation.

Occurrence of Cable Burn-outs. — The following table gives the number of cable burn-outs reported to the Underground Systems Committee of the N.E.L.A. in 1921.

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SIPICATION OF CABLE FAILURES ACCORDING TO VOLTAGE FOR YEAR 1920

	Voltages						
	6,000 to 9,000	9,000 to 12,000	12,000 to 15,000	15,000 to 18,000	18,000 to 21,000	21,000 to 24,000	24,000 to 27,000
ber of com-ies report-.....	6	5	7	1	1	5	3
of cable...	1151.4	1207.3	1093.1	5.7	80	408.7	37.1
failures...	48	98	108	0	8	17	5
failures....	11	32	90	0	6	28	0
failures....	59	130	198	0	14	45	5
es per 100 s of cable..	5.1	10.8	18.1	0	17.5	11.0	13.5
es per 100 s of cable 19.....	2.6	7.9	10.5	0	17.7	19.3	24.2

— The life of cables depends so much upon the type, excellence of manu- and conditions of service, that specific figures are of little use. Further- any of the earliest cables made are yet in satisfactory operation. For , there are at Buffalo, rubber-covered 11,000-volt cables that were in 1897, and in 1921 they were in perfect condition.

TS. — There are so many types of wires and cables and the prices e so greatly that it is impossible to give adequate cost data. The g examples will give a general idea of the cost of a few common types s:

Kind of wire or cable	Cost per 1000 ft.
14 code wire.....	$6.00 to $ 12.00
e conductor, 2500 volt, rubber ins., Park cable.	$85.00 to $115.00
e conductor, 1 circ. inch, 3/32" paper and 1/8" lead.....	$725.00 to $1350.00
e conductor, 0.35 circ. inch, 9/32 by 9/32, 1/8" lead	$1070.00 to $1710.00

IOGRAPHY. — Bauer, K., *Elektrische Kabel*, Berlin; Coyle, D., and . J., *Electric Cables*, London; Del Mar, W. A., *Electric Power Conductors*, rk; Meyer, E. B., *Underground Transmission and Distribution*, New Russel, A., *Theory of Electric Cables and Networks*, London; see also ds of the A.I.E.E.; National Electrical Code, Transactions of A.I.E.E., nmittee Reports of A.E.R.A., A.R.A., A.R.E.E., and N.E.L.A.

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WIRES, RESISTANCE. — (*See also Electromagnet Windings; Resistance and Conductance, Electric; Rheostats and Resistors; Wires and Cables, Bare; Wires and Cables, Insulated.*) Metals and alloys having high specific resistance or low temperature coefficient of resistance are largely used for resistors. Some of the principal metals used for this purpose are listed below. They are usually be obtained in the form of wires, ribbon or sheets. The data given Nichrome, Climax, Advance, Therlo, Yankee Silver, Ferro-nickel, Monel Metal, Kromore, No. 193 Alloy, and Nickel Silver were supplied by the Driver-Harris Co., those on Calido, Ideal, Akbar, Comet, Karma, Lucero, Nickel, Phenix and Rayo were supplied by the Electrical Alloys Co., those on Excello, Ia Ia, and Superior resistance metals were taken from the catalogue of H. Boker & Co., those on Acme, Electris, Excelsior, Eureka, Peerless, Premier Nickel Chrome, Sichrome, Superior Nickel Chrome and Tarnac were supplied by the Alloy Metal Wire Co., those on Chromel were supplied by the Hoskins Manufacturing Co., and those on Manganin by Baker & Co.

Acme is a nickel-steel-chromium alloy and is used in heat radiating elements. It is similar to No. 193 Alloy and Comet.

Advance is a copper-nickel alloy, containing no zinc. It is uniform in composition and constant in its resistance under all conditions of service. Because of its high thermal e.m.f. against copper, it cannot be used in electrical apparatus in which the generation of an electromotive force would cause errors, as for example, in a wheatstone bridge where a few microvolts would cause an error in the galvanometer deflection. It is used in switchboard voltmeters, street car heaters, and other forms of heating devices provided its operating temperature is not exceeded. For ordinary temperature measurements a commercial grade may be used as a thermo-couple element. For accurate temperature measurements, it should be purchased on specification.

It is similar to Excelsior and Ideal.

Akbar is an alloy of copper, nickel and manganese. It is used for heating purposes.

Calido is a high percentage nickel-chromium alloy. The melting point is about 1530° C. It is recommended for electrically heated devices at temperatures up to 1000° C.

Chromel is furnished in three grades: Chromel "A" is an alloy containing about 80 per cent nickel and 20 per cent chromium. It is used in heating devices such as hot plates at temperatures from 875° C. to 1100° C. Chromel "B" contains about 85 per cent nickel and 15 per cent chromium. It is more durable than Chromel "A" but is suitable for the same class of work where conditions are less severe. Chromel "C" is a nickel-chromium-iron alloy containing about 25 per cent iron and 11 per cent chromium. Its iron content somewhat lowers its durability at high temperatures. It is used extensively in flatirons where it is enclosed and thus protected to a certain degree against oxidation.

Climax is a high-resistance nickel-steel alloy. It is especially well suited for use in rheostats. It is one of the cheapest resistance metals, but has a tendency to rust and scale and should therefore not be used in smaller sizes than No. 20 A.W.G. It is similar to Electris and Phenix.

Comet is an alloy of nickel, chromium and steel. It is low in cost and is used extensively in heating devices at temperatures below red heat. This alloy with Ideal wire produces a thermocouple of high e.m.f. and as such is more durable than iron or copper. It is similar to Acme and No. 193 Alloy.

Constantan is a copper-nickel alloy. It is used primarily as an element

ɔcouples. Constantan, Advance and Ideal are very similar and used for
· purposes. When thermocouples are to be made up for use with cali-
: apparatus, the thermoelements should be purchased on specification
urities in very small quantities affect the thermal e.m.f. (see article on
ters).

:tris is used as resistance element at medium low temperatures in such
: as controlling devices and rheostats. It can be soldered with any stand-
x and is similar to Climax and Phenix.

eka is a nickel-copper alloy and is claimed to be superior to German
because it is free of zinc, which produces brittleness when the alloy is
ated. It is used for general heating purposes such as car heating. In
l it is similar to Lucero.

elsior is an alloy of nickel and copper. It has characteristics similar to
ce, Ideal and Constantan and is used for similar purposes. The manu-
r recommends it for use in heating pads and other light duty service.

ello is adapted for use in electric heating devices.

o-nickel has a high current-carrying capacity, on account of its low
: resistance. As it will rust, it can only be used where it is not attacked
isture.

man Silver is an alloy of copper, nickel and zinc. The "grade" of
e designates the percentage of nickel. The 18 per cent grade is the
ɔmmon. The resistance of any particular grade depends upon the
of annealing; hard wire is slightly higher in resistance than soft. Ger-
lver was for many years the only resistance alloy obtainable, but it is
ing generally displaced by materials of the same specific resistance but
rior qualities. (See article on *Alloys*.)

a is recommended for use in instruments and electrical devices where a
ıperature coefficient is desired.

l is an alloy of nickel and copper, and contains no zinc. The manu-
rs state that its temperature coefficient is "nil." It may be used
ɔcipient red heat of 520° C. Its use in general is the same as that of
e. When used with Comet wire it forms a very durable and desirable
couple. In general it is similar to Advance and Excelsior.

ne is a nickel-chromium alloy used for heating purposes at temperatures
100° C.

nore is a nickel-chromium alloy. It is used at temperatures up to
in heat radiating elements. It is similar to Peerless and Rayo.

ro is a nickel-copper alloy and is intended for use in place of German
It is used in car heaters and other similar heating devices. In general
ilar to Eureka.

ganin is a material developed by the Reichsanstalt, for use in
ents and standards. The alloy which was shown to be the best for
· purposes is one containing 85 per cent of copper, 12 per cent of man-
ınd 3 per cent of nickel. Prior to 1918 it was imported but now it is
ıanufactured in the United States and is known as Baker manganin.
ıer manganin contains a small amount of iron and is claimed to be an
ment over that formerly obtainable.

anin should be used with a double silk covering saturated with shellac
ı baked in an oven at 140° C. for at least 24 hours. The baking process
the wire and sets the shellac so as to exclude air from the wire which
ɔtherwise become slightly oxidized in use. Oxidation increases the
ture coefficient of resistance. When used in resistance standards and

precision apparatus the shellacked coils of wire should be sealed to exclud from the shellac, otherwise the shellac will absorb varying amounts of mo from the air under a variation of humidity. When the shellac absorbs mo it expands and changes the tension of the wire and thus changes its resis The resistance element should be adjusted to its desired value after the an ing process, as the resistance of the wire decreases by a few tenths of one cent upon annealing.

The change of resistance with temperature is not a straight line but a cu represented by the formula:

$$R_t = R_{20}[1 + \alpha(t - 20) - \beta(t - 20)^2],$$

in which R_{20} is the resistance at 20° C., R_t is the desired resistance at the t perature t in degrees centigrade, α is a constant given in Table I, β is a cons usually equal to 4×10^{-7}.

Monel Metal contains approximately three parts nickel to one of co In smelting and refining the ore from which monel metal is mad nickel and copper are not separated, and, therefore, appear in the fi alloy in the same relative proportions. The treatment of this ore co merely in eliminating the impurities, excepting a small percentage duced iron. As a result the metal is tough, strong, as non-corrosive a nickel, and is the same in appearance; whereas nickel, as a pure metal, tively expensive, owing to the difficulty of isolating it. This alloy is pro at a cost which permits favorable competition with German silver, etc. resistance varies somewhat in different lots, and according to temper variation is, however, no greater than that of 18 per cent German silver.

Nichrome is practically *non-corrosive*, has an extremely high melting (about 1550° C.) and is far superior to nickel in its ability to wi high temperatures. It is especially recommended for use in elec heated appliances and resistance elements generally where extreme co are encountered.

Nichrome II is strongly resistant to oxidation. It has been es developed for use in carbon combustion furnaces, and other labo furnaces where the more extreme temperatures are to be met.

Nickel, due to its high temperature coefficient, is very efficient for resistance thermometers and owing to its non-corrosive qualities it employed for rheostats where acid fumes are to be met with.

Nickel Silver, as commonly known, contains 18 per cent of nickel resistance varies somewhat in different lots and according to temper.

Peerless is an alloy of nickel and chromium used in such service as ovens and furnaces. It does not deteriorate when operating continuo 1100° C. with exposure to air. It is similar to Kromore and Rayo.

Phenix is a nickel-steel material suitable for resistances at compara low temperatures. It is readily soldered with any standard flux. It is extensively in arc lamps, rheostats, resistors for controllers and other heavy duty apparatus. It is similar to Electris and Climax.

Premier Nickel Chrome has a high resistivity and used in heating ances at temperatures up to 1000° C. It is similar to Nichrome and Cabl

Rayo is an alloy of nickel and chromium in such proportions that it withstand high temperatures and mechanical rubbing. It can be used con ously at temperatures up to 1100° C. without deterioration. It is used in elec ranges and ovens. It is similar to Kromore and Peerless.

Sichrome is a new alloy consisting of silicon, chromium and iron. It

TABLE I—PROPERTIES OF RESISTANCE METALS

Material	Maximum working temperature, ° C.	Microhm cm. at 20° C., ρ	Temperature coefficient per ° C. at 20° C., α	Microvolts per ° C. against copper	Specific gravity, δ	Tensile strength, lbs. per sq. in. (annealed)	Linear expansion coefficient per °C.
							$10^{-6}\times$
e	.....	87.3	0.00072	.....	8.15	.....	.....
ance	535	48.8	0.000018	43.9	8.9	60,000	14.4
ur	600	83.1	0.0006	25	.....	80,000	14
lo (see p. 2048)	1000	110.0	0.00025	12	8.15	90,000	16
ax	425	87.0	0.00098	.....	8.15	75,000	17.1
anel "A"	1090	103.0	0.00011	.....	8.23	.....	.....
anel "B"	980	89.0	0.00011	.....	8.40	.....	.....
anel "C"	.....	108.0	0.00018	.....	8.1	.....	.....
et	600	87.0	0.0007	5	8.15	80,000	12
tris	.....	83.2	0.0011	.....	8.1	.....	.....
ka	.....	46.5	0.00072	.....	8.8	.....	.....
ksior	.....	49.2	0.0000	.....	8.9	.....	.....
o-nickel	340	28.2	0.00207	.....	7.8	.....	.....
an silver 18% *	260	33.3	0.00031	25	8.5	.....	17.3
(soft)	.....	47.1	0.000005	.....	8.92	.....	.....
(hard drawn)	.....	50.2	0.000011	.....	8.92	.....	.....
l	500	49.2	0.000005	40	8.9	65,000	14
n	1100	103.0	0.00016	15	.....	90,000	15
nore	1100	94.6	0.000242	.....	8.9	80,000	.....
no	600	46.5	0.0007	30	8.9	75,000	14
ganin	100	49.9	0.00001	1.4	8.4	.....	.....
el metal	425	42.6	0.00191	.....	8.15	44,000	12.6
rome	980	109.5	0.000171	.....	8.9	98,000	.....
rome II	1040	109.5	0.000172	.....	8.02	98,000	16.4
el	700	10.6	0.00300	25	8.8	70,000	14.0
el silver, 18%	260	33.3	0.00027	.....	8.5	70,000	17.3
el silver, 30%	.....	48.2	0.00020	.....	8.5	75,000	.....
less	1100	95.5	0.00018	.....	8.05	.....	.....
ix	400	83.1	0.0011	4	8.10	75,000	14
nier nickel							
rome	1000	103.0	0.00036	.....	8.15	.....	.....
o	1100	95.7	0.00018	14	8.05	90,000	15
rome	1100	113.0	0.000025	.....	7.63	.....	.....
rior	550	87.2	0.00081	.....	8.04	.....	.....
rior nickel							
rome	1100	103.0	0.00011	.....	8.2	.....	.....
nac	.....	41	0.000025	2.0	8.89	.....	.....
rio	200	46.7	0.000006	— 1.5	8.15	78,000	19.4
kee silver	480	33.0	0.000155	.....	8.6	.....	15.9
193 alloy	650	87.2	0.00072	.....	8.15	60,000	17.1

o per cent German silver has substantially the same properties as Advance metal.

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claimed to have a less tendency to corrode than the nickel chromium al It is intended for use in heating elements at temperatures up to 1100° C. rather severe conditions. Its specific gravity is lower than that of an resistance wire.

Superior is a nickel-steel alloy recommended for use in rheostats, ar resistances, etc.

Superior Nickel Chrome is an alloy containing approximately 80 per nickel and 20 per cent chromium. It is used in heating devices at temperat up to 1100° C.

Tarnac is an English product which is very similar to manganin and is for the same purposes. For precision purposes it should be treated in the manner as manganin. The variation of its resistance with temperatu similar to that of manganin. The value of β in this case is usually 2.5 × It has a maximum resistance at 70° C.

Therio is an alloy of copper, manganese and aluminum for work w low thermo-electric effect against copper is demanded. Compared with ganin, this alloy gives a higher specific resistance, does not oxidize so fast, is more stable in its electrical and mechanical behavior. This material is cially suitable for shunts. Temperature coefficient is +0.0000031 per It cannot be soldered but has to be brazed. This characteristic is favorabl its proper use. It should be treated in the same way as manganin to pr accurate resistance coils.

Yankee Silver. — This is a new alloy with most of the qualities of "s cent German Silver." It will withstand repeated heating and cooling and gives satisfactory service where German silver fails.

No. 193 Alloy consists of nickel, iron and chromium. It serves as resi elements for elevator controllers and rheostats at temperature up to 640° is similar to Acme and Comet.

TABLE II. — RESISTANCE, WEIGHT AND CURRENT-CARRYI CAPACITY OF WIRES

$$\text{Resistance, ohms per foot at } 20^\circ \text{ C.} = \frac{K\rho}{1000},$$

where ρ is the resistivity of the metal in microhms per centimeter cube, taken Table I, and K is given in the table below.

$$\text{Weight, pounds per foot} = \frac{H\delta}{1000},$$

where δ is the specific gravity of the metal, taken from Table I, and H is given in table below.

$$\text{Current for given temperature rise, amperes} = \frac{10\, I_\theta}{\sqrt{\rho}},$$

where ρ is the resistivity of the metal in ohms per centimeter cube, taken from Ta and I_θ is given in the table below. This formula is based upon the following multi to convert the resistivity at 20° C. to that at the temperatures stated.

100° C.....	1.031
200° C.....	1.052
500° C.....	1.081
1000° C.....	1.118

These are correct for Calido wire. For any other wire, the current derived from formula must be multiplied by the factor $\sqrt{\frac{m_c}{m_x}}$, where m_c is a multiplier from the al table and m_x the corresponding multiplier for the wire in question.

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Resistance factor (a) K	Weight factor (b) H	Current-carrying Cap. I_0 for $\rho = 100$ (c)			
		100° C.	200° C.	500° C.	1000° C.
0.229	8.94	24.7	38.5	73.3	146.0
0.364	5.62	17.6	27.5	52.3	105.0
0.579	3.54	12.7	19.7	37.7	75.4
0.921	2.22	9.04	14.2	28.2	53.8
1.46	1.40	6.51	10.2	19.3	38.7
2.33	0.880	4.66	7.35	13.9	27.8
3.70	0.553	3.36	5.25	9.97	20.0
5.89	0.348	2.40	3.76	7.15	14.3
9.36	0.219	1.72	2.59	5.10	10.2
14.9	0.138	1.24	1.94	3.69	7.35
23.7	0.0865	0.89	1.39	2.64	5.27
37.6	0.0544	0.65	1.01	1.92	3.84
59.9	0.0342	0.47	0.75	1.42	2.92
95.2	0.0215	0.35	0.56	1.04	2.08
151	0.0135	0.26	0.41	0.79	1.54
241	0.00851	0.19	0.30	0.57	1.13
383	0.00537	0.14	0.22	0.41	0.84
608	0.00337	0.10	0.16	0.30	0.61

K is the resistance per 1000 feet for a resistivity of 1 microhm per cm.³
H is the weight per 1000 feet for a specific gravity of 1.
or a rise of temperature above 20° C. equal to the temperatures stated
n, for a wire stretched straight and freely exposed to air.

APHY. — Bash, F. E., *Manufacture and Electrical Properties of* n. Inst. Mining Eng. Bull., No. 153, p. 2409, 1919; Drysdale, C. *Resistance Standard*, London Electrician, Aug. 11, 1916, Vol. 77, r, T. S., *Electrical Resistivities of Iron Alloys*, Gen. Elec. Rev., , p. 566, Summerville, A. A., *Resistance Metals*, Phys. Rev., 1910, 1; Swoboda, H. O., *Properties of Resistor Materials Used for Heat-*El. W., April 23, 1921, Vol. 77, p. 944; *Nickle*, U. S. Bureau of ircular No. 100; Catalogues of the Alloy Metal Wire Co., Baker r-Harris Company, Electrical Alloy Co., H. Boker and Co., Hoskins

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WIRING OF BUILDINGS FOR LIGHT AND POWER.—

also Distribution of Electric Energy; Distribution Lines; Transmission Lin Wires and Cables; Wiring of Buildings for Miscellaneous Devices.)

The following is a brief table of contents of this article:

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General Requirements. — Wires and fittings designed to conduct el tricity in a building should be selected as to size and insulation and instal in such a manner that: (1) the attending fire risk and the possibility of electric shock to the inhabitants shall be a minimum; (2) the elec power efficiency of the system shall be reasonable; (3) the voltage at t receiver shall approximate the rated voltage of the receivers and shall rem sensibly constant; (4) the mechanical arrangement of the system shall simple and convenient for inspection and use; (5) the conductors shall mechanically protected from external injury; (6) the service shall not be in rupted under normal load; (7) the cost of the materials, labor of installa and replacement due to depreciation shall not be excessive, and (8) the ent wiring system shall conform to the rules and regulations of any author having jurisdiction over the building in question.

SYSTEMS OF WIRING. — For direct-current and single-phase dis bution the two-wire system (Fig. 1) and the three-wire system (Fig. 2

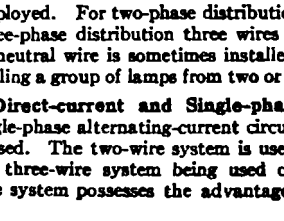


Fig. 1.

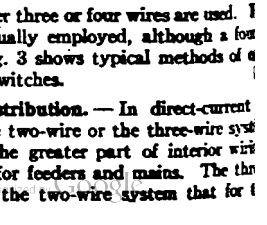


Fig. 2.

employed. For two-phase distribution either three or four wires are used. I three-phase distribution three wires are usually employed, although a fou or neutral wire is sometimes installed. Fig. 3 shows typical methods of c trolling a group of lamps from two or more switches.

Direct-current and Single-phase Distribution. — In direct-current single-phase alternating-current circuits, the two-wire or the three-wire syst is used. The two-wire system is used for the greater part of interior wirin the three-wire system being used chiefly for feeders and mains. The thr wire system possesses the advantage over the two-wire system that for t

e power transmitted at the same efficiency to receivers of the same voltage, three-wire system requires less weight of conductor. The neutral wire of a e-wire system is usually of the same size as either outside wire, the saving opper over the two-wire system then g 5/8 or 62.5 per cent (*see Distribution of tric Energy*). In some cases, buildings wired with the three-wire system in ch the neutral wire is made twice the of either outside wire so that if neces-, the system may be operated either as o-wire or a three-wire system; in the ier case the two outside wires are con-ed in parallel. Power may then be plied to the building from a local two-source of supply (isolated plant in the ding) or from an emergency three-wire t service.

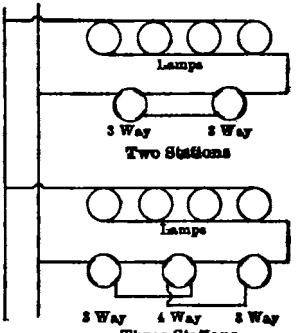


Fig. 3.

i this case wires of such size would be as would give normal efficiency and lation when used as a two-wire system; loss when used as a three-wire system ld then be only half as great.

he first cost of a three-wire system may not be less than that of a two-wire em because of the increased cost of the fittings, insulation and the labor of llation. The three-wire system is not as simple as the two-wire system, is subject to more disturbances unless the load is kept balanced. Some ric power companies limit the power which they will supply to a two-wire m and in such cases in new installations buildings taking power above the wire limit must be wired with the three-wire system. The two-wire system ed for either lighting or power loads while the three-wire system is used ither lighting or mixed lighting and power loads, motors in the latter case g connected between the outside wires.

wo-phase and Three-phase Distribution. — For distributing two-phase nating currents, either three or four wires are employed. A four-wire phase system may be treated as two separate two-wire systems, which ot in any case be connected in parallel. A single wire 41 per cent larger i either of the wires it displaces may be substituted for any two of the wires e four-wire two-phase system thus making a three-wire two-phase system. er three or four wires may be used for two-phase lighting or power loads. hree wires are usually employed on three-phase alternating-current circuits lying power to lighting or power loads. If the neutral is accessible, a neutral may also be used, making a four-wire three-phase system for lighting s, the lamps being connected between any outside wire and the neutral

TANDARD VOLTAGES FOR LIGHTING AND POWER LOADS. — all standard lighting loads the voltage across the lamps ranges from 100 25 volts in accordance with the rating of the lamps. In a few cases, lamps d between 200 and 250 volts are used with the corresponding voltages. voltage between the service wires of a constant-current series-arc or series-ndescent lamp system must not be greater than 5000 volts, the maximum tge for inside work allowed by the National Electrical Code (see p. 2063). stant-current systems are used chiefly in lighting large areas as in mills, ories, armories, etc. On power loads standard voltages of approximately 220 or 550 volts are used depending on the magnitude of the load supplied.

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STANDARD FREQUENCIES ON ALTERNATING-CURRENT CIRCUITS. — Alternating currents are usually supplied to lighting loads at a frequency of 60 cycles and to power loads at 25 cycles. In some cases a frequency of 40 cycles is used when the lighting and power loads are of about the same magnitude.

PRELIMINARY LAYOUT OF THE WIRING SYSTEM. — If power is to be supplied to the building from some outside source, the service entrance must first be located from plans or by an inspection of the building itself. In most cases, service entrances are made in the basement, although first-floor entrances may be substituted when basement entrances are impracticable. In overhead-service connections, the service wires are usually run in conduit on the outside of the building from the point where the wires are attached to the building to the service panel-board. In underground-service connections, the service wires are run in conduit from the street mains through the basement walls. In the latter case, the conduit should be tightly closed at the outlet to prevent gases from entering the building. Fig. 4 shows two types of service connections.

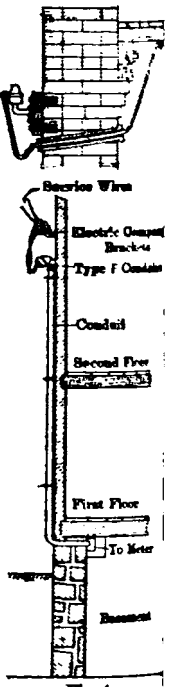


Fig. 4.

Location of Panel-Board. — The service panel-board should be placed securely in an accessible location and should contain space for the service cut-outs, service switch and meter. When power is supplied from within the building, the switchboard of the power plant must be located as a starting point in the design of the feeder system.

Location of Outlets, Switches, etc. — Outlets, control switches and cut-out cabinets should then be located throughout the building. Great care must be exercised in locating outlets and control switches in such positions as to accommodate the receiving devices planned for the building. Cut-out cabinets, which constitute the local distributing centers, should be located as near as possible to the dependent receiving devices and should at the same time be easily connected by feeders to the main switchboard. Fig. 5 shows a riser diagram and Fig. 6 a diagram of the wiring for one floor of an office building.

Number of Feeders. — Having located the outlets, control switches, distribution centers and the main switchboard, a feeder system must be planned to suit the conditions under which the system is to operate. The number of feeder sets required depends upon: (1) the power taken by the receiving devices; (2) the degree of control desired at the main switchboard; (3) the number of receiving devices which may rely upon one set of feeders; (4) the desired uniformity of voltage at the receiving devices, and (5) the character of the receiving devices. If the total current supplied to the building is roughly calculated and is found to exceed 650 amperes (the allowable carrying capacity of a 1,000,000 circular-mil rubber-insulated conductor), more than one set of feeders should be used, since it is impracticable to install feeders larger than one inch in diameter

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(Text continued on p. 2055.)

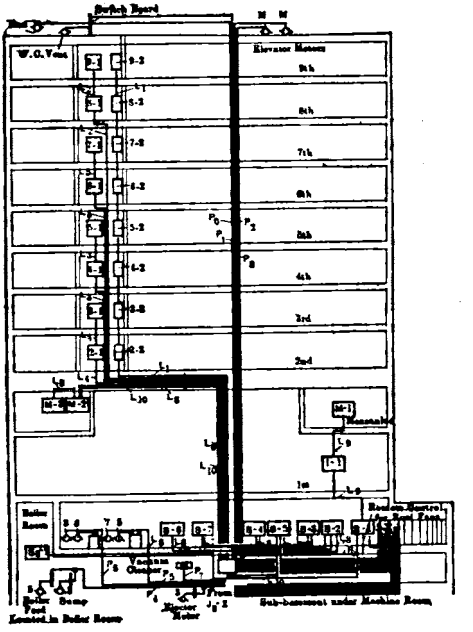


Fig. 5.

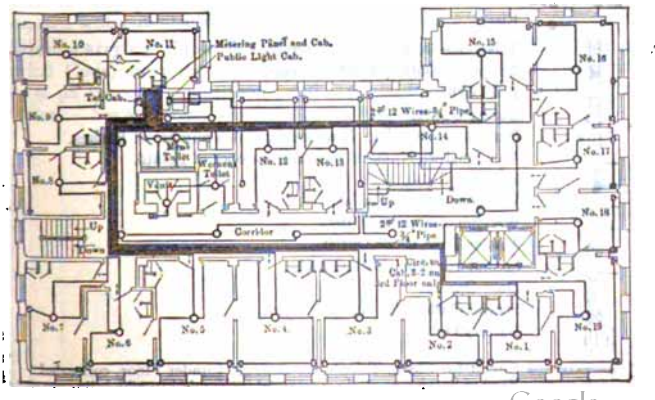


Fig. 6.

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STANDARD WIRING SYMBOLS

(Adopted by the National Electrical Contractors' Association and the American Institute of Architects.)


Ceiling Outlet; Electric only.*

Ceiling Outlet; Combination.† If gas only


Bracket Outlet; Electric only.*


Bracket Outlet; Combination.† If gas only


Wall or Baseboard Receptacle Outlet.*


Floor Outlet.*


Outlet for Outdoor Standard or Pedestal; Electric only.*


Outlet for Outdoor Standard or Pedestal; Combination.†


Drop Cord Outlet.


One Light Outlet, for Lamp Receptacle.


Arc Lamp Outlet.


Special Outlet, for Lighting, Heating and Power Current, as describe

Ceiling Fan Outlet.


S. P. Switch Outlet.


D. P. Switch Outlet.


3-Way Switch Outlet.


4-Way Switch Outlet.


Automatic Door Switch Outlet.

Electrolier Switch Outlet.

Show as many Symbols as there a Switches. Or in case of a very la group of Switches, indicate numb of Switches by a Roman numer thus; S^{3} XII; meaning 12 Sing Pole Switches.

Describe Type of Switch in Specifica tions, that is, Flush or Surface, Pu Button or Snap.


Meter Outlet.


Distribution Panel.


Junction or Pull Box.


Motor Outlet; Numeral in center indicates Horse-Power.


Motor Control Outlet.

Transformer.

Heights of Center-of-all Outlets (unless other wise specified):	
Living Rooms	5 ft. 6 in.
Chambers	5 ft. 0 in.
Offices	6 ft. 0 in.
Corridors	6 ft. 3 in.
Height of Switches (unless otherwise specified)	4 ft. 0 in.


Main or Feeder concealed under Floor.

Main or Feeder concealed under Floor above.


Main or Feeder run exposed.


Branch Circuit concealed under Floor.


Branch Circuit concealed under Floor above.

Branch Circuit run exposed.

Pole Line.


Riser.

Telephone Outlet; Private Service.

Telephone Outlet; Public Service.

Bell Outlet.


Buzzer Outlet.

Push Button Outlet; Numeral indicates number of Pushes.


Annunciator; Numeral indicates number of Points.


Speaking Tube.


Watchman Clock Outlet.


Watchman Station Outlet.


Master Time Clock Outlet.


Secondary Time Clock Outlet.


Door Opener.

Special Outlet; for Signal Systems.


Battery Outlet.


Circuit for Clock, Telephone, Bell, etc.§ under Floor, concealed.
Kind of Service wanted ascertained by Symbol to which line connects.


Circuit for Clock, Telephone, Bell, etc.,§ under Floor above, concealed

* Numeral indicates number of standard 16 C. P. incandescent lamps.

† Upper numeral indicates number of

Unless controlled by remote control switches, separate feeders must be
illed from the switchboard to receiving devices which are controlled at the
switchboard.

a single set of feeders is used on a lighting load, the possible extinction of
lights in a building by an open circuit in the main feeders may cause a
; on a power load an interruption of all the machinery for any length of
may cause a considerable loss of money. To avoid such a discontinuance
e service, it is customary to connect separate feeders to sectionalized parts
e load, so that the entire load may not be interrupted at one time.

e voltage at receiving devices may be made more uniform by the use of
ate feeders than by the use of one set of feeders, except when a single set
ders may be run to a distributing panel to which branch feeders of nearly
l length are connected. When the power taken by certain receiving devices
s extensively and rapidly, the voltage at all other devices connected to the
feeder will vary accordingly, and in such cases lamps must be connected
parate feeders to avoid undesirable flickering.

iring Diagram. — After deciding upon the number of feeders to be used in
nstallation, a diagram should be made showing the location and length of
eders and branch circuits. When the wiring system is sectionalized, each
n should be treated by itself as a complete system. Figs. 5 and 6 are
al wiring diagrams for an office building.

RING CALCULATIONS. — The proper size of wire for any feeder is
mined by three factors: (1) mechanical strength; (2) current-carrying
ity, and (3) the allowable potential drop in the feeder.

nimum Size of Wire. — The National Electrical Code specifies No. 14
G. as the minimum allowable size for all classes of rubber-insulated
, except that in fixture work and for pendant cords wires as small as
8 A. W. G. may be used. The minimum allowable size of varnished cloth
ted wire is No. 6 A. W. G., except by special permission.

ıd of Insulation. — Rubber insulated wire protected with an outside
d covering and varnished-cloth insulated wire also with an outside braided
ing may be used where not exposed to moisture.

ıd Sheaths. — Lead-covered wire should be used when installed in tile
for mechanical protection against abrasion and in underground runs in
, etc., where condensed moisture may be present.

rrent-carrying Capacity. — The following table, from the National
ical Code, gives the allowable carrying capacity of copper wires and
of 98 per cent conductivity, and must be followed in placing interior
ctors. See also *Wires and Cables, Insulated.*

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CURRENT-CARRYING CAPACITY OF COPPER WIRES
National Electrical Code Standard

Size of wire, A.W.G.	Maximum allowable amperes			Size of wire, circular mils	Maximum allowable amperes *		
	Rubber insulation	Varnished cambric insulation	Other† insulations.		Rubber insulation	Varnished cambric insulation	Oth...
18	3	.....	5	200,000	200	240	...
16	6	.....	10	250,000	250	300	1...
14	15	18	20	300,000	275	330	...
12	20	25	25	400,000	325	390	...
10	25	30	30	500,000	400	480	...
8	35	40	50	600,000	450	540	...
6	50	60	70	700,000	500	600	...
5	55	65	80	800,000	550	660	...
4	70	85	90	900,000	600	720	...
3	80	95	100	1,000,000	650	780	1...
2	90	110	125	1,100,000	690	830	1...
1	100	120	150	1,200,000	730	880	1...
0	125	150	200	1,300,000	770	920	1...
00	150	180	225	1,400,000	810	970	1...
000	175	210	275	1,500,000	850	1020	1...
0000	225	270	350	1,600,000	890	1070	1...
.....	.....	.....	....	1,700,000	930	1120	1...
.....	.....	.....	....	1,800,000	970	1160	1...
.....	.....	.....	....	1,900,000	1010	1210	1...
.....	.....	.....	....	2,000,000	1050	1260	1...

* For insulated aluminum wire the maximum allowable current is 84 per ce... of that given in the table for the corresponding type of insulation.

† This includes paper, slow-burning insulation, etc.

Currents Taken by Various Receiving Devices. — The current tak... by each receiving device if not stated in the specifications may be determi... roughly from the following tables.

CURRENT TAKEN BY INCANDESCENT LAMPS AT 114 VOLTS

Candle power	Amperes per lamp		
	Carbon	Gem	Tungsten
16	0.5	0.35	.....
20	.....	.....	0.22
32	1.0	0.7	.....
48	.....	.....	0.53
50	1.4	1.1	.....
80	.....	.....	0.88
100	2.7	2.2	.....

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CURRENT TAKEN BY ORDINARY ARC LAMPS

⅛-inch carbons

Type	Multiple*		Series	
	Volts	Amperes	Volts per lamp	Amperes
ect current	110	5 to 6.5	70	5 to 6.6
	220	3		
rnating current	110	6 to 8.5	70	6.6 to 7.5
	220	6		

On multiple-arc-lamp circuits, the conductors must be designed to carry 150 per f the normal current taken by the lamps.

CURRENT TAKEN BY DIRECT-CURRENT MOTORS*

Horse-power	Amperes at		
	110 volts	220 volts	500 volts
½	4.5	2.2	1
¾	6.8	3.4	1.5
1	9.0	4.5	2
1½	13.6	6.8	3
2	16.9	8.5	3.8
3	25.4	12.7	5.6
4	33.8	16.9	7.5
5	42.3	21.1	9.3
7½	56.5	32.2	12.4
10	75.3	37.6	16.6
15	113	56.5	24.9
20	150	75.3	33.1
25	188	94.1	41.6
30	226	113	49.7
40	301	150	66.3
50	376	188	82.8
60	452	226	99.4
70	527	263	116
80	602	301	132
90	678	339	149

* For single-phase a-c. motors divide current given by power factor of motor.

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CURRENT TAKEN BY THREE-PHASE INDUCTION MOTORS

Power factor taken as 80 per cent

Horse-power	Amperes per wire at line voltages of		
	110 volts*	220 volts*	550 volts*
1	6	3	1.2
2	12	6	2.4
3	18	9	4
4	24	12	5
5	28	14	6
10	56	28	11
15	85	42	17
20	112	56	22
25	140	70	28
30	167	83	33
40	222	110	44
50	278	140	58
60	330	165	66
70	385	192	77
80	440	220	88
90	490	245	98
100	550	275	110
150	790	395	158
200	1050	525	210
250	1320	660	264
300	1580	790	316

* These are volts between wires; the corresponding volts to neutral are 63.5, 127, 318, respectively.

WATTS TAKEN BY HOUSEHOLD APPLIANCES

Device	Watts	Device	Watts
Flatirons	350–500	Curling iron	90
Immersion heater	300–500	Vibrators	50
Water heaters	600–5000	Vacuum cleaner	150
Chafing dishes	420	Stove (4 burner and oven)	5720
Grill	660	Bake oven	5–50 kw
Coffee percolaters	420	Dish washer	200
Toasters	500	Washing machine	600
Heating pads	60	Ironing machine	2.5–6 kw
Cigar lighters	70	Hot plates (2)	2300
Glue pots	440–880	Hot plates (3)	3100
Luminous radiators	750–1500	Laboratory plate	860–43
Reflection heater	600	Industrial disc heater	1000–15
Air heater	500–1000	Soldering iron	100–50
Sewing machine	50	Office fans	30–60

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—In most installations the potential drop *per conductor* ance or switchboard and the farthest receiver is taken as · cent of the *voltage to neutral* at the service-entrance or s equivalent to a *total drop* (both wires) of 3 per cent of the in the case of a two-wire direct-current or single-phase ire systems the two outside wires are to be regarded as

or single-phase alternating-current systems the maximum *nductor* will then be $0.015 \times 110 = 1.65$ volts for a 110-volt a 220-volt system, etc. In three-phase systems the poten-

or will be $0.03 \times \frac{110}{\sqrt{3}} = 1.91$ volts for a 110-volt system,

olt system, etc. In feeders and branch circuits the drop ully made two-thirds and the drop in the branch circuits drop.

se of a lamp load the allowable drop of 3 per cent is based ponding to the *total connected load*, i.e., this is the maximum are burning. In ordinary buildings the actual maximum han one-third the connected load; consequently when the this basis the voltage at the lamps will seldom be more than the voltage at the service connection.

e of Wire. — Let

conductor in amperes,
tential drop *per conductor* in volts,
e conductor in feet,*
s-section of a copper wire in circular mils is

$$A = \frac{KIl}{v}, \qquad (1)$$

pending upon the specific resistance of the wire, the size res, the frequency and the power factor of the receiver. nating-current circuits is therefore not a constant but for ns its value for the sizes of wires and spacings (1 to 6 inches) terior wiring is approximately as given in the following ng-current values apply to single-phase, 2-phase 4-wire

System	Power factor	Values of K for copper
rrent.....	....	11*
ng current.....	....	....
g load only.....	1.00	11
g and power loads	0.95	12
g and power loads.	0.90	13.5
loads.....	0.85	15
loads.....	0.80	17

is practically exact, the others are approximate only.

stems at any frequency from 25 to 60 cycles per second. or single-phase 3-wire system proceed as for a 2-wire · presence of the neutral wire; the neutral wire should e size as each outside wire as thus calculated.

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ength of *each conductor;* the total length of wire for a two-wire

Commercial sizes of wire differ successively by about 25 per cent in the l
sizes and 60 per cent in the smaller sizes; the odd-numbered sizes smaller t
No. 1 are not generally manufactured, although No. 3, 5 and 9 are some
made. From the table below * select the size of wire corresponding to the
culated area. Unless the calculated area in circular mils agrees very clo
with the area of one of the conductors given in the table, the next larger
of wire should be selected.

600-VOLT RUBBER-INSULATED COPPER WIRE

(Single Braid, N.E.C. Standard; Conductivity of Copper, 98 per cent)

Size, A.W.G.	Cross-section of copper, circular mils	Over-all diameter, inches	Ohms per 1000 feet at 77° F.	Pounds per 1000 feet of insulated wire	Reactance per 1000 feet of each wire			
					Wires in contact †		6 inches between wires ‡	
					25 cycles	60 cycles	25 cycles	60 cycles
		stranded	stranded	stranded				
	1,000,000	1.50	0.0110	3556	0.0130	0.0313	0.0	
	900,000	1.44	0.0122	3223	0.0132	0.0317	0.0	
	800,000	1.37	0.0138	2888	0.0134	0.0320	0.0	
	700,000	1.31	0.0157	2554	0.0136	0.0328	0.0	
	600,000	1.24	0.0184	2215	0.0138	0.0332	0.0	
	500,000	1.09	0.0220	1805	0.0135	0.0324	0.0	
	400,000	1.00	0.0275	1477	0.0141	0.0340	0.0	
	300,000	0.90	0.0367	1133	0.0144	0.0347	0.0	
	250,000	0.84	0.0441	962	0.0148	0.0354	0.0	
0000	212,600	0.77	0.0520	807	0.0144	0.0347	0.0	
000	168,000	0.71	0.0656	656	0.0149	0.0358	0.0	
00	133,000	0.66	0.0827	535	0.0151	0.0362	0.0	
0	106,000	0.61	0.104	438	0.0159	0.0381	0.0	
1	83,700	0.57	0.133	350	0.0165	0.0396	0.0	
		solid	solid	solid				
1	83,700	0.53	0.126	340	0.0159	0.0381	0.0	
2	66,400	0.47	0.159	268	0.0160	0.0385	0.0	
3	52,600	0.44	0.201	221	0.0166	0.0400	0.0	
4	41,700	0.41	0.253	184	0.0168	0.0403	0.0	
5	33,100	0.39	0.320	153	0.0176	0.0422	0.0	
6	26,300	0.37	0.403	129	0.0179	0.0430	0.0	
8	16,500	0.27	0.641	76	0.0181	0.0434	0.0	
10	10,400	0.23	1.02	54	0.0193	0.0464	0.0	
12	6,530	0.21	1.62	40	0.0210	0.0505	0.0	
14	4,110	0.20	2.58	30	0.0221	0.0532	0.0	
16	2,580	0.16	4.10	20	0.0231	0.0554	0.0	
18	1,620	0.14	6.51	13	0.0245	0.0588	0.0	

* More extended wire tables will be found in the article on *Wires and Ca*

† Two insulated wires side by side, the insulation of the two wires in cont

‡ Measured from insulation to insulation, equals distance between centers

Check on Calculation of Size of Wire. — Calculation of Actual Potential Drop. — (*See also Alternating Currents.*) From the table, corresponding to the size of wire selected, take

r = the resistance per 1000 feet of conductor,
x = the reactance per 1000 feet of conductor,

put

l = length of each conductor in feet,
I = amperes per conductor,
V = volts to neutral at receiver,*
$\cos\phi$ = power factor of receiver,

$$R = \frac{rl}{1000} = \text{total resistance per conductor},$$

$$X = \frac{xl}{1000} = \text{total reactance per conductor}.$$

Then the actual volts drop *per conductor* is

$$v = \sqrt{(V\cos\phi + RI)^2 + (V\sin\phi + XI)^2} - V. \qquad (2)$$

With a very close approximation in all ordinary cases this is equal to

$$v = RI\cos\phi\left(1 + \frac{X}{R}\tan\phi\right). \qquad (3)$$

If the drop as calculated does not check within a reasonable value with the drop assumed in calculating the size of the wire, select another size of wire and recalculate, etc. This refinement will be found necessary, only in the case of very low power factors and when the size of wire as calculated is either exceptionally large or exceptionally small, in which case the values given for the factor K in the formula for A, equation (1), may be in error by a large amount (in limiting cases 50 per cent or more).

In addition to making sure that the drop will be within a reasonable amount, one should also note whether the conductor selected is large enough mechanically and has the proper current-carrying capacity (*see above*), remembering also that the National Electrical Code requires that conductors through which power is supplied to a motor shall have a current-carrying capacity equal to at least 25 per cent of the full-load current taken by the motor.

Example of Calculation for a D-C. or Single-phase System. — Incandescent lamps taking 0.5 ampere each are supplied with power from a 115-volt two-wire service through a set of feeders 200 feet in length which terminate at a distributing cut-out cabinet as shown in Fig. 7. The lamps are grouped in sets of 10 lamps each (only one set is shown) and each set is connected to the cut-out cabinet by a branch circuit conductors averaging 25 feet in length. Assuming a total allowable tential drop of 3 volts, the drop per conductor will be 1.5 volts. The drop per conductor in the branch circuit should then be one-third of 1.5 or 0.5 volt and the drop per conductor in the feeder circuit should be two-thirds of 1.5 or

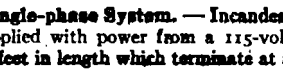


Fig. 7.

* For d-c. or a-c. single-phase or a-c. 2-phase, 2-wire systems $V = \frac{1}{2} \times$ (volts between wires); for a 3-phase system $V = \frac{1}{\sqrt{3}} \times$ (volts between wires); for a 2-phase 3-wire system $V = \frac{1}{2} \times$ (volts between either outside wire and middle wire). In calculating the normal drop in a single-phase 3-wire system pay no attention to the middle wire, i.e. assume a balanced load.

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1 volt. The respective calculations of the areas of the conductors in the feede and branch circuits may then be carried on independently. In the branch circuit, referring to equation (1), $I = 10 \times 0.5 = 5$, $l = 25$ and $v = 0.5$, when for copper wire

$$A = \frac{11 \times 5 \times 25}{0.5} = 2750 \text{ circular mils.}$$

From the wire table it is found that the next larger commercial size is No 1 A. W. G., which has a resistance of 2.58 ohms per 1000 feet, and a reactance (assuming a 2.5-inch spacing) of 0.106 ohms per 1000 feet.

Referring to equation (3), $V = 57.5$, $\cos\phi = 1$, $\tan\phi = 0$, $R = 2.58 \times 25/1000 = 0.0645$, $X = 0.106 \times 25/1000 = 0.00265$, whence

$$v = 0.0645 \times 5 = 0.323.$$

Equation (2) gives the same value. This voltage is 35.4 per cent less than the assumed voltage of 0.5 volt, but since No. 13 wire is not a commercial size a closer realization of the assumed voltage is impracticable.

In the same manner, the required area of the conductors used in the feeder circuit is determined by snbstituting the following values in equation (1): $I = 100 \times 0.5 = 50$ amperes, $l = 200$ feet, and $v = 1$ volt. Hence

$$A = \frac{11 \times 50 \times 200}{1} = 110{,}000 \text{ circular mils.}$$

From the wire table it is found that a No. 00 A. W. G. wire must be used.

The above calculations although made for a lighting load apply equally well to a motor load, except that in the final selection a wire must be chosen which will carry 125 per cent of the full-load current of the motor.

Example of Calculation for a Three-phase System. — Power is to be supplied by three feeders each 400 feet in length to a three-phase, 60-cycle, alternating-current motor (power factor 80 per cent), the voltage between any two line wires at the service entrance being 550 volts. At full load the current taken by the motor is 50 amperes. The voltage to neutral at the service entrance is $\frac{550}{\sqrt{3}}$ or 318 volts. The wires are to be spaced 6 inches apart.

Allowing a drop in each conductor of 3 per cent of the voltage to neutral, the drop will be 3 per cent of 318 or 10 volts approximately. The following values should then be substituted in equation (1): $K = 17$, $I = 50$ amperes, $l = 400$ feet and $v = 10$ volts, giving

$$A = \frac{17 \times 50 \times 400}{10} = 34{,}000 \text{ circular mils.}$$

From the wire table it is found that a No. 5 A. W. G. wire might be used considering the potential drop alone but since the carrying capacity of the conductor must be 1.25×50 or 62.5 amperes, it would be necessary to use a No. 4 wire.

Adopting a No. 4 wire and referring to equation (3), $V = 318$, $\cos\phi = 0.8$, $\tan\phi = 0.75$, $R = 0.253 \times 400/1000 = 0.101$, $X = 0.101 \times 400/1000 = 0.040$, whence

$$v = 0.101 \times 50 \times 0.8\left(1 + \frac{0.04 \times 0.75}{0.101}\right) = 5.3 \text{ volts,}$$

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ich is a little more than half the allowable drop of 10 volts. Equation (2) also es 5.3 volts.

AUTHORITIES GOVERNING THE INSTALLATION OF WIRING BUILDINGS. — As noted at the beginning of this article all interior ing must be installed in accordance with the regulations of the authorities ring jurisdiction over the building in question. In general, these authorities : (1) the fire underwriters; (2) the municipal authorities; and (3) the power pany supplying the current.

National Electrical Code. — This code is a set of instructions published in n years by the National Board of Fire Underwriters. A List of Electrical tings approved by the Underwriters' Laboratories, Inc. is published by the tional Board in April and October of each year. In order that fire insurance any building wired for electric light or power may be obtained from an urance company, the wiring must be installed in accordance with the rules of : National Electrical Code or such modifications of it as are required by law certain municipalities (*see Municipal Regulation, below*). Permission must o be obtained to use any fitting not included in the list of approved fittings. Both the Code and the List of Approved Fittings may be obtained gratis applying to the National Board of Fire Underwriters, 135 William St., New rk City. In view of this fact, and the frequent revisions of the rules and t it is not deemed advisable to give them in detail here. The general require- nts, however, are covered in the section below on *Methods of Installing iring.*

Municipal Inspection. — Many state legislatures have passed laws regu- ing the installation of electric wiring and empowering the appointment of micipal inspectors of wiring. In some states fines are imposed by legislative actment upon those who violate the inspector's rules. Although free to decide on the proper installation of electric wires, municipal inspectors have gener- y adopted the National Electrical Code as a standard with modifications ited to their desires. A copy of these modified rules can usually be obtained ntis from the municipal authorities.

Regulations of the Light and Power Companies. — The National Elec- cal Code is usually adopted by electric power companies with the addition of ecific requirements pertaining to service connections, placing of meters, type system, etc.

METHODS OF INSTALLING WIRING. — The National Electrical ode approves the use of the following methods of wiring: open work, moulding ooden moulding and metallic raceways), concealed knob and tube work, id conduit, flexible conduit, armored cable and flexible tubing (in short runs). hese methods are described in detail below, but first are given the more impor- nt general requirements regarding joints, protection, cut-outs, switches, etc., hich apply to all classes of wiring for voltages not exceeding 600.

General Requirements. — All joints must be mechanically and electrically cure without solder and unless made with some form of approved splicing rvice must be soldered and covered with an insulation equal to that on the nductor. Wires must be separated from contact with walls, floors, timbers partitions through which they may pass by non-combustible, non-absorptive sulating tubes, such as glass or porcelain, except at outlets where flexible tubing required. Unless inclosed in conduit or moulding, wires must be separated om any conducting material or from any other electric wire not more than wo inches away by some continuous and firmly fixed non-conductor creating permanent separation. In damp places wires must be separated from pipes y an air space and should be run over rather than under pipes upon which

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moisture may gather. Wires must be protected from mechanical injury by running-boards or guard-strips on low ceilings and by wooden boxing or metal conduit on side walls. Protection on side walls must extend not less than 6 feet from the floor. No method other than open wiring may be used when the difference of potential between any two wires exceeds 550 volts.

Automatic Cut-outs (fuses or circuit breakers) must be placed in the service wires (i.e., the leading-in wires from the street circuit), and at every point where a change is made in the size of wire unless the cut-out in the larger wire will protect the smaller wire. The cut-out in the neutral of a three-wire system may be omitted if the neutral wire is grounded and is of the same size as the outside wires. No set of incandescent lamps requiring more than 660 watts, whether grouped on one fixture or on several fixtures must be dependent upon one cut-out. Cut-outs must in general be inclosed in an approved cabinet although circuit breakers and inclosed fuses may be placed in plain sight in dry places where there is no danger of igniting any combustible material.

Heating devices, which singly or in groups require more than 660 watts must be protected by a cut-out and the supply conductors should preferably be installed in rigid conduit. Such conductors should be insulated with rubber.

Switches which disconnect *all* wires (i.e., switches having 2, 3 or more poles) must be placed in the service wires as near as possible to the point where they enter the building and in all circuits supplying current to motors, heating devices or lamps; except that in the case of motors of one-fourth horse-power or less in circuits where the voltage does not exceed 300 volts, and in circuits supplying not more than 660 watts of power to heating devices or lamps, single-pole switches may be used in two-wire systems or branches. Switches must always be placed in dry, accessible places and must be grouped as far as possible. When used in rooms where combustible flyings are liable to exist, switches must be placed in dust-tight cabinets and when flush switches are used, they must be inclosed in an approved steel box.

Open Wiring. — When the appearance of the wiring is not important exposed surface wiring supported on cleats or insulators furnishes one of the safest and best methods of wiring. The wires must be insulated in dry places with rubber, varnished cloth, slow-burning weatherproof or slow-burning insulation, in damp places with rubber insulation, and in locations where the wires are exposed to corrosive vapors with weather-proof, varnished cloth or rubber insulation.

Voltage	Inches from surface to insulation on wire		Inches between wires* from insulation to insulation
	Dry	Damp	
0–300	0.5	1	2.5
301–600	1	1	4

* In the case of 3-wire d-c. or single-phase systems the neutral may be placed between the two outers, these latter being 2.5 inches apart.

Spacing of Wires and Supports. — Wires must be separated from each other and spaced from the surface wired over as given in the accompanying table.

Wires must be supported under ordinary conditions at least every 4.5 feet, except that in mill construction, wires of not less than No. 8 A. W. G. gage, if separated about six inches, may be run from timber to timber and be supported at each timber only. Open wiring cannot be used in elevator shafts.

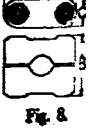


Fig. 8

Cleats. — Cleats are made in a variety of forms. The following are the dimensions of cleats of the form shown in Fig. 8, all dimensions being in inches.

DIMENSIONS AND COSTS OF CLEATS

te of wire, circular mils or A. W. G.	1-wire cleats			
	Dimensions, inches			Size of screw, inches
	A	B	C	
14–12	2	1¼	¾	3×8
10–8	2	1⅝	¾	3×8
6– 3	2¼	1¾	1	3×10
2	2½	1¾	1⅛	3½×12
1– 0	2½	2	1⅛	3½×12
00	2¾	2¼	1¼	3½×12
000	3	2¼	1¼	4×14
0000	3	3⅛	1¼	4×14
225,000- 500,000	3¼	2¾	1½	4½×16
600,000–800,000	4	3¼	2	5×18 or
900,000–1,000,000	4¾	3⅝	2	⅝×5 lag
	2- and 3-wire cleats			
14–12	3⅜	1⅜	⅝	3×8
10 6	3⅜	1⅜	⅝	3×8

Wooden Moulding. — When exposed wiring is not desired, and when it is practicable in old buildings or too expensive in new buildings to install concealed wiring, wooden moulding may be used, provided the difference of potential ween any two wires in the same moulding does not exceed 300 volts. Its is forbidden in elevator shafts and in concealed or damp places. Wooden ulding is manufactured in the following sizes. See table on next page. Moulding may be made inconspicuous by matching the wood of the moulding the finish of the room and by using a capping, which will conceal the purpose the moulding. In this manner, moulding may be made to simulate picture ulding, and on ceilings a panel effect can be obtained by the use of dead ulding. All wires used in wooden moulding must have a rubber insulation d must not be jointed or tapped in the moulding. Branch taps may be made th tap fittings designed for the purpose. Many other moulding fittings are nufactured, which, if used, reduce the labor of installation and improve the neral appearance of the work. Wooden moulding is fastened to walls by ans of thin screws or toggle-bolts and the capping is nailed on with brads. Kicking boxes" are usually placed around the end of moulding on floors to otect the wires and porcelain tubes from possible injury.

Metallic Moulding. — Metallic moulding may also be used to conceal and otect wires when the difference of potential between any two wires in the oulding is not more than 300 volts and the power transmitted through the ires contained in the moulding does not exceed 1320 watts. Metallic moulding manufactured in one width only, namely, 1 inch wide by ⅝ to ½ inch deep, e depth depending upon the type of moulding. The two types of metal

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STANDARD WOODEN MOULDING

No. of wires	Size of groove, inches	Dimensions, inches		Size of wire	
		Width over all	Depth, cap to base	A. W. G. or circular	
				Solid, 1 braid	Stranded, 1
2	¼	1 ½	13/16	14–12	
2	5/16	1 13/16	15/16	10–8	8
2	7/16	2	1	6–4	6–5
2	9/16	2 5/16	1 1/16	3–2	4–2
2	¾	3	1 ¾		1–000
2	⅞	3 ⅞	1 ¾		0000–250,0
2	1	4 ¾	2 ⅛		300,000–400,0
3	¼	2 ⅛	13/16	14–12	
3	5/16	2 7/16	15/16	10–8	8
3	7/16	2 13/16	1 ⅛	6–4	6–5
3	9/16	3 ⅛	1 ¼	3–2	4–2
3	¾	4 5/16	1 7/16		1–000
3	⅞	5 ⅛	1 ¾		0000–250,0
3	1	6 1 1/16	2 3/16		300,000–400,0

moulding in common use differ principally in the method of attaching capping. In the "Lutz" metal moulding the capping consists of a flat metal strip, which is slid into the two grooves that form the upper edge of moulding. In the "National" metal moulding the capping is snapped over base. "Lutz" moulding is made in 10-foot lengths while the National mould is made in 8-foot 4-inch lengths.

Metallic moulding cannot be used in concealed or damp places except t in passing through a floor, such moulding may be used if carried through iron pipe extending from the ceiling below up through the floor to a point feet above the floor or to a point at least 3 inches above the floor wi appearance is an essential feature. Such moulding may be carried thro walls and partitions provided it is in one continuous length and that the locat is dry. All parts of a metallic moulding system including outlet boxes, junct boxes and cabinets must be electrically connected and grounded. Fitti employed with metallic moulding must be so constructed as to protect the in lation of the wires from abrasion. Wires placed in metallic moulding must insulated and installed as in wooden moulding with the exception that in al nating-current systems two or more wires of the same circuit must be insta in the same moulding. It is suggested that this also be done for direct-curr systems when there is a possibility that an alternating-current system may used at some future time.

Concealed Knob and Tube Work. — This method of wiring is forbidd by the inspectors in many large cities, but when approved, it is employed buildings of frame construction when it is desired to install the wiring at

The wires when running parallel to beams or studding
os and when running through beams, studding or floors
lain tubes. When passing through floors at the bottom
; or through braces, the porcelain tubes insulating the
least four inches above the floor or brace. Split knobs
support of conductors smaller than No. 8 A. W G.
ins where a solid knob or strain insulator must be used.
than No. 8 A. W. G., solid knobs may be used. Wires
sulation and tie wires when used must have an insulation
nductors they confine.

een Wires. — Wires must be installed in such a manner
een *any* two wires is at least 5 inches and each wire must
surface wired over by a distance of at least 1 inch. If,
nch separation cannot be maintained, each wire must
l in a continuous length of approved flexible tubing.
ist be protected by flexible tubing extending in con-
the last porcelain support to at least 1 inch beyond the

'een Supports. — Wires must be supported under ordi-
y 4.5 feet and if the wires are liable to be disturbed the
supports must be shortened.

ıbes. — Two types of knobs are used, namely, the solid
The following table gives the dimensions of one type of
tubes:

Split knobs *		Tubes	
Height, inches	Diameter, inches	Inside diameter, inches	Outside diameter, inches
1¼	1½–1½	5/16	9/16
2	2	3/8	11/16
		5/8	15/16
		¾	1 5/16

folding single wire 1 inch away from wall.

– Although the most expensive method, rigid conduit is
best method of wiring and its use is required by inspectors
many large cities. Two kinds of conduit are manufactured:
a lining of insulating material, and unlined conduit, having
ısulating enamel. Unlined conduit is used more often than
se unlined conduit is cheaper to buy and to install and
awn in unlined conduit more easily than in lined conduit.
osive action on the conductors due to a possible leak in the
l by the insulating lining. The conductors used in lined
less than the conductors used in unlined conduit, because
in unlined conduit must have an additional layer of braid
ı in drawing in the wires. Rigid conduit is manufactured

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STANDARD RIGID CONDUIT

Made in 10-foot lengths

Standard size of pipe, inches	Internal diameter, inches	External diameter, inches	Nominal weight per 100 feet, lb.	No. of threads per in. of screw	Maximum size of double-braide wire used in a single conduit A. W. G. or cir. mils		
					1 wire	2 wires	3 wire
⅛	0.62	0.84	85	14	8	14	.....
¼	0.82	1.05	112	14	2	10	
1	1.04	1.31	167	11½	00	6	
1¼	1.38	1.66	224	11½	200,000	3	
1½	1.61	1.90	268	11½	400,000	1	
2	2.06	2.37	361	11½	800,000	200,000	
2½	2.46	2.87	574	8	1,300,000	350,000	250,0
3	3.06	3.50	754	8	2,000,000	500,000	400,0
3½	3.54	4.00	900	8	.....	800,000	500,0
4	4.02	4.50	1066	8	.....	1,200,000	850,0

Bushings, Bends, etc., in Rigid Conduit. — All parts of the c duit system including outlet or junction boxes must be mechanically se in place and must be electrically connected and grounded. At outlets or junct boxes rigid conduits must be provided with bushings or nipples to protect t wires from abrasion. The radius of curvature of the inner edge of an elbo bend must not be less than 3.5 inches and there must not be more than equivalent of 4 quarter bends from outlet to outlet, the bends at the outlet being counted. Bends should be used whenever possible in place of elbows the wires will pass more easily around a bend than an elbow. The various ki ing tools that are on the market consist of some form of lever, the end of wh may be slipped over the conduit while it is in position. When the number bends between outlets becomes excessive or when a large number of condu placed side by side must be deflected, pull boxes are installed so that the di tion of the conduit may be changed and the wires may be drawn in more easi In fireproof buildings conduit is frequently installed just after the steel wo has been erected and is then covered up by concrete or tiling.

Insulation of Wires Used in Rigid Conduits. — Wires used in ri conduit must have an approved rubber insulation and must not be spliced tapped within the conduit. Varnished cloth insulation may be used in perm nently dry locations. In alternating-current systems the two or more wires o circuit must be drawn in the same conduit. It is suggested that this be do for direct-current systems also when there is a possibility that an alternati current system may be used at some future time. The same conduit must n contain more than four two-wire or three three-wire circuits of the same syst and circuits of different systems must be run in separate conduits.

Wires should not be drawn in until all mechanical work on the building ha been completed. For short runs wires may be pushed in at one opening unt they come out at the other opening, but on long runs or where there are many bends, a spring-steel "fish-wire" or "snake" is first pushed through the conduit and a piece of sash cord attached to the "fish-wire" is pulled through. Th

ched to the sash cord and pulled through. When the through a conduit easily, powdered soapstone is blown uce the friction of the conductors.

Wires. — In vertical runs conductors must be supported dance with the following table:

, W. G. to o,	every	100 feet
.. W. G. to oooo,	"	80 "
W. G. to 350,000 cir. mils,	"	60 "
ir. mils to 500,000 cir. mils,	"	50 "
ir. mils to 750,000 cir. mils,	"	40 "
ir. mils,	"	35 "

pported by a turn of 90 degrees in the conduit system esigned for the purpose.

above, varnished cambric insulated conductors must be r ends of vertical runs by securely attaching the copper, ion has been removed, to a strain insulator.

2073 for tables, covering number of wires in a conduit.

— In distinction to flexible tubing, a non-metallic tubing, *etallic* tubing built up of spiral, convex and concave steel : in such a manner as to form a fairly smooth surface, ually. "Flexible conduit," which is metallic, is usually lexible tubing" (*see below*), which is non-metallic tubing. esses the advantage over rigid conduit in that it can be and quickly from outlet to outlet and if necessary may be ons or floors. Its chief disadvantages are that it is neither re-proof. Flexible conduit is manufactured in the follow-

TANDARD FLEXIBLE CONDUIT

Weight per 100 feet, pounds	Approx. feet in coil	Maximum size of double-braided wire used in single conduit A. W. G. or cir. mils		
		1 wire	2 wires	3 wires
20	250	14	.....	.....
34	250	12	.....	.....
68	100	8	12	.....
95	50	2	10	12
144	50	00	6	8
182	50	200,000	3	5
217	25–50	400,000	1	3
265	25–50	800,000	200,000	00

s to installation and wires used in rigid conduit apply as it.

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Armored Cable. — In place of flexible conduit in which wires must be drawn in after the conduit is installed, armored cable consisting of rubber-insulated conductors protected by interlocking spiral steel strips may be used. Where installed in damp places, leaded armored cable, which has a lead covering between the insulation and the steel armor, must be used. Armored cable is employed extensively in wiring old buildings where it would be impossible to install rigid conduit without cutting up the walls and floors. Armored cable for interior wiring is manufactured in the following sizes:

STANDARD ARMORED CONDUCTORS

Size of each conductor A. W. G.	Number of bunched conductors		Approximate outside diameter, inches	Weight per 100 feet, pounds	Approximate feet in coil
14	1	Steel armored	0.37	20	250
12	1		0.40	21.5	250
10	1		0.435	23	250
8	1		0.500	28	250
6	1		0.640	54	250
10*	1		0.435	23	250
8*	1		0.500	28	250
6*	1		0.640	54	250
4*	1		0.690	59	200
2*	1		0.770	71	200
1*	1		0.860	98	100
10*	1	Lead covered and steel armored	0.555	48	250
8*	1		0.620	54	200
6*	1		0.760	81	200
4*	1		0.820	90	150
2*	1		0.900	120	150
1*	1		0.985	165	100

* Stranded.

All requirements as to mechanical and electrical connections to outlet boxes, grounding, splicing and tapping of wires, assembling of conductors in alternating-current systems, etc., applying to rigid conduit also pertain to armored cable. Bends in armored cable may be of smaller radius than in rigid conduit, however, the minimum allowable radius of a bend being 1.5 inches for armored cable.

Flexible Tubing. — In addition to its use in all places where it is necessary to add to the insulation of the conductors, if the difference of potential between the wires is not over 300 volts, continuous flexible tubing may be used to protect individual wires when fished for short distances in dry places. Although not allowed by some inspectors, flexible tubing is extensively used in this manner in conjunction with moulding or knob and tube work, especially in old buildings where it is necessary to fish the wires to avoid

.NDARD ARMORED CONDUCTORS — Continued

Number of bunched conductors		Approximate outside diameter, inches	Weight per 100 feet, pounds	Approximate feet in coil
2	Steel armored	0.630	44	150–250
2		0.640	45	150–250
2		0.675	52	150–250
2		0.818	81	100–150
2		1.066	114	100
2	Lead covered and steel armored	0.636	75	100–200
2		0.688	78	100–200
2		0.861	108	100–150
2		0.900	125	100–150
3	Steel armored	0.648	53	150–250
3		0.675	55	150–250
3		0.755	66	100–200
3		0.900	99	100–150
3	Lead covered and steel armored	0.694	79	100–150
3		0.766	88	100–150
3		0.901	117	100–150

* Stranded.

, floors, or ceiling Flexible tubing is manufactured in the fol-

STANDARD FLEXIBLE TUBING

iside meter, ches	Feet in coil	Weight per 1000 feet, pounds	Largest size of wire accommodated, A. W. G.
¼	250	75	14
⅜	250	110	12
½	200	125	8
⅝	200	155	4
¾	150	200	2
1	100	275	00
1¼	100	360	200,000
1½	100	400	400,000
1¾	100	440	600,000
2	Odd lengths	600	800,000
2¼	Odd lengths	700	1,100,000

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SIZE OF CONDUITS FOR WIRES AND CABLES

Electrical Trade Sizes, Inches

I. All Conductors of Same Size

Size of conductor, A. W. G. or circular mils	Number of conductors in a conduit			
	1	2	3	4
14	½	½	½	¾
12	½	¾	¾	¾
10	½	¾	¾	1
8	½	1	1	1
6	½	1	1¼	1¼
4	¾	1¼	1¼	1½
3	¾	1¼	1¼	1½
2	¾	1¼	1½	1½
1	¾	1½	1½	2
0	1	1½	2	2
00	1	2	2	2½
000	1	2	2	2½
0000	1¼	2	2½	2½
200,000	1¼	2	2½	2½
250,000	1¼	2½	2½	3
300,000	1¼	2½	2½	3
400,000	1¼	3	3	3½
500,000	1½	3	3	3½
600,000	1½	3	3½	.....
700,000	2	3½	3½	.....
800,000	2	3½	4	.....
900,000	2	3½	4	.....
1,000,000	2	4	4	.....
1,250,000	2½	4½	4½	.....
1,500,000	2½	4½	5	.....
1,750,000	3	5	5	.....
2,000,000	3	5	6	.....

EXCEPTION. — For sizes not greater than No. 10 A. W. G. one more conductor than permitted by the above table may be installed, provided the conduit is not longer than 30 feet and has not more than the equivalent of two right-angle bends from outlet to outlet, the bends at the outlets not being counted.

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II. Three Conductors

Two numbers and	One number	Size conduit inches
14	10	¾
12	8	¾
10	6	1
8	4	1
6	2	1¼
5	1	1¼
4	0	1½
3	00	1½
2	000	1½
1	0000	2
0	250,000 Cir. mils	2
00	350,000	2½
000	400,000	2½
0000	550,000	3
250,000 Cir. mils	600,000	3
300,000	800,000	3
400,000	1,000,000	3½
500,000	1,250,000	4
600,000	1,500,000	4
700,000	1,750,000	4½
800,000	2,000,000	4½

GENERAL RULE FOR ANY NUMBER OF WIRES

size of conduit for a given combination of wires may also be estimated as : Find the total *circular inches** of area of insulated wire to be put in nduit and divide by the following factor:

1 conductor	0.56
2 conductors	0.32
3 conductors	0.42
4 conductors	0.40
Over 4 conductors	0.37

result will be the circular inches inside area of conduit required. The diameter of conduit will be the square root of this figure.

example, what size conduit is required for six No. 8 and four No. 2 wires? erall diameter of a No. 8 is 0.27 in. and of a No. 2 is 0.47 in. Their areas ular inches are $0.27 \times 0.27 = 0.073$ and $0.47 \times 0.47 = 0.22$, respectively. es 0.073 is 0.436 and four times 0.22 is 0.88. The total is $0.436 + 0.880 =$ ircular inches, which divided by 0.37 gives 3.56 circular inches. The root of this is 1.89 which is the diameter of pipe required The next rd size is 2 inches.

e area in circular inches of any circle is equal to the square of its diameter es.

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COST OF WIRING. — The total cost of wiring a building is made up of three elements: materials, labor and engineering. The labor and engineering charge will depend upon local conditions, and these costs may be estimated accurately only by reference to similar costs in completed work of the same general character. In regard to labor, the local conditions must include the factor of wages paid in the vicinity and the amount of work completed in a given time by the class of labor available. In determining the engineering charge the contractor must estimate the amount for each contract which should be charged to office expense and solicitation of business.

Office Estimates. — The cost of the materials is usually determined from a supply catalogue. This may be accomplished by finding (1) the costs of the wiring materials between outlets and (2) the costs of the special devices such as outlet boxes, switches, cut-out cabinets, etc., and adding the two together.

Cost of Complete Installations. — According to 1920 prices of materials the cost of wiring various types of buildings per outlet (switches counting as outlets) is as follows:

Residences wired with armored cables	$5.50–$7.
Office buildings, hotels, lofts, factories, etc., with wires installed in rigid conduit	8.00– 9

Knob and tube and cleat wiring is not now much less in cost than conduit work on account of the high labor cost.

Field Estimates. — In order to enable its representative to make a rapid estimate of the cost of wiring a building while he is interviewing the owner or agent, the contract department of a lighting company usually provides its solicitors with a schedule of wiring costs, based (1) upon the number of lamp sockets and *switch* outlets to be provided, or (2) upon the *total* number of outlets (both lamp and switch), or (3) upon the number of lamp sockets and the number of *lamp* outlets required. Such wiring schedules are usually applicable only to finished buildings; the cost of wiring a building while it is being erected is usually much less than the cost of wiring the same building after it has been completed.

First Method. — The buildings to be wired are divided into classes and the cost of wiring a building in any class is based upon the number of lamp sockets, the number of *switch* outlets, and the type of switches and receptacles installed. The disadvantage of this method is that it does not take into account the number of lamp outlets. In two buildings in which the same number of lamp sockets are installed, the number of lamp outlets may differ widely and as a result the labor and material required for the work will differ in the two buildings although the cost of the wiring may be the same. In most instances however, this defect is not serious, because of the close relationship between the number of lamp sockets and the number of lamp outlets which are usually installed in the buildings for which the schedule is intended.

Second Method. — The various openings for switches, receptacles, drop cords and fixtures are considered as outlets and on the number of these is based the cost of work in houses of different classes of construction. An extra charge is made for hardware and for work installed under double or hardwood floors. With this method the number of lamp sockets installed in two houses for which the cost of wiring is the same may differ considerably. For schedules of cost see *Elec. World*, *1910*, *Vol. 56*, *p. 1134*.

Third Method. — The buildings to be wired are divided into classes and the cost of wiring a building in any class is based upon the number of lamp outlets and lamp sockets and the type of switches installed. This method

provement on Methods I and II as it does take into account the average ber of lamp sockets per lamp outlet, and while the cost of the wiring in two ings requiring the same labor and material may differ slightly, such differ- will not be as frequently encountered as in the other two methods. As an ple of this type of schedule see article in *Elec. World, 1912, Vol. 59, p. 548,* iptive of the method used by the Consolidated Gas, Electric Light and r Company of Baltimore, Md.

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WIRING OF BUILDINGS FOR MISCELLANEOUS DEVICES

— (*See also Wiring of Buildings for Light and Power.*) In addition to the wi designed to conduct electrical energy to lamps, motors and heating devices building, wires may be installed in connection with telephone (q.v.), telegr (q.v.), district messenger and call-bell circuits, fire and burglar alarms, do opening devices, gas lighters, watchman's clocks and electric clocks. Since of these devices are operated at low voltage, it is unnecessary to use the same ca in selecting and installing the wires as in the higher voltage systems, except th in all low-voltage systems care must be exercised that the conductors shall n become crossed with light and power circuits.

Protection of Low-voltage Wiring. — When the conductors of any lo voltage system are brought into a building from the outside, an approved pr tective device must be located as near as possible to the entrance of the wi to the building. With the exception of instrument circuits of telegraph system where cut-outs only are required, protective devices must contain a lightni arrester with a ground connection and a cut-out or heat-coil (*see Telephone Instruments and Circuits*). The conductors beyond the protective device low-voltage systems need be insulated only sufficiently to prevent short-circui and the consequent interruption of service. When bunched together in vertic runs the wires must be inclosed in a fire-resisting covering to prevent the wi from carrying fire from floor to floor. Low-voltage circuits may be run in t same shaft with light and power circuits, provided the two classes of wires separated by at least two inches or one of the classes is run in a non-combusti tubing. Low-voltage wires may not be run in any case in the same tube w lighting or power wires.

Telephone Wiring. — (*See also Telephone Instruments and Circuits.*) In in large buildings, rubber-insulated twisted pairs of wire are used exten for telephone work. The twisted wires may be fished between partitions concealed in moulding and if open wiring is not objectionable, the wires carried along the finish of the room and fastened with insulating staples tacks. In new buildings the wires are frequently installed in conduit and th connections are made at connection boxes designed for the purpose. In lar buildings, when the number of telephones in use becomes very great, lead-cove insulated cable containing multiple pairs of conductors is installed in wire-wa provided for the purpose. Distributing connection boxes to which local circuits may be connected are then installed on each floor.

Bell Wiring. — In its simplest form a bell-wiring system consists of a battery (usually a Leclanché type or dry battery), a bell-push, a bell or buzzer and the connecting wire. Paraffine-impregnated double-cotton covered wires ranging in size from No. 16 to No. 22 A.W.G. gauge are usually employed, either singly or in the form of twin wires. The wires may be fished, concealed in moulding or run exposed along the finish of the room. When a large number of bell-wires must be run together through a building as in the case of a hotel annunciator system, the wires are frequently inclosed in a cotton braid or in a tube made of zinc or impregnated paper. In many buildings supplied with an alternating current source of power a small step-down transformer is used in place of the batteries, thus effecting a savi in the cost of the installation and eliminating the possibility of run-down ba

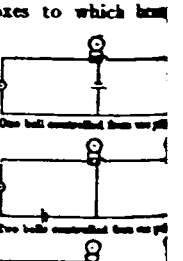
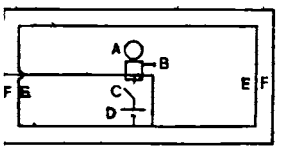


Fig. 1.

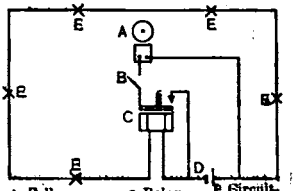
s. In Fig. 1 are shown several systems of bell wiring; these figures are explanatory.

urglar Alarms. — In place of the bell-push used in bell-wiring systems, the circuit may be closed by some circuit-closing device attached to windows, rs, etc., so that the opening of any window or door in the building will be le known by the ringing of a bell. As such a system has the objection that ill not operate if the battery is run down or if the wires are cut, a closed-circuit em is preferable, in which the opening of a window or door opens the circuit



A Bell B Constant Ringing Drop
C Day Switch D Battery
E and F Wires to which closing springs are connected

Fig. 2. Open-circuit Burglar Alarm



A Bell C Relay E Circuit-opening Springs
B Day Switch D Battery

Fig. 3. Closed-circuit Burglar Alarm

a relay in turn closes the bell circuit. In Fig. 2 is shown a typical open-uit and in Fig. 3 a typical closed-circuit system. In Fig. 4 are shown a spring *A* and a window spring *B*.

ire Alarms. — In the manually-operated system glass disks are placed at renient points throughout the building and with each disk is provided a mer, with which the disk may be broken in case ire. The breaking of the disk opens or closes an ric circuit by means of which electric gongs are throughout the building. In the automatic sys- the expansion or fusion by heat of elements in uit-closing or opening devices usually placed on ngs, causes gongs to ring throughout the building the watchman's office.

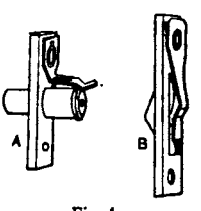


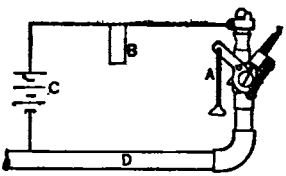
Fig. 4.

oor-opening Devices and Electric Clocks. — rs may be opened by pressing a button at some ant point and thereby closing a circuit, through ch current flows, energizing a magnet, which releases the nosing in the door ne. In the same manner, a moving disk on a master clock may periodically e a circuit, through which a magnet is energized which operates a pawl ched to the hands of another clock.

Watchman's Clock. — Circuit-closing devices are placed at different points ughout a building so that a watchman on his rounds may close the circuit means of a handle or special key. The closing of the circuit at any station es a record on a dial in the watchman's clock indicating the time at which circuit was closed at each particular station, the stations being designated numbers. To obviate the possibility of run-down batteries, magneto systems often installed, a small magneto being placed at each station.

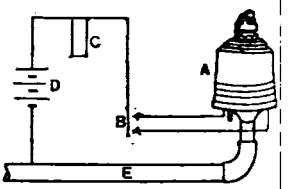
Gas Lighters. — In the "pull-burner" and "automatic-burner" systems, en the gas is turned on, an electric circuit is made and broken by means of tacts placed at the tip of the burner. To intensify the spark at the burner, ark coil is always connected in series with the circuit. In the "pull-burner" tem (Fig. 5) the pulling of a chain or the turning of a key on the gas jet ns on the gas and at the same instant makes and breaks the circuit by contacts

placed near the burner. In this system one wire connects the battery in se with a spark coil to the contact device, the other terminal of the contact dev being grounded to the gas pipe through which connection is made to the ot terminal of the battery.



A Pull Burner C Battery
B Spark Coil D Gas Pipe

Fig. 5.



A Automatic Burner D Battery
B Two-Button Push E Gas Pipe
C Spark Coil

Fig. 6.

In the "automatic-burner" system (Fig. 6) three wires are run from a t button push to one pole of the battery and one terminal each of the two magn on the automatic burner, the other terminals of the battery and the two magn being grounded on the gas pipe. The two push buttons are usually made bl and white respectively, the white button being pushed to light the gas and t black one to extinguish it. When the white button is pushed, a circuit is cl connecting the battery, the magnet which turns on the gas, the vibrating c tactor and the spark coil in series. When the black button is pushed, a circ is closed connecting the battery and the magnet, which turns off the gas, series.

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RAYS. — (*See also Generators, Static; Induction Coils.*) X-rays or Röntrays are generated when the cathode rays of a vacuum tube impinge a any solid substance. The form of X-ray tube commonly used, known as focus tube," is shown in Fig. 1. When a high unidirectional e.m.f. is imsed between the anode (*A*) the cathode (*C*), the cathode emitted from (*C*) strike upon anti-cathode (*B*) from which X-rays originate. The de and cathode are made of ninum because of its low of disintegration under ious discharge. The antiode is made of platinum to stand the intense heat of odic bombardment. The -cathode must be electrically nected to the anode to pre- the possible emanation of ode rays from its surface. The cathode is concaved spherically so that ays are focussed upon the anti-cathode, the rays falling within a spot not e than 0.08 inch in diameter. Owing to the repulsion between the particonstituting the cathode rays, the optical focus point of the cathode should just in front of the surface of the anti-cathode, so that the actual focus t will fall upon the surface of the anti-cathode. The vacuum tube, made in glass to reduce the absorption of the X-rays, is blown in spherical form ithstand the external pressure most effectively.

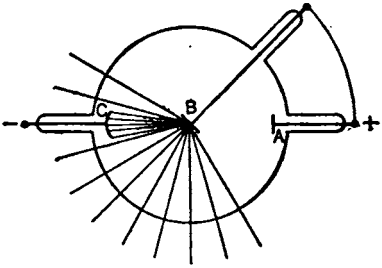


Fig. 1. X-ray Tube

haracter of X-Rays. — Numerous attempts made to prove that X-rays are adulatory form, similar to that of light, have been unsuccessful. It has been d that X-rays are neither reflected nor refracted and are not deflected like ode rays by a magnetic force. Barkla (*Phil. Trans., 1905, p. 467*) found such rays may be polarized and his conclusions have been confirmed other investigators. According to the existing information, it may only resumed that, when the negatively electrified particles constituting the ode rays strike any solid substance, they lose their charge and give rise to the emely high vibrations known as X-rays. It has been shown that such rays ot emanate from the impact spot on the anti-cathode but from a ring surding the spot, and travel in all directions from the surface of the antiode, the densest emanation being in a direction normal to the surface.

roperties of X-Rays. — All substances, many of which are opaque to nary light, transmit X-rays to a greater or less degree. In most cases the sparency of any substance to such rays is (roughly) inversely proportional s specific gravity. In the accompanying table are given the relative transncies of various substances and their specific gravities, the transparency of r being taken as unity.

hen X-rays are passed through gases, the gases become ionized and their rical conductivity is accordingly increased. This property has been used means of measuring the relative strengths of X-rays.

ertain substances fluoresce under the action of X-rays making the existence -rays visible to the eye. The fluorescent screens ordinarily used for anatomexaminations are coated with barium platino-cyanide, potassium platinoide or calcium tungstate.

-rays are to a considerable degree chemically active and photographs may nade of objects generally opaque to the eye but built up of substances of

TRANSPARENCY OF VARIOUS SUBSTANCES TO X-RAYS

Material	Specific gravity, water = 1	Transparency, water = 1
Pine wood	0.56	2.21
Walnut	0.66	1.50
Paraffin	0.87	1.12
Rubber	0.93	1.10
Cardboard	....	0.80
Ebonite	1.14	0.80
Wool-cloth	....	0.76
Celluloid	....	0.76
Silk	....	0.74
Cotton	....	0.70
Charcoal	....	0.63
Bone	1.9	0.56
Aluminum	2.67	0.38
Glass	2.6	0.34
Tin	7.28	0.118
Zinc	7.20	0.116
Iron	7.87	0.101
Nickel	8.67	0.095
Brass	8.70	0.093
Copper	8.96	0.084
Silver	10.5	0.070
Lead	11.38	0.055
Mercury	13.59	0.044
Gold	19.36	0.030
Platinum	22.07	0.020

different transparencies to the X-rays, so that the internal structure of the ject is revealed in the photograph. Such photographs made with highly sen tive plates are called radiographs or skiagraphs.

Considerable use is also made of X-rays in the electro-therapeutic treatm of certain diseases especially those of the skin.

Manipulation of the Tube. — It is important that the tube be connect in the proper polarity as a reverse current in the tube will cause it to blac The voltage used with the tube depends upon its size and the degree of vac attained. The ordinary tube requires a voltage of from 50,000 to 100,000 v or, as usually stated, a voltage which will puncture a needle gap of from 5 10 inches in air. The source of e.m.f. used with the tube is usually an in tion coil (q.v.) and in some cases a static generator (q.v.). The voltage quired to puncture a tube is materially reduced if a sheet of tinfoil electric connected to the cathode terminal is wrapped around the outside of the tube the cathode end and covering about one-third of its surface. The current tak by a tube is extremely small so that the connecting wires need only be lar enough to withstand breakage but must be heavily insulated. Under contin ous use the internal pressure of the gas in the tube decreases due to the occ sion of the gas content by the metals and glass of which the tube is constructed

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the internal pressure in the tube decreases, it may become inoperative and uld then be heated in an oven to release the occluded gases and reëstablish proper pressure. Certain "regenerative" tubes contain palladium which ludes gas at ordinary temperatures and gives off gas under heat, thereby ntaining a constant pressure within the tube.

"Hard" and "Soft" Tubes; Condition of Tubes.—The penetrating er of an X-ray tube is proportional, within certain limits, to its vacuity. igh-vacuum tube, known as a "hard" tube, will emit a few rays of great pene- ing power, whereas a low vacuum tube, known as a "soft" tube will emit reater number of rays of less penetrability. In most cases better contrast btained upon the photographic plate or fluorescent screen when a "soft" e is used than when a "hard" tube is used, since the rays emitted by a rd" tube may penetrate all the constituent parts of the object examined nearly equal strength.

he condition of a tube under operation may be easily detected by observing color of the vacuous discharge. When running under normal conditions, tube will glow with a greenish-yellow light; the face of the anode will emit nary-yellow light, but in the space behind the anode, a violet glow will ap- . The question of correct polarity may then be checked by this appearance he anode. A pinkish light within the tube indicates that the vacuum is low, and the absence of any glow indicates too high a vacuum. A needle connected in parallel with the tube will show when the voltage is too high protects the tube from excessive voltages.

e Coolidge Tube.—In the ordinary X-ray tube, shown in Fig. 1, the ation from the cathode is due to the bombardment of the cathode by ive ions. The stability of tion of the tube is there- dependent upon the main- ce of a constant gas press- within the tube. In the dge tube (Fig. 2), use is : of the principle of emis- of electrons from hot s, the cathode being con- ted of an electrically d spiral of tungsten (*c*) unded by a focussing sur- (*S*) of tungsten or some other refractory material. The anti-cathode or t (*A*), which also serves as anode, consists of a piece of wrought tungsten. ressure within the tube is made as low as possible, usually not more than hundredths of a micron. The tungsten spiral is heated by current sup- from a storage battery, while the terminals of the tube are connected to -potential source of direct or alternating current. The operating tem- ure of the tube is lower with direct than with alternating current.

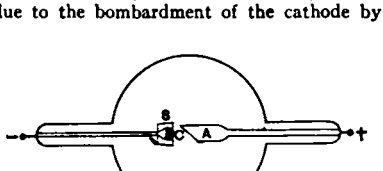


Fig. 2.

principal advantages of the Coolidge tube over the ordinary Röntgen ure (1) the use of either direct or alternating current, (2) the independent ol of the penetrating power and intensity of the X-rays by adjusting the ssed voltage or the temperature of the cathode, (3) the continuous stable tion of the tube under any adjustment for several hours, (4) the reduction perature and absence of the fluorescence of the glass and (5) the produc- f intense X-rays of any desired penetrating power.

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TANDARDS OF THE A. I. E. E.

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APPENDIX

STANDARDS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CHAPTER I

GENERAL PRINCIPLES UPON WHICH THE A. I. E. E. STANDARDS ARE BASED

temperatures in this and the following chapters are given in centigrade degrees.)

HEATING

30. General Principles.— The General Principles by reference to which atings of electrical machines are fixed, so far as their heating is concerned, it that the life of insulating materials depends upon the temperatures to h these materials are subjected. Taking, as a basis, the results of experi- with machinery in practical service and the results of laboratory tests of us insulating materials, limiting "hottest-spot" temperatures have been blished for various classes of insulation *for purposes of standardization.* ting "observable" temperatures are deduced from these limiting "hottest- " temperatures by subtracting therefrom a specified number of degrees h, *for purposes of standardization* represents the margin fixed between the ing hottest spot and the limiting observable temperatures.
is margin may be designated as the "*conventional allowance.*"

31. Methods of Temperature Measurement. — There are three funda- al methods of temperature measurement, namely:

1. The Thermometer Method.
2. The Resistance Method, and,
3. The Embedded-Detector Method.

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The General Principles stated in Section 1000 permit of the use of whichever method is best suited to the class of machine, or part thereof, to be tested, by introducing appropriate values for the limiting observable temperature by each method. All the values of the observable temperatures are based upon the "hottest-spot" limitation adopted *for purposes of standardization* for the class of insulation employed.

1002. Methods of Temperature Measurement Defined. — These three fundamental methods of making temperature measurements are designated Methods 1, 2 and 3, and are defined as follows:

TABLE 109

Methods of Temperature Measurement

Method	Description of Method
1.	Thermometer Method This method consists in the measurement of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the completed machine. This method does not include the use of thermocouples or resistance coils embedded in the machine as described under Method No. 3.
2.	Resistance Method This method consists in the measurement of the temperature of windings by their increase in resistance. In the application of this method, *thermometer measurements shall also be made wherever practicable without disassembling the machine,** in order to increase the probability of obtaining the highest observable temperature. The measurement indicating the higher temperature shall be taken as the "observable" temperature.
3.	Embedded Temperature-Detector Method This method consists in the measurement of the temperature by thermocouple or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When Method No. 3 is used, it shall, when required, be checked by Method No. 2. The highest observable temperature obtained from the readings of the embedded detectors shall not exceed the values permitted by the Rules for Method 3, and the highest observable temperature obtained by Method 2 shall not exceed the values permitted by the Rules for Method 2.

* Note. As one of the few instances in which the thermometer check cannot be applied in Method II, the rotor of a turbo alternator may be cited.

1003. Conventional Allowances for the Three Methods of Temperature Measurement. — The specified differences by which the "observable" temperatures shall, *for purposes of standardization*, be assumed to be lower than the "hottest spot" temperatures, (which may be designated the "Conventional Allowances"), are as follows:

Method 1..... 15° C.
" 2..... 10° C.
" 3..... (See following table)

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TABLE 101

Conventional Allowance for Method 8

Method 8	
windings with two coil-sides per slot ith detectors between top and bottom il-sides (and between coil-sides and ore).	5° C.
windings with one coil-side per slot for 000 volts or less, with detectors between il-side and core and between coil-side nd wedge.	10° C.
windings with one coil-side per slot for ore than 5000 volts, with detectors be- ween coil-side and core and between coil- de and wedge.	10° C. plus 1° C. for every kv. of terminal pressure of the machine above 5 kv.

M. **Classification of Insulating Materials.** — The insulations employed i rical Machinery are subdivided into four main classes, designated O, A, C and defined as follows:

TABLE 102

Classification of Insulating Materials

ss	Description of Material
	Cotton, silk, paper and similar materials when neither impregnated nor immersed in oil.
	Cotton, silk, paper and similar materials when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire.
	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing the insulation or mechanical qualities of the insulation. (The word "impair" is used in the sense of causing any change which could disqualify the insulation for continuous service.)
	Materials capable of resisting higher temperatures than Class B, such as pure mica, porcelain, quartz, etc.

105.* **Limiting "Hottest Spot" Temperatures.** — The limiting "hotte " temperatures are, *for purposes of standardization*, taken at the followi s:

For Class O material.....	90° C.
For Class A material.....	105° C.
For Class B material.....	125° C. (See Note)
For Class C material.....	no limit yet specified

105) The Institute recognises the ability of manufacturers to employ Class ation successfully at maximum temperatures of 150° C. or even higher. Howev fficient data covering experience over a period of years at such temperatures esent unavailable, the Institute adopts 125° C. as a conservative limit for this cl sulation, and any increase above this figure should be the subject of special guaran e manufacturer.

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If different insulating materials are used on various parts of one winding (for instance in the slot and for the end windings) the temperature of each material shall not exceed the limit set for that material.

When insulation consists of layers of materials having different temperature limits (for instance high-temperature limit material adjacent to the copper and lower-temperature limit material adjacent to the iron or to the air) the temperature of each material shall not exceed the limit set for that material.

1006. Limiting Observable Temperatures. — The limiting observable temperatures for use with Methods 1, 2 and 3, are arrived at by subtracting the "conventional allowances" from the limiting "hottest-spot" temperatures for insulating materials. They are set forth as follows:

TABLE 103

Limiting Observable Temperatures

		Class O Material	Class A Material	Class B Material
Method 1		75° C.	90° C.	110° C.
Method 2		80° C.	95° C.	115° C.
Method 3	For windings with two coil-sides per slot with detectors between top and bottom coil-sides and between coil-sides and core.	85° C.	100° C.	120° C.
	For windings with one coil-side per slot with detectors between coil-side and core and between coil-side and wedge.	80° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts.)	95° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).	115° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).

* See also Note, Section 1005.

1007. Limiting Observable Temperature of Oil. — The oil in which apparatus is permanently immersed shall, in no part, have a temperature, observable by thermometer, in excess of 90° C.

1008. Standard Ambient Temperatures of Reference. — The following values are adopted for the standard ambient temperatures of reference:

For Air..... 40° C.
For Water..... 25° C.

These values for the standard ambient temperatures of reference apply to conditions where the actual ambient temperature does not exceed them.

1009. Limiting Observable Temperature Rises. — The limiting observable temperature rises in the following Table 104 are obtained by subtracting the standard ambient temperatures of reference given in § 1008 from the limiting observable temperatures given in Table 103. The limiting observable temperature rises to be used in practice are given later in the Rules. They are in some cases greater and in other cases smaller than those given in Table 104. See § 1010.

For the purpose of rating, the limiting observable temperature rise must not be increased even when the ambient temperature is lower than the standard ambient temperature of reference.

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TABLE 104

Limiting Observable Temperature Rises

		Air Cooled		
		Class O	Class A	Class B*
:thod 1		35° C.	50° C.	70° C.
:thod 2		40° C.	55° C.	75° C.
:thod 3	For windings with two coil-sides per slot, with detectors between top and bottom coil-sides and between coil-sides and core.	45° C.	60° C.	80° C.
	For windings with one coil-side per slot with detectors between coil-side and core and between coil-side and wedge.	40° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts.)	55° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).	75° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).

ee also Note, Section 1005.

10. General Comments on Special and Specific Cases. — In the foregoing s been assumed for the purpose of presenting a comprehensive, logical and istent plan, that the Rules actually used in the industry are exactly in accord the General Principles. Practical experience indicates the necessity of blishing definite Rules to cover Special as well as Specific Cases. These s are set forth in later chapters. Any case not specifically dealt with may e under the General Principles.

11. Comments on the Method of Measurement to be Employed. — In the nce of definite Rules, the manufacturer may, on the occasion of the acceptt test, use any of the three methods for the temperature measurements. In cases, however, restrictions on the choice of method are imposed. These et forth in the Rules.

12. Comments on Temperature Limits in Special Cases. — Temperature s are prescribed in the Rules for special cases where conditions determined by tice, by experience, or by agreements, require departures (often arbitrary) the limits of temperature rise corresponding to the General Principles.

13. Hottest Spot Temperature the Primary Point of Reference. — The est spot temperature is the primary point of reference, or the "benchk" used as the basis for the foregoing scheme or temperature delimitation, not employed in commercial transactions or in the ordinary course of testing peration of electrical machinery.

14. Observable Temperature Rise the Working Standard. — The observtemperature rise is the working standard. A summary of working data explanatory notes, will be found in Table 200.

15. Duration of Temperature Test and Correction to Time of Shut Down. — ttever method of temperature measurement be employed, it is required that

(a) operation shall be continued until constant temperatures are determined if the machine has a continuous rating, or for the full period if the machine has a short time rating, and

(b) when measurements cannot be made while the machine is loaded, appropriate corrections to raise the temperature readings to the time of shut down shall be applied. See Chapter II.

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MECHANICAL AND COMMUTATION LIMITATIONS

These limitations are set forth in subsequent Chapters dealing with spec kinds of machines.

WAVE SHAPE

1300. The sine wave shall be considered as standard except where the ture therefrom is inherent in the operation of the system of which the mac forms a part.

DIELECTRIC STRENGTH AND INSULATION RESISTANCE

(See §§ 2350 to 2380 incl.)

1300. The injury produced by dielectric stress applied to insulation is rela to the time during which the stress is applied. A stress up to a certain lim may be applied for an indefinite period without injury to the insulation somewhat greater stress will cause heating of the insulation and a progress deterioration, eventually resulting in breakdown. Higher values of str cause more rapid deterioration and a quicker breakdown. It is customary determine whether machinery will withstand the voltage stresses met in prac by a preliminary test for a definite period of time at a voltage considera higher than the normal voltage to which the machinery is to be subjected not high enough to produce injury to the insulation during the period of test

1301. The test voltage which shall be applied to determine the suitabili insulation for commercial operation is dependent upon the kind and size of machine, and its operating voltage, upon the nature of the service in which to be used, and upon the severity of the mechanical and electrical stresses which it may be subjected. The voltages and other conditions of test which recommended have been determined as reasonable and proper for the ex majority of cases, and are proposed for general adoption, except when spec reasons make a modification desirable.

1400. The insulation resistance of machinery is of doubtful significance compared with the dielectric strength. It is subject to wide variation w temperature, humidity and cleanliness of the parts. When the insula resistance falls below prescribed values it can, in most cases of good design where no defect exists, be brought up to the required standard by cleaning drying the machine. The insulation resistance therefore may afford a use indication as to whether the machine is in suitable condition for applicatio the dielectric test.

EFFICIENCY

(See §§ 2331 to 2333 incl.)

1500. The conditions under which efficiency is determined are those rel to the operation of the machine. These include voltage, current, power fact frequency, wave shape, speed, temperature, or such of them as may apply in ea particular case.

1501. The efficiency at all loads of all apparatus shall be corrected to a ref ence temperature of 75° C.

1502. In the case of machinery, two efficiencies are recognized, conventio efficiency (§ 3524) and directly measured efficiency. Unless otherwise specifi the conventional efficiency is to be employed. When the efficiency of a machi is stated without specific reference to the load conditions, rated load is always be understood, whether the efficiency be the conventional or directly measur efficiency.

RATING

(See §§ 2202 to 2232 incl.)

1600. Principle of Machine Rating. — (a) *Rating by Temperature Rise:* Th principle upon which machine rating is based, so far as relates to thermal cha acteristics, has been stated in earlier sections.

(b) *Rating by Limitations Other than Temperature Rise:* In some machine the rating is limited by other than thermal considerations. In such cases, th principle upon which machine rating is based is that the rated load applied co tinuously or for a stated period, shall not cause the various limitations specifie

later chapters; *e.g.*, §§ 4250–4252 inclusive, to be exceeded. The rating ll be based upon the capacity as limited by heating unless the capacity as ited by other characteristics, is less.

CHAPTER II

GENERAL RULES

he expressions "machinery" and "machines" are here employed in a eral sense, in order to obviate the constant repetition of the words "machin- or induction apparatus."

o ensure satisfactory results, electrical machinery should be specified to con- to the Institute Standards, in order that it shall comply in operation, with roved limitations in the following respects, so far as they are applicable.

Operating temperature	Efficiency
Mechanical strength	Power factor
Commutation	Wave shape
Dielectric strength	Regulation
Insulation resistance	

OPERATION

Temperature Limits

84. Permissible Temperatures with Insulations of More than One Class. (1) If different insulating materials are used on various parts of one winding instance in the slot and for the end windings) the temperature of each rial shall not exceed the limit set for that material.

(2) When insulation consists of layers of materials having different tempera- limits (for instance high-temperature limit material adjacent to the copper lower-temperature-limit material adjacent to the iron or to the air) the erature of each material shall not exceed the limit set for that material.

85. Temperatures of Metallic Parts of Machines. — (a) *Parts Adjacent to lating Material:* Metallic parts of machines in contact with or adjacent to kind of insulation, shall not attain a temperature in excess of that allowed e adjacent insulation.

Parts not Adjacent to Insulating Material: All parts of machines other those covered by § 2116 (a) may be operated at such temperatures as shall e injurious in any other respect.

90. Protection against Short Circuit. — The Institute recognizes the self- ctibility, both mechanical and thermal, of certain sizes and types of ines, when subjected to severe short-circuits, and recommends that ample ction be provided in such cases, external to the machine if necessary.

RATING

General

92. Expression of Rating. — Except where otherwise specified the machines be rated in terms of their available *output*. For exceptions see §§ 4223, 6204 and 6223.

94. Institute Rating. — The Institute Rating of a machine shall be its when operating with a cooling medium of the ambient temperature of nce specified in §§ 2211 and 2212 and with barometric conditions within nge given in § 2215. See §§ 2300, 2310, 2311, 4110 and 4300.

Ambient Temperature of Reference and Altitude Correction

91. Ambient Temperature of Reference for Air. — The standard ambient rature of reference, when the cooling medium is air, shall be 40° C.

93. Ambient Temperature of Reference for Water-Cooled Machinery. — ater-cooled machinery, the standard temperature of reference for incom-

2213. Machines Cooled by Other Means. — Machines cooled by means other than air or water shall receive special consideration.

2214. Outdoor Machinery Exposed to Sun's Rays. — Outdoor machinery not protected from the sun's rays at times of heavy load, shall receive special consideration.

2215. Altitude. — Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which a machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet). For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 feet) the permissible temperature rise at sea level, shall be reduced by 1 per cent for each 100 meters (330 feet) by which the altitude exceeds 1000 meters.

Kinds of Rating

There are various kinds of rating such as:

2220. Continuous Rating. — A machine rated for continuous service shall be able to operate continuously at its rated output, without exceeding any of the limitations established herein.

In the absence of any specification as to the kind of rating, the continuous rating shall be understood.

2221. Short-Time Rating. — A machine rated for discontinuous or short-time service (*i.e.*, service including runs alternating with stops of sufficient duration to ensure substantial cooling), shall be capable of operating at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations established herein. Such a rating is a short-time rating.

2222. Duty-Cycle Operation. — Many machines are operated on a cycle duty which repeats itself with more or less regularity. For purposes of rating either a continuous or a short-time equivalent load may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty-cycle.

2223*. Standard Short-Time Ratings. — The following periods shall be used for short-time ratings: 5, 10, 15, 30, 60 and 120 minutes.

2224. A. I. E. E. and I. E. C. Ratings. — When the prescribed conditions of test are those of the A. I. E. E. Standards the rating of the machine is the Institute Rating. (See § 2401.) When the prescribed conditions of the test are those of the I. E. C. Rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate. I. E. C. stands for "International Electrotechnical Commission."

2225. Continuous Rating Implied. — Machines marked "A. I. E. E. Rating" or "I. E. C. Rating" shall be understood to have a continuous rating, unless otherwise marked in accordance with §§ 2223, 5201 or 5202.

Rating by Temperature Rise

2230. Limiting Observable Temperature Rises. — The following limiting observable temperature rises have been adopted.

(2223) When, for example, a short-time rating of 10 minutes duration is adopted for the thermally equivalent load is 25 kw. for that period, then such a machine shall be said to have a 10-minute rating of 25 kw.

In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are within 5° C. of the ambient temperature at the time of starting the test.

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TABLE 200

ing Observable Temperature Rises for Machines for Operation in Locations where the Ambient Temperature will not Exceed 40° C. for Air or 25° C. for Water.

Class A insulation use the values in the table.
Class O insulation use 15° C. lower values.
Class B insulation use 20° C. higher values (or 45° C. higher in the cases ed by the Note in § 1005).
Class C insulation no limits yet specified.

Items	Method 1	Method 2	Method 3	
			For windings with two coil-sides per slot with detectors between top and bottom coil-sides and between coil sides and core	For windings with one coil-side per slot with detectors against core and against wedge
1. Insulated windings other than 2.3 Note 1	50° C. Note 1	55° C. Note 1	60° C. Note 1	55° C. minus 1° for every 1000 volts by which the terminal pressure of the machine exceeds 5000 volts. Note 1
2. Single layer field windings with exposed surfaces uninsulated	60° C.	60° C.		
3. Short-circuited insulated windings	60° C.			
4. Field Windings (other than 5)		55° C.		
5. Single layer field windings with exposed surfaces uninsulated	60° C.	60° C.		
6. Windings in slots	50° C.	55° C.		
7. Short-circuited insulated windings	60° C.			
8. Transformers and Induction Regulators		55° C.		

1 — (a) The temperature of the windings of transformers and induction regulators is to be ascertained by Method 2.

off immediately at the end of the temperature run and air intake shall be closed to prev
further admission of cooling air. In checking the temperatures ascertained by resista
the readings of thermometers well distributed and in good contact with the coils shall
noted and the maximum temperature indicated by them, if higher than that determ
by resistance, shall be taken as the maximum observable temperature of the windi
With the above procedure, the observable temperature rise for air-blast transformers m
attain a value not in excess of 60° C. as determined by thermometer, although it ma
not exceed 55° C. as determined by resistance.

(c) Method 3 shall be applied to all stators of machines with cores having a width M
and over; it shall also be applied to all machines of 5000 volts and over M of over 500 k
regardless of core width.

(d) Method 2 shall not be used for circuits of low resistance (other than transfor
windings), such as interpole windings, where external joints and connections form a c
siderable part of the total resistance.

(e) For all other cases it is optional to employ either Method 1 or Method 2. Th
equivalent to authorizing Method 1 with a 5° C. lower limit of observable temperat
than is permitted for Method 2).

Note 2. — For enclosed machines (rotating) the limiting observable temperature
shall be taken as 5 degrees higher than the values set forth in the Table for Items 1 an

Note 3. — A further limitation to this Table relates to the restriction of its appli
to machinery for operation in locations whose altitude is not more than 1000 meters
sea level. Recommendations relating to the limiting temperature rise for machine
operation at higher altitudes are given in §§ 2215 and 2231.

Note 4. — If different insulating materials are used on various parts of one wi
(for instance in the slot and for the end windings) the temperature of each material
not exceed the limit set for that material.

When insulation consists of layers of materials having different temperature-limits
instance high-temperature-limit material adjacent to the copper and lower-temperat
limit material adjacent to the iron or the air) the temperature of each material sha
exceed the limit set for that material.

2231. Exceptions to Table 200. — (a) When the thermometers are app
directly to the surfaces of bare windings, such as an edgewise strip conduc
a cast copper winding, the limiting observable temperature rise shall be 10
higher than given for Method 1 in the table.

(b) For commutators, collector rings, or bare metallic surfaces not
part of a winding, the limiting observable temperature rise shall be 15° C. hig
than given for Method 1 in the table.

(c) Any machinery destined for use with higher ambient temperatures
cooling mediums, and also any machinery for operation at altitudes for w
no provision is made in § 2215, should be the subject of special guarantee be
manufacturer. The methods of test and performance set forth in these Ru
will, however, afford guidance in such cases.

2232. Limiting Observable Temperature of Oil. — The oil in which appara
is permanently immersed shall in no part have a temperature, observable
thermometer, in excess of 90° C.

TESTS

Ambient Temperature

**2300.* Measurement of the Ambient Temperature During Tests of Mach
ery.** — (a) *General:* The ambient temperature is to be measured by mean
several thermometers placed at different points around and half-way up
machine at a distance of 1 to 2 meters (3 to 6 feet), and protected from dra
and abnormal heat radiation, preferably as in § 2301.

(b) *Mean Temperature:* The value to be adopted for the ambient tempe
ture during a test, is the mean of the readings of the thermometers (placed
above), taken at equal intervals of time during the last quarter of the durati
of the test.

(c) *Use of Idle Units:* It is sometimes desirable to avoid errors due to th
lag in temperature changes, by employing an idle unit of the same size and st

(2300) The cooling fluid may either be led to the machine through ducts, or the a
pipes, or merely surround the machine freely. In the former case the ambient tempe
ture is to be measured at the intake of the machine itself.

ted to the same conditions of cooling as the unit under test, for obtaining the bient temperature.

1309. Oil Cup. — In order to avoid errors due to the time lag between the nperature of large machines and the variations in the ambient air, all reasonle precautions must be taken to reduce these variations and the errors arising erefrom. Thus, the thermometer for determining the ambient temperature all be immersed in a suitable liquid, such as oil, in a suitably heavy metal cup. is can be made to respond to various rates of change, by proportioning the ount of oil to the metal in the containing cup. A convenient form for such oil cup consists of a massive metal cylinder, with a hole drilled partly through This hole is filled with oil and the thermometer is placed therein with its lb well immersed. The larger the machine under test, the larger should be the tal cylinder employed as an oil cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a tal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in. gh).

Machine Temperatures

1310. Temperature Rise for Any Ambient Temperature. — A machine may tested at any convenient ambient temperature, preferably not below 10° C., t whatever be the value of this ambient temperature, the permissible rises of nperature must not exceed those given in Table 200.

1311. Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference. — Numerous experiments have shown that deviation of temperature of the cooling medium from that of the standard of reference, the time of the heat run, has a negligible effect upon the temperature rise of chines; therefore, no correction shall be applied for this deviation.

1312. Duration of Temperature Test of Machine for Continuous Service. — e temperature test shall be continued until sufficient evidence is available to w that the maximum temperature and temperature rise would not exceed requirements of the rules, should the test be prolonged until the attainment a steady final temperature.

1313. Duration of Temperature Test of Machine with a Short-Time Rating. The duration of the temperature test of a machine with a short-time rating ll be the time required by the rating. In every case the equivalent short- e test shall commence only when the windings and other parts of the machine within 5° C. of the ambient temperature at the time of starting the test. § 2235.

1314. Duration of Temperature Test for Machine Having More than One ting. — The duration of the temperature test for a machine with more than rating shall be the time required by that rating which produces the greatest nperature rise. In cases where this cannot be determined beforehand, the chine shall be tested separately under each rating.

1315. Temperature Measurements During Heat Run. — When possible, nperature measurements shall be taken during operation, as well as when the chine is stopped. The highest figures thus obtained shall be adopted. In ler to abridge the long heating period, in the case of large machines, reason- e overloads of current during the preliminary period are suggested for m.

1316. Rules for Correcting to Time of Shut-Down. — (a) Whenever a sufficnt time has elapsed between the instant of shut-down and the time of the al temperature measurement to permit the temperature to fall, suitable corctions shall be applied, so as to obtain as nearly as practicable the temperae at the instant of shut-down. This can sometimes be approximately effected plotting a curve with temperature readings as ordinates and time as abscissas, d extrapolating back to the instant of shut-down. In other instances, accept- e correction factors can be applied; *e.g.*, in the case of machines manu-

factured in large quantities, the correction obtained from tests made on representative machines may be used.

(b) Exception. In cases where successive measurements show increasing temperatures after shut-down, the highest value shall be taken.

Details of Testing Methods

2320. Covering of Thermometer. — Thermometers used for taking temperatures of machinery shall be covered by felt pads 4 cm. × 5 cm. (1½ in. × 2 in.) 3 mm. (⅛ in.) thick cemented on; oil putty may be used for stationary and small apparatus.

2321.* Temperature Coefficient of Copper. —The temperature coefficient of copper shall be deduced from the formula $1/(234.5+\theta)$. Thus, at an initial temperature $\theta = 40°$ C., the temperature coefficient of increase in resistance per degree centigrade rise is $1/(274.5 = 0.00364)$. The following table, deduced from the formula, is given for convenience of reference.

TABLE 201

Temperature Coefficients of Copper Resistance

Temperature of the winding, in degrees C. at which the initial resistance is measured	Increase in resistance of copper per °C., per ohm of initial resistance
0	0.00427
5	0.00418
10	0.00409
15	0.00401
20	0.00393
25	0.00385
30	0.00378
35	0.00371
40	0.00364

2322. Temperature Measurement of Low Resistance Circuit. — In circuits of low resistance, where joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used. (Except transformers, for which see § 6320.)

2323.* Location of Embedded Temperature Detectors. — Embedded temperature detectors should be placed in at least two sets of locations. One of these should be between a coil-side and the core and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge. A liberal number of detectors shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur. See § 1002.

(2321) Temperature by Resistance: The temperature by resistance may be calculated by the following formula:

Let R_θ = resistance at $\theta°$ C., R_{θ_2} = resistance at $\theta_2°$ C. Then

$$\theta_2 = \frac{R_{\theta_2}}{R_\theta}(234.5+\theta) - 234.5.$$

(2323) A coil side is one of the two active sides of the coil lying in a slot.

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Efficiency

31.* Efficiencies Recognized. — Two efficiencies are recognized, conven-
al efficiency and directly measured efficiency. Unless otherwise specified,
conventional efficiency is to be employed. See §§ 3514 and 3524.
put and output determinations of efficiency may be made directly, measur-
he output by brake, or equivalent, where applicable. Within the limits of
tical application, the circulating power method, sometimes described as the
kinson or " loading-back " method, may be used.

32.* Normal Conditions for Efficiency Tests. — (a) *General:* The efficiency
correspond to, or be corrected to, the normal conditions herein set forth,
h shall be regarded as standard. These conditions include voltage, current,
er-factor, frequency, wave-shape, speed, temperature, or such of them as
apply in each particular case.
) *Load:* When the efficiency of a machine is stated without specific refer-
to the load conditions, rated load is always to be understood whether the
ency be the conventional or directly measured efficiency.
) *Wave Shape:* The sine wave shall be standard, unless a different wave
is inherent in the operation of the system. See § 2350.
d) *Temperature of Reference:* The efficiency of all apparatus at all loads
be corrected to a reference temperature of 75° C., but tests may be made
ny convenient ambient temperature, preferably not less than 15° C.
) *Power Factor:* The efficiency of alternators and transformers shall be
d at the rated power factor.

33. Direct Measurement of Efficiency. — (a) *General:* Electric power shall
easured at the terminals of the apparatus.
) *Polyphase Machines:* In polyphase machines, sufficient measurements
be made on all phases to avoid errors of unbalance.
) *Mechanical Power:* Mechanical power delivered by machines shall be
sured at the pulley, gearing or coupling, on the rotor shaft, thus excluding
loss of power in the belt or gear friction. See, however, an exception in
02.

Wave Shape

60. Standard Wave Shape. — The Sine Wave shall be considered as stand-
except where departure therefrom is inherent in the operation of the system
hich the electrical machine forms a part.

Tests of Dielectric Strength

350. Condition of Machine to be Tested. — Commercial tests shall, in
eral, be made with the completely assembled machine and not with indi-
ual parts. The machine shall be in good condition, and high-voltage tests,
ss otherwise specified, shall be applied before the machine is put into com-
cial service, and shall not be applied when the insulation resistance is low
to dirt or moisture. High-voltage tests to determine whether specifications
fulfilled are admissible on new machines only.

351. Where High-Voltage Tests are to be Made. — Unless otherwise agreed
n, high-voltage tests of machines shall be made at the factory.

352. Temperature at which High-voltage Tests are to be Made. — High-
tage tests shall be made at the temperature assumed under normal operation
it the temperature attained under the conditions of commercial testing.

2331) The need for assigning conventional values to certain losses arises from the
that some of the losses in electrical machinery are practically indeterminable, and
t, in many cases, either be approximated by an approved method of test, or else values
ommended by the Institute and designated "conventional" values shall be employed
them in arriving at the "conventional efficiency."
2332 d) In calculating plant or system efficiency it may be desirable to calculate the
es in each individual machine or part of the system at the actual temperature of that
nsformer or part during the specified interval. These losses may be appreciably
erent from the losses at 75° C., which latter shall be the standard temperature of refer-
e for all efficiency guarantees.

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2358. Points of Application of Voltage. — (a) *General:* The test voltage s
be successively applied between each electric circuit and all other electric cir
and metal parts grounded.

(b) *Interconnected Polyphase Windings:* Interconnected polyphase wind
shall be considered as one circuit. All windings except that under test sha
connected to ground.

2354. Frequency and Wave Shape of Test Voltage. — The frequency of
testing voltage shall be not less than the rated frequency of the machine te
A sine wave shape is recommended (see §§2340 and 4351). The test sha
made with alternating voltage having a crest value equal to $\sqrt{2}$ times
specified test voltage.

2355. Duration of Application of Test Voltage. — (a) *General:* The te
voltage for machines shall be applied continuously for a period of 60 seco
See exception § 2355 (b).

(b) *Standard Machines and Devices produced in large quantities:* Stan
machines and devices produced in large quantities for which the standard
pressure is 2500 volts or less, may be tested for one second with a test pres
50 per cent higher than the one-minute test pressure.

2356.* Standard Test Voltage. — (a) *General:* The standard test voltage f
all machines, except as otherwise specified, shall be twice the normal voltage
the circuit to which the machine is connected plus 1000 volts. See exceptio
§§ 2357, 4361, 6361, 7323 (b).

2357. Assembled Apparatus. — Where a number of pieces of apparatus a
assembled together and tested as an electrical unit they shall be tested with
per cent lower voltage than the lowest required on any of the individual pie
of apparatus.

2358. Measurement of Voltage in Dielectric Strength Tests. — There a
two methods of measuring the voltage used in making dielectric strength tes
namely:

1. The voltmeter method.
2. The spark-gap method, using either the sphere spark-gap or the needl
spark-gap.

2359.* Use of Voltmeters and Spark-gaps in Dielectric Tests. — When mak
ing high-voltage tests on electrical machinery every precaution must be take
against the occurrence of spark-gap discharges in the circuits from which th
machine is being tested. A non-inductive resistance of about one ohm per vo
of test pressure shall be inserted in series with one terminal of the spark-gap.
the test is made with one electrode grounded, this resistance shall be inserte
directly in series with the non-grounded electrode; if neither terminal is ground
one-half shall be inserted directly in series with each electrode. In either ca
this resistance shall be as near the measuring gap as possible and not in seri
with the tested apparatus. A water tube is the most suitable form of resistor.

2360. Use of Spark-gap with Machines of Low Capacitance. — When th
machine under test does not require sufficient charging current to distort th
high-voltage wave shape, or change the ratio of transformation, the spark-gap
should be set for the required test voltage and the testing apparatus adjusted t
give a voltage at which this spark-gap just breaks down. This adjustmen
should be made with the machine under test disconnected. The machin
should then be connected, and with the spark-gap about 20 per cent longer, th
testing apparatus again adjusted to give the voltage of the former breakdown

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(2358) All dielectric strength tests shall be based on the normal voltage of th
system, even if apparatus is applied on a part of the system which ordinarily operate
somewhat below the normal voltage.

(2359) The resistance will damp high-frequency oscillations at the time of breakdown
and limit the resulting current.

Carbon resistors should not be used because their resistance may become very low a
high voltages.

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h is the assumed voltage of test. This voltage shall be maintained for the ired interval.

§1.[a] Use of Spark-gap with Machines of High Capacitance.— When the ging current of the machine under test may appreciably distort the voltage : or change the effective ratio of the testing transformer, the first adjustment ltage with the gap set for the test voltage shall be made with the machine r test connected to the circuit and in parallel with the spark-gap.

§2. Measurements with Voltmeter. — In measuring the voltage with a neter, the instrument should preferably derive its voltage from the high- sure circuit, either directly, or by means of a voltmeter coil placed in the ng transformer, or through an auxiliary *ratio transformer*. It is permissible easure the voltage at other places such as the transformer primary, pro- l corrections can be made for the variations in ratio caused by the charging nt of the machine under test, or provided there is no material variation in ratio. In any case when the capacitance of the machine to be tested is such cause wave distortion, the testing voltage must be checked by a spark-gap t forth in §§2364 and 2366 or by a crest-voltage meter. If the crest-voltage r is calibrated in crest volts, its readings must be reduced to the correspond- r.m.s. sinusoidal value by dividing by $\sqrt{2}$.

§3. Measurements with Spark-gaps. — (a) *General:* If proper precautions taken, spark-gaps may be used to advantage in checking the calibration of meters for high-voltage tests of machines.

(b) *Range of Voltages:* For the calibrating purposes set forth above, the re gap shall be used for voltages above 50 kv., and is preferred down to 30 kv. needle spark-gap may, however, be used for voltages from 10 to 50 kv.

§4. Needle Spark-gap. — The needle spark-gap shall be between new ng needles, supported axially at the ends of linear conductors, which are at : twice the length of the gap. There must be a clear space around the gap i radius at least twice the gap length.

§5. Needle-gap Sparking Distances. — The sparking distances in air be- a No. 00 double long sewing needle points for various root-mean-square soidal voltages shall be assumed to be as shown in Table 202.

TABLE 202

Needle-Gap Spark-Over Voltages

(At 25° C. and 760 mm. barometer)

R. M. S. Kilovolts	Millimeters	R. M. S. Kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41		

he values in Table 202 refer to a relative humidity of 80 per cent. Variations this humidity may involve appreciable variations in the sparking distance.

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381) When making arc-over tests of large insulators, leads, etc., partial arc-over of tested apparatus may produce oscillations which will cause the measuring gap to dis- ge prematurely. The measured voltage will then appear too high. In such tests the uivalent ratio" of the testing transformer should be measured by gap to within 20 per of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. measuring gap should then be greatly lengthened out and the voltage increased until tested apparatus also over. This arc-over voltage should then be determined by multi- ng the voltmeter reading by the equivalent ratio found above. Direct measurement he spark-over voltage over one gap by another gap should always be avoided.

2366.* Sphere Spark-gap. — The standard sphere spark-gap shall be betw two suitably mounted spheres. No extraneous body, or external part of circuit, shall be nearer the spheres than twice their diameter.

The shanks shall be not greater in diameter than ¼th the sphere diam Metal collars, etc., through which the shanks extend, shall be as small as pra able and shall not, during any measurement, come closer to the sphere tha maximum gap length used in the measurement.

The sphere diameter should not vary more than 0.1 per cent, and the cu ture, measured by a spherometer, should not vary more than 1 per cent fr that of a true sphere of the required diameter.

2367.* Use of Spherometer. — In using the spherometer to measure cu ture, the distance between the points of contact of the spherometer feet sha within the limits as indicated in Table 203.

TABLE 203

Spherometer Specifications

Diameter of sphere in mm.	Distance between contact points in mm.	
	Maximum	Minimum
62.5	35	25
125	45	35
250	65	45
500	100	65

2368. Sphere-gap Sparking Distances. — The sparking distance betwe spheres for various r.m.s. sinusoidal voltages shall be assumed to be as show Table 204.

2369.* Correction of Gap Spacing for Air-density. — The spacing at wh it is necessary to set a gap to spark over at some required voltage, is found a follows. Divide the required voltage by the correction factor given in Table 2 and use the new voltage thus obtained, to find the corresponding spacing fro Table 204, using a graph of the latter, if more convenient.

2370.* Correction of Voltage for Air-density. — The voltage at which a g sparks over is derived from the voltage corresponding to the spacing in Table 2 by multiplying by the correction factor.

(2366) When used as specified, the accuracy obtainable should be approximately 2 p cent.

(2367) In using sphere-gaps constructed as indicated in § 2366 and § 2367, it is assum that the apparatus will be set up for use in a space comparatively free from external dielec tric fields. Care should be taken that conducting bodies forming part of the circuit, or circuit potential, are not so located with reference to the gap that their dielectric fields a superposed on the gap, *e.g.*, the protecting resistance should not be arranged so as to pres large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approx imately five diameters above the floor or ground.

(2369 and 2370) Effect of Air-density on Spark-over Voltage. The spark-o voltage, for a given gap, decreases with decreasing barometric pressure and increasi temperature. This variation may be considerable at high altitudes. When the variati from sea level is not great, the relative air density may be used as the correction facto when the variation is great, or greater accuracy is desired, the correction factor corr sponding to the relative air density should be taken from Table 204 in which

$$\text{Relative air-density} = \frac{0.392b}{273+t}$$

b = barometric pressure in mm.

t = temperature in deg. C.

Corrected curves may be plotted for any given altitude, if desired. It will be noted Table 213 that for values of relative air density above 0.9 the correction factor does n differ greatly from the relative air density.

TABLE 204

Sphere-gap Spark-over Voltages

(At 25° C. and 760 mm. barometric pressure)

Sparking Distance in Millimeters							
62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
4.2	4.2						
8.6	8.6						
14.1	14.1	14.1	14.1				
19.2	19.2	19.1	19.1				
25.5	25.0	24.4	24.4				
34.5	32.0	30	30	29	29		
46.0	39.5	36	36	35	35		
62.0	49.0	42	42	41	41	41	41
	60.5	49	49	46	45	46	45
		56	55	52	51	52	51
		79.7	71	64	63	63	62
		108	88	78	77	74	73
		150	110	92	90	85	83
			138	109	106	97	95
				128	123	108	106
				150	141	120	117
				177	160	133	130
				210	180	148	144
				250	203	163	158
					231	177	171
					265	194	187
						214	204
						234	221
						255	239
						276	257

e sphere-gap is more sensitive than the needle-gap to momentary rises of ge and the voltage required to spark over the gap should be obtained by / closing the gap under constant voltage, or by slowly raising the voltage a fixed setting of the gap. Open arcs should not be permitted in proximity : gap during its operation, as they may affect its calibration.

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TABLE 205

Air-density Correction Factors for Sphere Gaps

Relative air-density	Diameter of standard spheres in mm.			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

Insulation Resistance

2380. General. — The insulation resistance test shall be made with all circuits of equal voltage above ground connected together. Circuits or groups of circuits of different voltage above ground shall be tested separately.

2381. Voltage for Insulation Resistance Test. — Insulation resistance tests shall, if possible, be made at a d-c. pressure of 500 volts. Since the insulation resistance varies with the pressure, it is necessary that, if a pressure other than 500 volts is to be employed in any case, this other pressure shall be clearly specified.

2382.* Minimum Values. — The insulation resistance of a machine at its operating temperature shall be not less than that given by the following formula:

$$\text{Insulation Resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rating in kv-a.} + 1000}.$$

The formula applies only to dry apparatus. Such high values are not attainable in oil-immersed apparatus.

Regulation

2390. Conditions for Tests of Regulation. — (a) *Speed and Frequency:* The regulation of generators shall be determined at constant speed, and that of alternating-current machines at constant frequency.

(b) *Wave Form:* A sine wave of voltage shall be assumed in determining the regulation of alternating-current machinery receiving electric power, except where expressly specified otherwise. See § 2340.

(2382) The order of magnitude obtained by this rule is shown in the following table:

TABLE 206

Insulation Resistance of Machines Excluding Oil-immersed Apparatus

Rated voltage of machine	Megohms		
	100 kv-a	1000 kv-a.	10,000 kv-a.
100	0.091	0.05	
1,000	0.91	0.50	0.091
10,000	9.1	5.0	0.91
100,000	.....	50	9.1

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) *Temperature:* It is desirable that all parts of the machine affecting the lation be maintained at constant temperature between the two loads and re the influence of temperature is of consequence, a reference temperature of C. shall be considered as standard. If change of temperature should occur ng the tests the results shall be corrected to the reference temperature of C.

CONSTRUCTION

Rating Plates

01. Marking of Rating Plate. — (a) *Distinctive Marking:* It is recomded that the rating plate of machines which comply with the Institute s shall carry a distinctive special sign, such as "A.I.E.E. 1922 Rating" or " Rating.

) *Significance of Marking:* The absence of any statement to the contrary he rating plate of a machine implies that it is intended for continuous service for the standard altitude and ambient temperature. See §§ 2211, 2212, , and 2220.

) *Marking for Various Ratings:* The rating plate of a machine intended to r under various kinds of rating must carry the necessary information in rd to those kinds of ratings.

CHAPTER III

GENERAL DEFINITIONS

i this chapter are given definitions which are of general application to electric its, machines and systems. Definitions pertaining to a specific class of ratus are given in the chapter on the class of apparatus in question. The itions here given are primarily descriptive rather than scientifically precise. he definitions given below for currents are also applicable, in most cases, to romotive forces, potential differences, magnetic fluxes, etc.

DEFINITIONS

General

00. Ambient Temperature. — The ambient temperature is the tempera- of the air or water which comes into contact with the heated parts of a hine and carries off its heat. See §§ 2300 and 2301.

10. Electrical Tension.—Electrical tension is electromotive force, or differ- of potential.

11. Voltage.—Voltage is electrical tension expressed in volts.

20. Resistivity. — The resistivity of a material is the resistance expressed hms between two opposite faces of a centimeter cube of the material, and is ally coupled with a statement of the temperature. See § 9050.

Apparatus

64. Resistor. — A resistor is a device used primarily because it possesses property of electrical resistance. Resistors are used in electric circuits for poses of operation, protection, or control. See § 7017.

76. Inductor. — An inductor is a device used primarily because it possesses property of inductance.

78. Reactor. — A reactor is a device used primarily because it possesses property of reactance. Reactors are used in electric circuits for purposes peration, protection or control. See § 7018.

Kinds of Currents

04. Direct Current. — A direct current is a unidirectional current. As inarily used, the term designates a practically non-pulsating current.

08. Pulsating Current. — A pulsating current is a current which has regu- y recurring variations in magnitude. As ordinarily employed the term rs to a unidirectional current.

12. Continuous Current. — A continuous current is a practically non-

3116. Alternating Current. — An alternating current is a current the direction of which reverses at regularly recurring intervals. Unless distinctly otherwise specified, the term *alternating current* refers to a periodically varying current with successive half waves of the same shape and area. See § 3212.

3120. Oscillating, or Free Alternating Current. — An oscillating, or free alternating current is the current following any electro-magnetic disturbance in a circuit having capacity, inductance, and less than the critical resistance. When the critical resistance of a circuit is reached the current becomes aperiodic.

Alternating Currents

3204. Cycle. — A cycle is one complete set of positive and negative values of an alternating current.

3206. Period. — The period of an alternating current is the time required for the current to pass through one cycle.

3208. Frequency. — The frequency of an alternating current is the number of cycles through which it passes per second, that is, the reciprocal of the period.

3212. Wave Shape. — The wave shape, or wave form, of an alternating current is the shape of the curve obtained when the instantaneous values of the current are plotted against time in rectangular coordinates.

Two alternating quantities are said to have the same wave shape when the ordinates of corresponding phase bear a constant ratio to each other. The wave shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is plotted.

3214. Sine Wave, or Simple Alternating Current. — A sine wave, or simple alternating current, is a current whose wave shape is sinusoidal.

3218.* Root-Mean-Square or Effective Value. — The root-mean-square or effective value of an alternating current is the square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated r.m.s. Unless otherwise specified, the numerical value of an alternating current refers to its r.m.s. value. The word " virtual " is sometimes used in place of r.m.s., particularly in Great Britain.

3222. Phase. — Phase is the fraction of the period of an alternating current which has elapsed since the current passed through the zero position of reference.

This fraction is usually expressed in angular measure, and the period corresponding to one complete cycle is taken as representing 2π radians or 360 degrees. The angles are frequently called electric angles, and the degrees electric degrees.

In the usual equation $$i = I_m \sin(\omega t + \phi)$$

the quantity $(\omega t + \phi)$ is the phase and ϕ is the phase angle of the current.

3224.* Phase Difference; Lead and Lag. — The phase difference of two alternating quantities of the same frequency is the difference between their phases at any instant. That quantity whose maximum occurs first in time is said to lead the other, and the latter is said to lag behind the former.



Fig. 3–1.

3228. Vector Representation and Angular Velocity. — A sine-wave current or voltage may be represented by a vector of constant length rotating counter-clockwise at a constant angular velocity ($\omega = 2\pi f$); this angular velocity is frequently termed the angular velocity of the current or voltage.

3230.* Counter-clockwise Convention. — It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector, as in Fig. 3-1 where OI rep-

(3218) The r.m.s. value of a sine wave (see Section 3214) is equal to its maximum, or crest value, divided by $\sqrt{2}$.

(3224) When the two alternating quantities do not have the same wave form, the phase difference as here defined may not be identical with equivalent phase difference as defined in Section 3262.

(3230) See Publication 12 of the International Electrotechnical Commission (Report of Turin meeting, Sept. ...

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sents the vector of a current in a simple alternating-current circuit lagging hind the vector OE of impressed electromotive force.

3234. Power. — Power is the rate of transfer of energy. In the case of an ernating-current circuit the word power is generally used to denote the aver- e value of the power over a cycle. The power in an electric circuit at any tant is equal to the product of the values of the current and voltage at that tant, and is generally called the instantaneous power.

3238. Apparent Power or Volt-amperes. — The apparent power, or volt- pperes, in an alternating-current circuit is the product of the r.m.s. value of e voltage across the circuit by the r.m.s. value of the current in the circuit. pparent power is also expressed in kilovolt-amperes, abbreviated kv-a.

3242.* Power Factor. — Power factor is the ratio of the power to the appar- t power.

3243. Power Factor in Polyphase Circuits.—The power factor of a polyphase rcuit, either balanced or unbalanced, is the ratio of the total active power in itts to the total vector volt-amperes.

The total vector volt-amperes is the square root of the sum of the squares of e total active power and the total reactive power.

The total reactive power is the algebraic sum of the reactive powers correspond- g to the separate harmonic components of the system.

3244. Momentary and Average Power Factors.—Power factors are either omentary power factors or integrated "average power factors"; i.e., extended er a specific time interval by averaging the active and reactive powers over e interval. Thus, a power factor may be an integrated average five-minute wer factor, or an integrated average hour power factor, or an integrated erage monthly power factor, etc.

The difference between a polyphase power factor (momentary) and a poly- ase power factor (integrated average) lies only in the period of time over hich the active and reactive powers are taken.

3246.* Reactive Volt-amperes. — The reactive volt-amperes in a circuit is e square root of the difference between the square of the apparent power and e square of the power.

3250.* Reactive Factor. — The reactive factor is the ratio of the reactive lt-amperes to the total volt-amperes.

3254.* Active Component. — The active component of the current in a cir- uit is the average power divided by the voltage.

3256.* Reactive Component. — The reactive component of the current in a rcuit is the square root of the difference between the square of the current and ie square of the active component of the current.

3260. Equivalent Sine Wave. — An equivalent sine wave is a sine wave hich has the same frequency and the same r.m.s. value as the actual wave.

3262. Equivalent Phase Difference. — The equivalent phase difference pplicable to non-sinusoidal currents and voltages) is the phase difference etween the equivalent sine waves of current and voltage when so related as to ave the same power factor as the non-sinusoidal quantities.

There are cases, however, where this equivalent phase difference is misleading,

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(3242) The power factor when both the current and voltage are sinusoidal is equal to e cosine of the angle which expresses their difference in phase (see Section 3224).

(3246) The reactive volt-amperes, when both current and voltage are sinusoidal, is ual to the volt-amperes times the sine of the angle which expresses the phase difference tween current and voltage.

(3250) The reactive factor, when both current and voltage are sinusoidal, is equal to ie sine of the angle which expresses their phase difference.

(3254) The active, or in-phase component of the current in a circuit corresponds to verage power passing in a given direction through the circuit. With sine-wave voltage nd current, the active component of the current is in phase with the voltage.

(3256) The reactive, or quadrature, component of the current in a circuit corresponds power alternating in direction in the circuit so that the average value of the power ansferred in a given direction through a cycle is zero. With sine-wave current and oltage the reactive component of the current is in quadrature with the voltage.

since the presence of harmonics in the voltage wave, current wave, or in both may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e.g.*, the case of an arc lamp. In such cases, the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

3266.* Crest Factor or Peak Factor. — The crest factor or peak factor of a wave is the ratio of the crest, or maximum, value to the r.m.s. value.

3270.* Form Factor of a Wave. — The form factor of a wave is the ratio of the r.m.s. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle.

3274. Deviation Factor of a Wave. — The deviation factor of a wave is the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave to the maximum ordinate of the equivalent sine wave when the waves are superposed in such a way as to make this maximum difference as small as possible.

3278. Telephone Interference Factor of a Wave. (See § 4352.) — The telephone interference factor is the ratio of the square root of the sum of the squares of the weighted values of all the sine-wave components (including the alternating waves both fundamental and harmonics) to the r.m.s. value of the wave.

Circuits and Phases

3304. Electric Circuit. — An electric circuit is a path in which an electric current may flow. Strictly speaking, an electric circuit is a complete circuitous path, but the term circuit is commonly employed to designate a specific part of a complete path. When part of a complete path is referred to, such as a branch circuit, a derived circuit, or a conductor, both the terminals and the conductor which form that path should be specified in order to avoid ambiguity; *e.g.*, the circuit *a-b-c*. When the whole circuit is referred to, it may be designated as a complete or closed circuit.

3324.* Single-phase Circuit. — A single-phase circuit is a circuit energized by a single alternating electromotive force.

3326.* Three-phase Circuit. — A three-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by one-third of a cycle; *i.e.*, 120 degrees.

3328.* Quarter-phase or Two-phase Circuit. — A quarter-phase or two-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by a quarter of a cycle; *i.e.*, 90 degrees.

3330.* Six-phase Circuit. — A six-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by one-sixth of a cycle, *i.e.*, 60 degrees.

3338. Polyphase Circuit. — A polyphase circuit is a circuit of more than one single phase. This term is ordinarily applied to symmetrical systems.

3344. Symmetrical Voltages and Currents. — Polyphase voltages or currents are symmetrical when the voltages or currents have the same wave shape and r.m.s. value and differ in phase each from the next by the same angle.

3348. Symmetrical Polyphase System. — A symmetrical polyphase system is a polyphase system in which the voltages are symmetrical.

(3266) The crest factor of a sine wave is $\sqrt{2}$.

(3270) The form factor of a sine wave is $\frac{\pi}{2\sqrt{2}}$ or 1.11.

(3324) A single-phase circuit is usually supplied through two wires. The currents in these two wires, counted outwards from the source, differ in phase by 180 degrees or a half-cycle.

(3326) In practise the phases may vary several degrees from the specified angle.

(3328) In practise the phases may vary several degrees from the specified angle.

(3330) In practise the phases may vary several degrees from the specified angle.

382.* **Balanced Polyphase System.** — A balanced polyphase system is a yphase system in which both the currents and voltages are symmetrical.

Loads

404. Reactive Load. — A reactive load is a load in which the current lags ind or leads the voltage across the load.

406. Non-reactive Load. — A non-reactive load is a load in which the cur- : is in phase with the voltage across the load. (The term non-inductive load metimes used for non-reactive load.)

408. Inductive Load. — An inductive load is a reactive load in which the ent lags behind the voltage across the load.

410. Condensive Load. — A condensive load is a reactive load in which the ent leads the voltage across the load.

414.* **Balanced Polyphase Load.** — A balanced polyphase load is a load to ch symmetrical currents are supplied when it is connected to a system having metrical voltages.

424. Connected Load. — The connected load on any system, or part of a em, is the combined continuous rating of all the receiving apparatus on con- ers' premises which is connected to the system, or part of the system under ideration.

434. Peak Power. — The peak power is the average power during a time rval of specified duration occurring within a given period of time, that rval being selected during which the average power is greatest.

438. Load Factor. — The load factor is the ratio of the average power to the k power.

In each case, the interval of maximum load and the period over which the age is taken should be definitely specified, such as a "half-hour monthly" factor. The proper interval and period are usually dependent upon local litions and upon the purpose for which the load factor is to be used.

442. Plant Factor. — The plant factor is the ratio of the average load to the d capacity of the power plant; *i.e.*, to the aggregate ratings of the generators.

454. Demand of an Installation or System. — The demand of an installation ystem is the load which is drawn from the source of supply at the receiving minals averaged over a suitable and specified interval of time. Demand is essed in kilowatts, kilovolt-amperes, amperes, or other suitable units.

458. Maximum Demand. — The maximum demand of an installation or em is the greatest of all the demands which have occurred during a given od. It is determined by measurement, according to specifications, over a scribed time interval.

460. Demand Factor. — The demand factor of any system or part of a em, is the ratio of the maximum demand of the system, or part of a system, he total connected load of the system, or of the part of the system under ideration.

464. Diversity Factor. — The diversity factor of any system, or part of a em, is the ratio of the sum of the maximum power demands of the sub- ions of the system, or part of a system, to the maximum demand of the e system, or part of the system under consideration, measured at the point pply.

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382) The term balanced polyphase system is applied also to a quarter-phase (or two- e) system in which the voltages have the same wave form and r.m.s. value and in the currents have the same wave form and r.m.s. value and differ in phase by ninety rical degrees.

414) The term balanced polyphase load is applied also to a load to which are supplied currents having the same wave form and r.m.s. value and differing in phase by ninety rical degrees when it is connected to a quarter-phase (or two-phase) system having ages of the same wave form and r.m.s. value.

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Machinery and Apparatus

3504. Capacity (or Properly, Capability). — The word "capacity" is frequently used in the general sense of "capability." It is also used in a more exact sense to denote the load which, when carried by a machine, apparatus or device will, under specified conditions of test, cause it to reach *any one of its physical limitations*, such for example, as operating temperature or ability to maintain required voltage.

Capacity should be distinguished from rating. On account of the different senses in which it has been employed (see § 3508), capacity is less used than formerly was, rating being more useful commercially.

3508.* Rating. — A rating of a machine, apparatus or device is an arbitrary designation of an operating limit.

(The rating of a machine is the output marked on the rating plate, and shall be based on, but shall not exceed the maximum load which can be taken by the machine under prescribed conditions of test. This is also called the normal output. *Maximum possible rating obviously corresponds with capability as defined in* § 3504).

3514. Efficiency. — The efficiency of an electric machine or apparatus is the ratio of its useful output to its total input. Unless otherwise specified the terms output and input shall mean the power output and the power input respectively.

3524.* Conventional Efficiency. — The conventional efficiency of an electric machine or apparatus is the ratio of the output to the sum of the output and losses, or of the input minus the losses to the input, when, in either case, conventional values are assigned to one or more of these losses.

3534. Plant, or System, Efficiency. — Plant, or system, efficiency is the ratio of the energy delivered from the plant or system to the energy received by it in a specified period of time. In calculating plant, or system, efficiency it may be desirable to calculate the losses in each individual machine, or part of the system, at the actual temperature of that machine, or part, during the specified interval. These losses may be appreciably different from the losses at 75° C., which shall be the standard temperature of reference for all efficiency guarantees. This definition is not applicable to storage batteries. See § 2332.

3535. Regulation. — The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be expressed as the "percentage regulation," which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at one or the other load, taken as the normal value. The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a-c. generators.

It is assumed that all parts of the machine affecting the regulation are at constant temperature between the two loads, and where the influence of temperature is of consequence a reference temperature of 75° C. shall be considered as standard.

Systems

3560. Normal Voltage.—In systems employing transformers, the normal voltage of the system or circuit is defined as the highest rated voltage of the secondaries of transformers supplying the system or circuit. This voltage rating applies to all parts of that particular system or circuit.

(3508) The term maximum load does not refer to loads applied solely for the purpose of commutation, or similar tests.

(3524) The need for assigning conventional values to certain losses arises from the fact that some of the losses in electric machinery are practically indeterminable, and may in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

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TABLE 801

SYMBOLS AND ABBREVIATIONS

Name of quantity	Symbol for the quantity	Unit	Abbreviation for the unit
celeration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
lmittance	Y, y	mho	.....
gular velocity	ω	radian per second	.....
pacitance (Electrostatic capacity)	C	farad	.....
nductance	g	mho	.....
nductivity	γ	*mho per centimeter	mho per cm
rrent	I, i	ampere	.....
electric constant	K	.....	.....
ficiency	η	per cent	.....
ectrical tension	E, e or V, v	volt	.....
ectromotive force, abbreviated e.m.f.	E, e	volt	.....
ectrostatic field intensity	F	.....	.....
ectrostatic flux	Ψ	.....	.....
ectrostatic flux density	D	.....	.....
ergy, in general	U or W	joule, watt-hour	.....
equency	f	cycle per second	$\sim$
pedance	Z, z	ohm	.....
ductance (or coefficient of self-induction)	L	henry	.....
tensity of magnetization	J	.....	.....
ngth	l	centimeter	cm.
gnetic field intensity	$H, \mathfrak{H}$	gilbert per centimeter	gilbert per cm.
gnetic flux	Φ, ϕ	maxwell	.....
gnetic flux density	$B, \mathfrak{B}$	gauss	.....
gnetic reluctance	$\mathcal{R}$	oersted	....
gnetomotive force, abbreviated m.m.f.	$\mathcal{F}$	gilbert*	.....
ass	m	gram	g
utual Inductance (or coefficient of mutual induction)	M	henry	.....
mber of conductors or turns	N	convolution or turn of wire	.....
rmeability	$\mu = B/H$	.....	.....
ase displacement	θ, ϕ	degree or radian	°
tential difference, abbreviated p. d.	V, v or E, e	volt	.....
wer	P, p	watt	.....
antity of electricity	Q, q	coulomb, ampere-hour	.....
actance	X, x	ohm	.....
sistance	R, r	ohm	.....

804) An additional unit for magnetomotive force is the "ampere-turn," for fl
"line," for magnetic flux-density "maxwells per sq. in."
he numerical values of resistivity and conductivity are *ohms resistance* and *mhos co*
nce between two opposite faces of a cm. cube of the material in question, but t
ct names are as given, not ohms and mhos per cm., cube, as commonly stated.
he value 980.665 for g_0 has been the accepted standard value for many years and w
erly considered to correspond accurately to 45° latitude and sea-level. La
urches, however, have shown that the most reliable value for 45° and sea-level
ıtly different; but this does not affect the standard value given above.

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TABLE 301—*Continued*

Name of quantity	Symbol for the quantity	Unit	Abbreviation for the unit
Resistivity	ρ	*ohm-centimeter	ohm-cm.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665*	g_0	centimeter per second per second	cm. per sec. per sec.
Susceptance	b	mho	.....
Susceptibility	$\kappa = J/H$	.....	.....
Temperature	θ	degree centigrade	°C.
Time	t	second	sec.
Velocity of rotation	n	revolution per second	rev. per sec.
Voltage	E, e or V, v	volt	.....

3608. Symbols for Maximum, Instantaneous and R.M.S. Values. — I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r.m.s. values (see §3218) and P for the average value of power, or the active power. These distinctions are not necessary in dealing with direct-current circuits. In print, vector quantities should be represented by bold-face capitals.

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CHAPTER IV

STANDARDS FOR ROTATING MACHINES (OTHER THAN RAILWAY MOTORS, RAILWAY SUBSTATION MACHINERY CARRYING TRACTION LOADS, AND AUTOMOBILE PROPULSION MACHINES)

The A. I. E. E. Standards for Rotating Machines are the General Standards shown in Chapters II and III and the Standards in other chapters which are applicable to the devices involved, together with the modifications and additions given in this chapter.

DEFINITIONS

General

Certain rules applying exclusively to railway machinery have, for convenience, been placed in Chapter V, with cross-references in all cases in this chapter. The rules of Chapter IV apply to railway machinery except as they are modified by rules of Chapter V.

4000. Classification of Electric Rotating Machinery. — Rotating electric machinery may be classified in various ways, these classifications over-lapping or interlocking in considerable degree. *First*, Rotating electric machinery may be classified as Direct-Current and Alternating-Current; *Second*, according to the function of the machines; *e.g.*, Motors, Generators, Boosters, Motor-Generators, Dynamotors, Double-Current Generators, Converters and Phase Advancers; *Third*, according to construction or principle of operation; as Commutating, Synchronous, Induction, Unipolar, Rectifying. Obviously some of these machines could be rationally included in either classification, as Motor-Generators and Rectifying Machines.

In the following, self-evident definitions have for the most part been omitted.

Functional Classification of Rotating Electric Machines

4001. Generator. — A generator is a machine which transforms mechanical power into electric power.

4002. Motor. — A motor is a machine which transforms electric power into mechanical power.

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3905. Booster. — A booster is a generator inserted in series in a circuit to ge its voltage. A booster may be driven by an electric motor (in which e it is termed a motor-booster) or otherwise.

3904. Motor-generator Set. — A motor-generator set is a transforming ce consisting of one or more motors mechanically coupled to one or more erators.

3906. Dynamotor. — A dynamotor is a transforming device combining both tor and generator action in one magnetic field, either with two armatures, or h one armature having two separate windings and independent commutators.

3906. Direct-current Compensator or Balancer. — A direct-current com-sator or balancer is a machine which comprises two or more similar direct-rent machines (usually with shunt or compound excitation) directly coupled ach other and connected in series across the outer conductors of a multiple-e system of distribution, for the purpose of maintaining the potentials of the rmediate wires of the system, which are connected to the junction points ween the machines.

3907. Double-current Generator. — A double-current generator is a machine ch supplies both direct and alternating currents from the same armature-ding.

3908. Converter. — A converter is a machine which employs mechanical tion in changing electric energy from one form into another. There are ral types of converters, as defined in §§ 4009 to 4013 below.

3909. Direct-current Converter. — A direct-current converter is a machine ch converts from a direct current to a direct current, usually with a change oltage. Such a machine may be either a motor-generator set or a dynamotor.

3910. Synchronous Converter. — A synchronous converter (sometimes called tary converter) is a machine which converts from an alternating to a direct ent, or vice-versa. It is a synchronous machine with a single closed-coil mature winding, a commutator and slip rings.

3911. Cascade Converter. — A cascade converter (also called a motor con-er) is a combination of an induction motor with a synchronous converter, secondary circuit of the former feeding directly into the armature of the r; *i.e.*, a synchronous converter concatenated with an induction motor.

3912. Frequency Converter. — A frequency converter is a machine which rerts the power of an alternating-current system from one frequency to ther, with or without a change in the number of phases, or in the voltage.

3913. Rotary Phase-converter. — A rotary phase-converter is a machine ch converts from an alternating-current system of one or more phases to an rnating-current system of a different number of phases, but of the same uency.

3914. Phase Advancer. — A phase advancer is a machine which supplies tive volt-amperes to the system to which it is connected. Phase advancers be either synchronous or asynchronous.

3915. Synchronous Condenser or Synchronous Phase Advancer. — A syn-nous condenser or synchronous phase advancer is a synchronous machine, ning either idle or with load, the field excitation of which may be varied so as odify the power factor of the system, or through such modification to influ-the load voltage.

Constructional Classification of Rotating Electric Machines

3916. Direct-current Commutating Machines. — A direct-current commu-g machine comprises a magnetic field of constant polarity, an armature, a commutator connected therewith. Specific types of direct-current com-ating machines are: Direct-Current Generators; Direct-Current Motors; ct-Current Boosters; Direct-Current Motor-Generator Sets and Dyna-ors; Direct-Current Compensators or Balancers; and Arc Machines.

3917. Alternating-current Commutating Machine. — An alternating-current mutating machine comprises a magnetic field of alternating polarity, an ature, and commutator connected therewith. See §§ 4071 to 4074.

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4018. Synchronous Commutating Machine. — Synchronous commutating machines include synchronous converters, cascade-converters, and dou current generators.

4019. Synchronous Machine. — A synchronous machine comprises a stant magnetic field and an armature receiving or delivering alternating-cu in synchronism with the motion of the machine; *i.e.*, having a frequency wh proportional to the speed of the machine. Specific types of synchron machines are defined in §§ 4020 to 4023 below.

4020. Alternator. — An alternator is a synchronous alternating-cu generator, either single-phase or polyphase.

4021. Polyphase Alternator. — A polyphase alternator is a polyphase chronous alternating-current generator, as distinguished from a single-p alternator.

4022. Inductor Alternator. — An inductor alternator is an alternator in wh both field and armature windings are stationary, and in which masses of iro inductors, by moving past the coils, alter the magnetic flux through them. may be either single-phase or polyphase.

4023. Synchronous Motor. — A synchronous motor is a machine structu identical with an alternator, but operated as a motor.

4024. Induction Machine. — An induction machine is a machine wh primary and secondary windings rotate with respect to each other; *e.g.*, in tion motors, induction generators, certain types of frequency converter certain types of rotary phase-converters.

4025. Induction Motor. — An induction motor is an alternating-cu motor, either single-phase or polyphase, comprising independent primary secondary windings, one of which, usually the secondary, is on the ro member. The secondary winding receives power from the primary by el magnetic induction.

4026. Induction Generator. — An induction generator is a machine st turally identical with an induction motor, but driven above synchronous s as an alternating-current generator.

4027. Engine Type Generator. — An engine type generator is one cons an engine in such a way that it cannot be run independently of the engine.

4028. Unipolar or Acyclic Machine. — A unipolar, or acyclic machine, direct-current machine, in which the voltage generated in the active conduc maintains the same direction with respect to those conductors.

Speed Classification of Motors

4035. Constant-speed Motor. — A constant-speed motor is one whose spe either constant or does not materially vary; such as a synchronous motor, induction motor with small slip, and an ordinary direct-current shunt motor.

4036. Multispeed Motor (or Change Speed Motor). — A multispeed mot a motor which can be operated at any one of several distinct speeds (these spe being practically independent of the load), but which cannot be operated intermediate speeds.

4037. Adjustable-speed Motor. — An adjustable-speed motor is one in wh the speed can be varied gradually over a considerable range, but when adjusted remains practically unaffected by the load; such as a shunt mo designed for a considerable range of speed variation.

4038. Base Speed of an Adjustable-speed Motor. — The base-speed of adjustable-speed motor is that speed of the motor obtained with full field an full load with no resistor in the armature circuit.

4039. Varying-speed Motor. — A varying speed motor is one whose sp varies with the load, ordinarily decreasing when the load increases; such a series motor, a compound-wound motor, and a series-shunt motor. As a c class of varying-speed motors, may be cited adjustable varying-speed moto or motors in which the speed can be varied over a considerable range at a given load, but when once adjusted, varies with the load; *e.g.*, compound wound motors arranged for adjustment of speed by varying the strength of th shunt field.

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Classification of Rotating Electric Machines Relative to their Degree of Enclosure

1041. Open Machine. — An open machine is of either the pedestal-bearing or l bracket type where there is no restriction to ventilation, other than that ssitated by good mechanical construction.

1042. Protected Machine. — A protected machine is one in which the armae, field coils, and other live parts are protected mechanically from accidental careless contact, while free ventilation is not materially obstructed.

1043. Enclosed Ventilated Machine. — An enclosed ventilated (or semiosed machine is one in which the ventilating openings in the frame are tected with wire screen, expanded metal, or other suitable perforated covers, ing apertures not exceeding ½ square inch (3.2 sq. cm.) in area. See § 4316.

1044. Totally Enclosed Machine. — A totally enclosed machine is one so losed as to prevent circulation of air between the inside and the outside of the e, but not sufficiently to be termed air-tight.

1045. Separately Ventilated Machine. — A separately ventilated machine its ventilating air supplied by an independent fan or blower external to the chine.

1046. Self-ventilated Machine. — A self-ventilated machine differs from a arately ventilated machine only in having its ventilating air circulated by a , blower, or centrifugal device integral with the machine.
f the heated air expelled from the machine is conveyed away through a pipe ached to the machine, this should be so stated.

1047. Water-cooled Machine. — A water-cooled machine is one which inly depends on water circulation for the removal of its heat.

1048. Drip-proof Machine. — A drip-proof machine is one so protected as to lude falling moisture or dirt. A drip-proof machine may be either open or ii-enclosed, if it is provided with suitable protection integral with the machine, o enclosed as to exclude effectively falling solid or liquid material.

1051. Explosion-proof Machine (or Flame-proof Machine). — An explosionof machine is a machine in which the enclosing case can withstand, without ny, any explosion of gas that may occur within it, and will not transmit the se to any inflammable gas outside it.

1052. Machine with Explosion-proof Slip-ring Enclosure. — A machine in ich the slip rings and brushes alone are included within an explosion-proof e should not be described as an explosion-proof machine, but as a machine h explosion-proof slip-ring enclosure.

Classification of Alternating-Current Commutator Motors

An alternating-current commutator motor may be classified under more than one of the following groups)

ssification by Phases of Energy Supply.

1061. Single-phase Commutator Motor. — A single-phase commutator motor ne that receives the whole of its energy from only one phase of an alternatingrent supply system, without requiring external phase-converting apparatus.

1062. Polyphase Commutator Motor. — A polyphase commutator motor is that receives its energy from a plurality of phases of an alternating-current ply system, or from a single-phase system through phase-converting apparatus ernal to the motor.

ssification by Speed Characteristics.

1063. General. — For convenience, alternating-current commutator motors y be classified with reference to their speed characteristics as (1) constanted motors, (2) multi-speed motors, (3) adjustable-speed motors, and (4) ying-speed motors. Definitions of these terms as given in §§ 4035 to 4039 motors in general, should be adopted for alternating-current commutator tors, in so far as they are applicable.

ssification by Excitation.

1064. Stator-excited Commutator Motor. — A stator-excited commutator tor is one in which the torque-producing field is due to a current in a winding

located on the stator. By the "torque-producing field" is meant that component of the magnetic field which, with the in-phase component of the current produces the torque of the motor.

4065. Rotor-excited Commutator Motor. — A rotor-excited commutator motor is one in which the torque-producing field is due to a current in a winding located on the rotor. See § 4064.

4066. Stator- and Rotor-excited Commutator Motor. — A stator- and rotor-excited commutator motor is one in which the torque-producing field is due to currents in windings located on the stator and on the rotor. See § 4064.

4067.* Constant-field Commutator Motor. — A constant-field commutator motor is one in which the torque-producing field remains practically constant independent of the load. See § 4064.

4068.* Varying-field Commutator Motor. — A varying-field commutator motor is one in which the torque-producing field varies in some proportion to the current in the armature (which latter is generally the rotor). See § 4064.

Classification by Neutralization and Compensation.

4069. Neutralized Commutator Motor. — A neutralized commutator motor is one in which use is made of a winding for producing a magnetizing force which at each instant and at each point in the air-gap under the pole face is practically equal and opposite to the magnetizing force due to the armature current.

4070. Compensated Commutator Motor. — A compensated commutator motor is one in which means, other than a neutralizing winding, are provided within the motor for improving the power-factor.

Classification by Energy Reception.

4071. Conduction Commutator Motor. — A conduction commutator motor is one in which the working energy is supplied to only one of the members, and is conveyed to it by conduction. By "working energy" is meant the energy which is directly converted into mechanical energy, and which includes the shaft energy output plus core losses and friction.

4072. Transformer Commutator Motor. — A transformer commutator motor is one in which the working energy is transmitted from one member to the other by transformer action.

A motor in which the energy required by its armature (which is generally the rotor) is conveyed to it by electromagnetic induction or transformer action, is properly be referred to either as an "induction motor," or as a "transformer motor." Although it is equally applicable to a motor having a commutator, the term "induction motor" is usually applied to a motor without a commutator. The term "transformer commutator motor" is therefore recommended for use with motors of the induction, or transformer type, having commutators.

4073. Transformer-conduction Commutator Motor. — A transformer-conduction commutator motor is one in which the energy required by its armature (which is generally the rotor) is conveyed to it by both conduction and electromagnetic induction.

4074. Repulsion Commutator Motor. — A repulsion commutator motor is a transformer commutator motor in which use is made of brushes for short-circuiting a number of coils of the commutated winding.

Miscellaneous Definitions

4085. Saturation Factor. — The saturation factor of a machine is the ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal

(4067) Alternating-current commutator motors of this class will in general have low-speed characteristics similar to those of the direct-current shunt motor, but such alternating-current commutator motors having such load-speed characteristics are constant-field machines.

(4068) Such a motor will in general have load-speed characteristics similar to those of the direct-current series motor.

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ted and voltage. It is determined from measurements of saturation made on
en circuit at rated speed.

4088. Percentage Saturation. — The percentage saturation of a machine at
y excitation may be found from its saturation curve (generated voltage as
inates, against excitation as abscissas), by drawing a tangent to the curve at
ordinate corresponding to the assigned excitation, and extending the tangent
intercept the axis of ordinates drawn through the origin. The ratio of the
ercept on this axis to the ordinate at the assigned excitation, when expressed
per cent, is the percentage saturation, and is independent of the scales selected
excitation and voltage. This ratio as a fraction, is equal to the reciprocal of
saturation-factor at the same excitation, deducted from unity; or, if f be the
uration factor and p the percentage saturation,

$$p = 100\left(1 - \frac{1}{f}\right).$$

4088.* Variation in Alternators. — The variation in alternators, or alter-
ing-current circuits in general is the maximum angular displacement,
ressed in electrical degrees (see § 3222) of corresponding ordinates of the
tage wave and of a wave of absolutely constant frequency equal to the aver-
frequency of the alternator or circuit in question, and may be due to the
iation of the prime mover. See §§ 14010 and 14011.

4089. Per cent Resistance Drop. — The per cent resistance drop in an electric
chine is the ratio of the internal resistance drop at 75° C. to the terminal
tage expressed in per cent.
Unless otherwise specified this per cent drop shall be referred to rated load
l rated power factor.
The per cent resistance drop in an induction motor is expressed in terms of
internally induced electromotive force.

4090. Per cent Reactance Drop. — The per cent reactance drop in an electric
chine or apparatus is the ratio of the internal reactance drop to the terminal
age, expressed in per cent.
Unless otherwise specified this per cent drop shall be referred to rated load
rated power factor.
The per cent reactance drop in an induction motor is expressed in terms of the
rnally induced electromotive force.

4091. Per cent Impedance Drop. — The per cent impedance drop in an electric
chine is the ratio of the internal impedance drop at 75° C. to the terminal
tage, expressed in per cent.
Unless otherwise specified this per cent drop shall be referred to rated load and
ed power factor.
The per cent impedance drop in an induction motor is expressed in terms of the
rnally induced electromotive force.

4092. Magnetic Degree. — A magnetic degree is the 360th part of the angle
tended, at the axis of a machine, by a pair of its field poles. One *mechanical*
ree is thus equal to as many magnetic degrees as there are pairs of poles in the
chine.

4094. Regulation of D-C. Generators. — The regulation of a d-c. generator
sually stated by giving the numerical values of the voltage at no load and
ed load, and in some cases it is advisable to state regulation at intermediate
ds. The regulation of d-c. generators refers to changes in voltage correspond-
to gradual changes in load, and does not relate to the comparatively large
mentary fluctuations in voltage that frequently accompany instantaneous
nges in load.

4095. Regulation of Constant-potential A-C. Generators. — In constant-
ential a-c. generators, the regulation is the rise in voltage (when the specified
l at specified power factor is reduced to zero) expressed in per cent of normal
ed-load voltage.

(4088) If p is the number of pairs of poles, the variation of an alternator is p times the
ation of its prime mover, if direct-connected, and pn times the variation of the prime
ver if rigidly connected thereto in such a manner that the angular speed of the alternator
times that of the prime mover.

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4096. Regulation of Constant-current Machines. — In constant-current machines the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit or minimum limit of operation), to the rated-load current.

4097. Regulation of Constant-speed Motors. — In constant-speed direct-current motors and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

4098. Regulation of Converters, Dynamotors, Motor-Generators and Frequency Converters. — In converters, dynamotors, motor-generators, and frequency converters, the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal voltage at rated load.

OPERATION

Temperature Limits

4105. Exceptions to General Temperature Limits Given in Chapter II.

(a) Railway Motors: See §§ 5202 and 5101.

(b) Automobile Propulsion Machines: See § 5205.

(c) Railway Substation Machines: See §§ 5201 and 5102.

(d) Squirrel Cage and Amortisseur Windings. The temperature may attain any value such as will not occasion mechanical injury to the machine.

(e) Field Control Railway Motors: See § 5204.

4106. Collector Rings. — The observable temperature of collector rings shall not be permitted to exceed the values set forth in § 2231 (b) for the insulation employed either in the collector rings themselves or in adjacent insulation whose life would be affected by the heat from the collector rings.

4107. Commutators. — The observable temperature shall in no case be permitted to exceed the values given in § 2231 (b) for the insulation employed either in the commutator or in an insulation whose life would be affected by the heat of the commutator. These temperature limits are intended only to protect the insulation of the commutator and of the adjacent parts and are not intended as a criterion of successful commutation.

4108. Cores. — The observable temperature of those parts of the iron cores in contact with insulating materials shall in no case be permitted to exceed the values given in §§ 2231 (b) for the insulation employed.

4109. Other Parts (Such as Brush-holders, Brushes, Bearings, Pole-tip Cores, etc.). — All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material may be operated at such temperatures as shall not be injurious in any other respect.

4110. Maximum Temperature Rise in Service. — Whatever may be the ambient temperature when the machine is in service, the limits of the maximum observable temperature or of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of temperature: such as commutation, stalling load and mechanical strength. For similar reasons, loads in excess of the rating should not be taken from a machine.

RATING

Units in Which Rating Shall be Expressed

4220. Rating of D-C. Generators.—The rating of direct-current generators shall be expressed in kilowatts (kw.) available at the terminals at a specified voltage.

4221. Rating of Alternators.— The rating of alternators shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified voltage and power factor.

4222.* Rating of Motors. — It is strongly recommended that the rating

(4222) Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horsepower.

notors shall be expressed in kilowatts (kw.) available at the shaft. (An exception to this rule is made in the case of railway motors, which, for some purposes, re also rated by their *input*.) See § 5203.

4333. Rating of Auxiliary Machinery. — Auxiliary machinery, such as regulators, balancer sets, synchronous-condensers, etc., shall have their ratings appropriately expressed. It is also essential to specify the voltage (and frequency, a-c.), of the circuits on which the machinery may appropriately be used.

Limitations Other than Temperature Rise

4350.* Mechanical Limitations. — *(a) *General:* All types of rotating achines shall be so constructed that they will safely withstand an over-speed 25 per cent, except in the case of steam turbines, which, when equipped with nergency governors, shall be constructed to withstand 20 per cent over-speed.
(b) *Generators:* Water-wheel generators shall be constructed for the maximum runaway speed which can be attained by the combined unit.
(c) *Motors:* Motors for continuous service shall, except when otherwise ecified, be required to develop running torque at least 175 per cent of that rresponding to the running torque at their rated load, without stalling. bviously, duty-cycle machines must carry their peak loads without stalling.

4351. Commutation Limitations. — (a) *Continuously Rated Machines:* Continuously rated machines shall be required to commutate successfully momentary ads of 150 per cent of the amperes corresponding to the continuous rating, keeping e rheostat set for rated-load excitation. Successful commutation is such that ither brushes nor commutator are injured by the test. See §§ 2220 and 5203.

(b) *Machines for Duty-cycle Operation:* Machines for duty-cycle operation th widely fluctuating loads shall commutate successfully under their specified erating conditions. See §§ 2222 and 2223.

4352. Limitations of Stability. — Continuously rated machines shall be quired to carry momentary loads of 150 per cent of the amperes corresponding the continuous rating, keeping the rheostat set for rated-load excitation.
In the case of direct-connected generators, this clause is not to be interpreted requiring the prime mover to drive the generator at this overload.

TESTS

Ambient Temperature

4300. Measurement of the Ambient Temperature During Tests of Machines. (See § 2300) (a) *Machines Cooled by Forced Draught:* In the testing of rotating achines, cooled by forced draught, a conventional weighted mean shall be ployed, a weight of four being given to the temperature of the circulating air pplied through ducts and a weight of one to the surrounding room air. See oo Note.

(b) *Machines Below Floor Line:* Where machines are partly below the floor e in pits, the temperature of the rotor shall be referred to a weighted mean of pit and room temperatures, the weight of each being based on the relative portions of the rotor in and above the pit. Parts of the stator constantly in pit shall be referred to the ambient temperature in the pit.

Machine Temperatures

4316. Machines with Small Ventilating Apertures. — Machines having ventiing openings smaller than 0.02 sq. in. (0.13 sq. cm.) in area, when intended to operated in locations or under conditions where the openings are liable to ome clogged, should be considered as totally enclosed machines and tested as

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wever, on account of the hitherto prevailing practise of expressing mechanical output orsepower, it is recommended that for machinery of this class the rating should, for present, be expressed both in kilowatts and in horsepower; as follows:

Kw.————Approx. equiv. h.p.————

or the purposes of these rules the horsepower shall be taken as 746.0 watts.
n order to lay stress upon the preferred future basis, it is desirable that on rating tes, the rating in kilowatts shall be shown in larger and more prominent characters a the rating in horsepower.
One kilowatt is equal to 102 kilogrammeters per second.
4250 a) In the case of series motors, it is impracticable to specify percentage values the guaranteed overspeed, on account of the varying service conditions.

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such with openings closed, and in all cases the rating on this basis should be indicated on the rating plate.

4319. Exception to Temperature Limits Used in Method 1. — In the case of enclosed motors and generators, the limits of the observable temperature rise shall be 5° C. higher than allowed by the general rule. This rule does not apply to those types of machines defined in §§ 4043, 4045 and 4046.

4320. Exception to Temperature Limits Used in Method 2. — In the case of enclosed motors and generators, the limits of the observable temperature rise shall be 5° C. higher than allowed by the general rule. This rule does not apply to those types of machines defined in §§ 4043, 4045 and 4046.

4321. Method of Temperature Measurement Used in Determining Temperature of Stators of Machines. — Method 3 should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) or over. It should also be applied to all machines of 5000 volts or more, if rated over 500 kv-a., regardless of core width.

Efficiency

4324.* Classification of Losses. — Losses are classified as shown in Table 401.

4325.* Losses to be Considered in Machines. — Conventional efficiency shall be based upon the losses listed in Table 402, and these losses shall be measured as specified in §§ 4336–4342 inclusive.

TABLE 401

Classification of Losses in Machinery

Accurately Measurable	Approximately Measurable or Determinable	Indeterminable
No-load core losses including eddy-current losses in conductors at no-load	Brush Friction loss	Iron loss due to distortion
Load I^2R losses in windings No-load I^2R losses in windings	Brush-contact loss	Eddy-current loss conductors due transverse flux caused by the currents
	Losses due to windage and to bearing friction	Eddy-current loss conductors due tooth saturation resulting from distortion of the main
		Tooth-frequency loss due to flux distortion under load
	Dielectric losses	Short-circuit loss commutation

(4334) The losses in constant-potential machinery, either of the stationary type or the constant-speed rotary type, are of two classes; namely, those which remain essentially constant at all loads, and those which vary with the load. The former include core losses, windage and friction, also I^2R losses in any shunt windings. The latter include losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no load, deducting any series I^2R losses. The total loss at any load may be computed from the measured resistance of the armature and the given load current.

4336. I^2R Loss. — (a) *General:* The I^2R loss shall be based upon the current d the measured resistance.

(b) *Polyphase Induction-motor Rotor:* The I^2R loss in the rotors of polyphase luction motors should be determined from the slip, whenever the latter is curately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{output} \times \text{slip}}{1 - \text{slip}}.$$

TABLE 402

Losses in Rotating Electric Machines

(References are to Sections)

	I^2R loss windings	Friction and windage	Brush friction	Core loss	Brush contact I^2R loss	Stray load losses	Miscellaneous losses when present
-C. commutating machines (Note 1)	4336(a)	4337(a)	4338	4339	4341 5341	Note 5	4343(a)(b)(c)
-C. commutating machines (Note 1)	4336(a)	4337(a)	4338	4339	4341	Note 5 5339	4343(b)
ailway motors	4336(a)	5337 5338	5338 5339	5339	4341	Note 5 5339	4343(b)
nchronous motors and enerators (Note 4)	4336(a)	4337(a)	4338 Note 3	4339 4339	4341 Note 3	4342(a)	4343(a)(b)(c)
nchronous converters	4336(c)	4337(a)	4338	4339(a) 4339(b)		Note 5	4343(a)
duction machines	4336(b)	4337(a)	4338	4339(a) 4339(c)	4341 Note 2	4342(b)	4343(b)

otes: (1) Except railway motors.

) When there are collector rings.

) Brush friction and brush contact losses are negligible except in the case of revolv- rmature machines.

) For the booster type of synchronous converter, where the booster forms an integral of the unit, its losses shall be included in the total converter losses in estimating the iency.

) These losses, while usually of low magnitude, are erratic, and the Institute is not his time prepared to make recommendations for approximating them.

large slip-ring motors, in which the slip cannot be directly measured by ling, the rotor I^2R loss shall be determined by direct resistance measure- it; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}.$$

(335) This simple method of determining the losses and hence the efficiency is only roximate, since the losses which are assumed to be constant do actually vary to some nt with the load, and also because the actual loss in the copper windings is sometimes reciably greater than the calculated I^2R loss. The difference between the approximate es, as above determined, and the actual losses, is termed "stray-load losses." These r are due to distortions in electric or magnetic fluxes from their no-load distributions values, brought about by the load current. They are usually only approximately surable, or may be indeterminable, but certain of them reach values in various kinds achinery, which require that they should be taken into account.

lectric losses are usually negligible.

he stray-load losses include the items in the column of Table 401 headed "Indeter- able" but do not include the increased core losses due to increased excitation for resating internal drop under load.

This equation applies to three-phase rotors. For rotors wound for two-pha use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 kw. or lar The factor K usually decreases as the size of motor is reduced, but no gen value can be stated for smaller sizes.

(c) *Synchronous Converters:* The I^2R losses in the armature winding shall derived from those corresponding to its use as a direct-current generator, by us suitable factors.

4337. Bearing Friction and Windage. — (a) *General:* Drive the machine tr an independent motor, the output of which shall be suitably determined. T machine under test shall have its brushes removed and shall not be excit This output represents the bearing friction and windage of the machine us test.

(b) *Induction Motors:* The bearing friction and windage of induction mot may be measured by running motors free at the lowest voltage at which th will rotate continuously at approximately rated speed; the watts input, mi I^2R loss, under these conditions being taken as the friction and windage.

(c) *Engine-type Generators:* In the case of engine-type generators (see § 433 the windage and bearing friction loss is ordinarily very small, amounting to fraction of one per cent of the output. This loss shall be neglected owing to small value and the difficulty of measuring it.

(d) *D. C. Railway Motors:* See § 5337.

4338. Brush Friction of Commutator and Collector Rings.—(a) *Gener* Drive the machine from an independent motor, the output of which shall suitably determined. The brushes shall be in contact with the commutator collector rings, but the machine shall not be excited. The difference between t output obtained in the test in § 4337 and this output shall be taken as the bru friction. The surfaces of the commutator and brushes should be smooth a glazed from running when this test is made.

(b) *D. C. Railway Motors:* See § 5338.

4339. Core Losses. — (a) *General:* Drive the machine from an independe motor, the output of which shall be suitably determined. The brushes shall in contact, and the machine shall be excited, so as to produce at the terminal voltage corresponding to the calculated internal voltage for the load un consideration. The difference between the output obtained by this test and th obtained by test under § 4338 (a) shall be taken as the core loss.

(b) *Synchronous Machines:* The internal voltage of synchronous machi shall be determined by correcting the terminal voltage for the resistance dr only.

(c) *Induction Motors:* The core loss of an induction motor may be determi by measuring the watts input to the motor when running free at rated volta and frequency and subtracting therefrom the no-load copper loss, bearing fri tion and windage.

(d) *D. C. Railway Motors:* See § 5339.

4341.* Brush-contact I^2R Loss. — (a) *General:* One volt drop per brus shall be considered as the Institute standard drop corresponding to the I^2 brush-contact loss, for carbon and graphite brushes with pigtails attache

(4341) The brush-contact I^2R loss depends largely upon the material of which th brush is composed.

As indicating the range of variation the following table will be of interest:

TABLE 403
Brush-contact Drop

Grade of brush	Volts drop across one brush-contact (Average of positive and negative brushes)
Hard carbon	1.1
Soft carbon	0.9
Graphite	0.5 to 0.8
Metal-graphite types	0.15 to 0.5 (The former for largest proportion of metal)

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and one-half volts per brush shall be allowed where pigtails are not attached. al-graphite brushes shall be considered as special.

) *Automobile Motors:* See § 5341.

342.* Stray Load-losses.—(a) *Synchronous Machines:* These include iron s, and eddy-current losses in the copper, due to fluxes varying with load also to saturation.

ray load-losses shall be determined by operating the machine on short uit and at rated-load current. This, after deducting the windage and ion and I^2R loss, gives the stray load-loss for polyphase generators and ors. These losses in single-phase machines are large; but the Institute is yet prepared to specify a method for measuring them.

) *Induction Machines:* These include eddy-current losses in the stator ver, and other eddy-current losses due to fluxes varying with the load. In lings consisting of relatively small conductors, these eddy-current losses usually negligible.

Vith rotor removed, measure the power input to the stator with different ies of current at the rated frequency. The curve plotted with these values s the combined I^2R and stray load-losses due to eddy-currents in the stator ver. Deduct the I^2R loss determined from the resistance, and the differ- will represent the stray load-losses corresponding to the various currents. ile this method is not accurate for some types of motors it usually represents efficiently good approximation.

343. Miscellaneous Losses. — (a) *Field-rheostat Losses:* Field-rheostat es shall be included in the generator losses where there is a field rheostat in es with the field magnets of the generator, even when the machine is sepa- ly excited.

) *Ventilating Blower:* When a blower is supplied as part of a machine set, power required to drive it shall be charged against the complete unit, but not nst the machine alone.

) *Other Auxiliary Apparatus:* Auxiliary apparatus, such as a separate ter for a generator or motor, shall have its losses charged against the plant hich the generator and exciter are a part, and not against the generator. exception should be noted in the case of turbo-generator sets with direct- nected exciters, in which case the losses in the exciter shall be charged against generator. The actual energy of excitation and the field-rheostat losses, if , shall be charged against the generator. See § 4343 (a).

Wave Shape

351. Deviation Factor of a Wave. — The deviation factor of the open circuit minal voltage wave of synchronous machines shall not exceed ten per cent ess otherwise specified. See § 3274.

352. Telephone Interference Factor of a Wave. — (For trial only.) (See 178.) — (a) *Conditions of Test.* The weighting of the sine-wave components lifferent frequencies shall be as given in Fig. 4-1.

he telephone interference factor of a voltage wave, corresponding to this ghting, may be measured by the use of the network shown in Fig. 4-2.

Vith this network the telephone interference factor of a voltage wave is the o of the current I in micro-amperes in the meter branch of the network to voltage E applied to the external terminals of the network. The measure- nt may be made on the low-tension side of a potential transformer. A sensi- vacuum thermo-couple provided with a shunt, and a direct-current mil- meter have been found convenient for measuring the current.

b) The appropriate limiting value of the telephone interference factor of a re (see §3278), either for machines or for circuits, has not yet been determined, l cannot now be specified. The whole matter of interference, including

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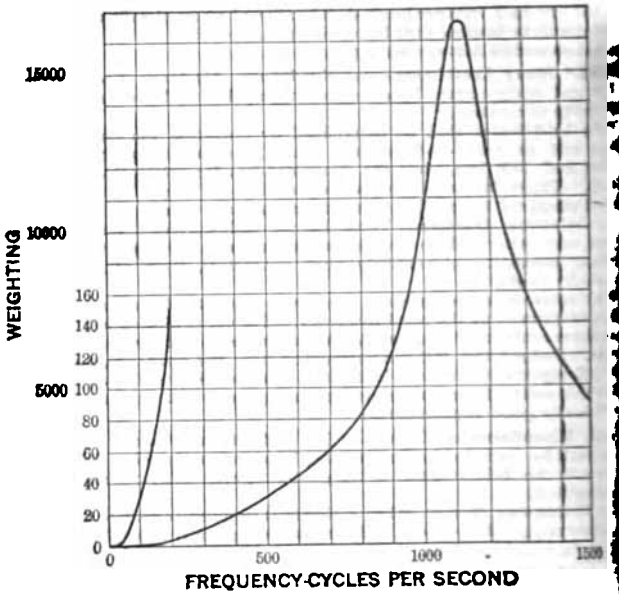
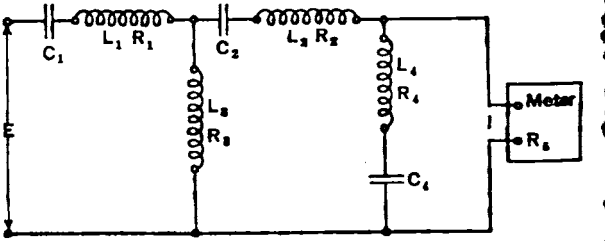


Fig. 4-1



Network Constants

$C_1 = 0.0$ mf.	$L_1 = 0.023$ henry	$R_1 = 5$ ohms $\pm 2\%$
$C_2 = 0.9$ "	$L_2 = 0.0205$ "	$R_2 = 12$ " $\pm 2\%$
$\pm 0.5\%$	$\pm 0.5\%$ $L_3 = 0.068$ "	$\pm 0.5\%$ $R_3 = 73$ " $\pm 1\%$
$C_4 = 7.5$ "	$L_4 = 0.019$ "	$R_4 = 22.5$ " $\pm 2\%$
		$R_5 = 43$ " $\pm 1\%$

Fig. 4-2

Tests of Dielectric Strength

4358. Frequency of Test Voltage. — In d-c. machines, and in general commercial application of a-c. machines, the testing frequency of 60 cycles per second is recommended.

4361.* Exceptions to Standard Test Voltage Given in Section 2286.

(a) *Field Windings of Alternating-current Generators:* Field windings of alternating-current generators shall be tested with 10 times the exciter voltage, but in no case with less than 1500 volts nor more than 3500 volts.

(b) *Field Windings of Synchronous Machines:* Field windings of synchron- machines including motors and converters which are to be started with alter- ing current are to be tested as follows:
When machines are to be started with field short-circuited, the field windings ll be tested as specified in § 4361 (a).
When machines are to be started with fields open-circuited and sectionalized ile starting, the field windings shall be tested with 5000 volts.
When machines are to be started with fields open-circuited and connected all eries while starting, the windings shall be tested with 5000 volts for less than volts excitation and 8000 volts for excitation of 275 volts to 750 volts.
(c) *Phase-wound Rotors of Induction Motor:* The secondary windings of ind rotors of induction motors shall be tested with twice their normal induced tage, plus 1000 volts. When induction motors with phase-wound rotors are be reversed, while running at approximately normal speed, by reversing the nary connections, the test shall be four times the normal induced voltage s 1000 volts.
d) *Small Motors and Generators:* Small machines taking not over 660 watts aving an output not exceeding ½ h. p. (373 watts), such as fractional horse- er motors, and intended solely for operation on supply circuits not exceeding volts, shall be tested with 900 volts.
e) *Alternating-current Machines Connected to Permanently Grounded Single- se Systems:* Alternating-current machines connected to permanently unded single-phase systems, for use on permanently grounded circuits operat- at more than 300 volts shall be tested with 2.73 times the voltage of the uit to ground, plus 1000 volts. This does not refer to three-phase machines i grounded star neutral.
(f) *Machines for Use on Circuits of 25 Volts or Lower:* Machines for use on uits of 25 volts or lower, such as bell-ringing apparatus, electric machines l in automobiles, machines used on low-voltage battery circuits, etc., shall ested with 500 volts.

Regulation

390. Conditions for Tests of Regulation (see § 2390). — (a) *Power Factor:* alternating-current generators the power factor of the load to which the ulation refers should be specified. Unless otherwise specified, it shall be erstood as referring to non-inductive load, that is, to a load in which the ent is in phase with the e.m.f. at the terminals of the machine.
) *Excitation:* In commutating machines, rectifying machines and syn- nous machines, the regulation shall be determined under such conditions e maintain the field adjustment constant at a value which gives rated-load age at rated-load current. These conditions are as follows:
i the case of separately excited fields: constant excitation.
i the case of shunt machines: constant resistance in the shunt-field circuit.
i the case of series or compound machines: constant resistance shunting the es field windings.

391.* Tests and Computation of Regulation of A-C. Generators. — (a) *hods Available:* The regulation of alternating-current generators may be rmined by any one of the three following methods, which are given in the er of preference:
) *Method I. By Loading:* The regulation can be measured directly, by ing the generator at the specified output and power factor, then reducing load to zero, and measuring the terminal voltage, with speed and excitation ained to the same values as before the change. This method is not generally licable for shop tests, particularly on large generators and it becomes neces- to determine the regulation from such other tests as can be readily made.
(c) *Method II. From Test Curves:* This method consists in computing the

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361 b) Series-field windings should be regarded as part of the armature circuit and ed as such.
361 c) By normal induced voltage is here meant the voltage between slip rings on circuit at standstill with normal voltage impressed on the primary.
361 f) The present National Electrical Code limit for a single outlet is 660 watts.
391 c) Method II for deducing the load-saturation curve, at any assigned power

regulation from experimental data of the open-circuit saturation curves and the zero-power-factor saturation curve. The latter curve, or one approximating very closely to it, can be obtained by over-exciting the generator while carrying a load of idle-running under-excited synchronous motors. The power factor under these conditions is very low and the load-saturation curve approximates very closely the zero-power-factor saturation curve. From this curve and the open-circuit curve, points for the load-saturation curve for any specified power factor can be obtained by means of vector diagrams.

regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.

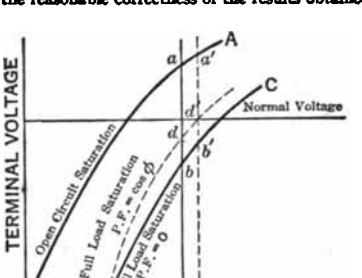


Fig. 4-3

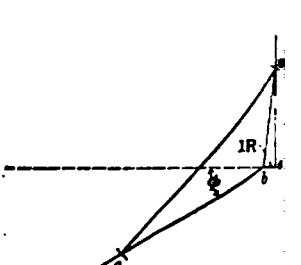


Fig. 4-4

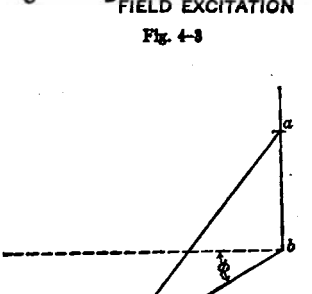


Fig. 4-5

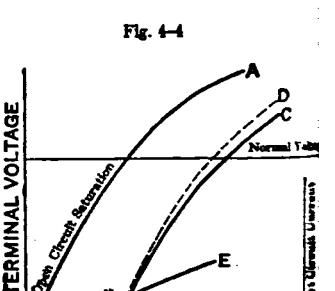


Fig. 4-6

To apply Method II, it is necessary to obtain from test the open-circuit saturation curve Fig. 4-3, and the load-saturation curve $B\,C$ at zero power factor and rated-load current. At any given excitation $O\,c$, the voltage that would be induced on open circuit is $c\,a$; the terminal voltage at zero power factor is $c\,b$ and the apparent internal drop is $a\,b$. The terminal voltage $c\,d$ at any other power factor can then be found by drawing an exact diagram as in Fig. 4-4, where ϕ is an angle such that $\cos\phi$ is the power factor of the load, $b\,e$ the resistance drop ($I\,R$) in the stator winding, $b\,a$ the total internal drop and $a\,c$ the total induced voltage; $b\,a$ and $a\,c$ being laid off to correspond with the values obtained from Fig. 4-3. The terminal voltage at power factor $\cos\phi$ is then c-b Fig. 4-4, which when laid off in Fig. 4-3 gives point d. By finding a number of such points, the curve $B\,d\,d'$ for power factor $\cos\phi$ is obtained and the regulation at this power factor (expressed in per cent) is $\frac{100\times a'\,d'}{c'\,d'}$ since $a'\,d'$ is the rise in voltage when the load at power factor $\cos\phi$ is thrown off at normal voltage $c'\,d'$.

Generally, the ohmic drop can be neglected as it has little influence on the regulation.

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(d) *Method III. From Estimated Zero-power-factor Curve.* Where it is not sible to obtain by test a zero-power-factor curve as in Method II this curve be estimated closely from open-circuit and short-circuit curves, by reference tests at zero power factor on other machines of similar magnetic circuit. ving obtained the estimated zero-power-factor curve, the load saturation for other power factor is obtained as in Method II, § 4394 (c).

396. Compound Wound D-C. Generator. — In determining the regulation compound-wound d-c. generator, two tests shall be made, one bringing the d down and the other bringing the load up, between no-load and rated load. ese may differ somewhat, owing to residual magnetism. The mean of the results shall be used.

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s where regulation at unity power factor is being estimated. For low power factors effect is negligible in practically all cases. If resistance is neglected, the simpler gram Fig. 4-5, may be used.

4394 d) Method III is the same as Method II except that the zero-power-factor curve st be estimated. This may be done as follows. In Fig. 4-6, $O A$ is the open-circuit ration curve and $O E$ the short-circuit line as obtained from test. The zero-power- or curve corresponding to any current $B F$ will start from point B, and for machines gned with low saturation and low reactance, will follow parallel to $O A$ as shown by dotted curve $B D$, which is $O A$ shifted horizontally parallel to itself by the distance . In high-speed machines, or in others having low reactance, and a low degree of ration in the magnetic circuit, the zero-power-factor curve will be quite close to $B D$ ticularly in those parts that are used for determining the regulation. This is the case h many turbo-generators and high-speed water-wheel generators.

n many cases, however, the zero-power-factor curve will deviate from $B D$, as shown by and the deviation will be most pronounced in machines of high reactance, high satura- and large magnetic leakage. The position of curve $B C$ with relation to $B D$ can be roximated with sufficient exactness by investigating the corresponding relation as ained by test at zero power factor on machines of similar characteristics and magnetic uit. Curve $B C$ can also be calculated by methods based on the results of test at power factor. After curve $B C$ has been obtained, the load-saturation curve and lation for any other power factor can be derived as in Method II, § 4394 (c).

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CHAPTER V

STANDARDS FOR ELECTRIC RAILWAYS AND FOR AUTOMOBILE PROPULSION MACHINES

The A. I. E. E. Standards for Electric Railways and for Automobile Propulsion Machines are the General Standards shown in Chapters II and III, and the Standards in other Chapters which are applicable to the devices involved, together with the modifications and extensions given in this Chapter.

DEFINITIONS

General

5000. Contact Conductors. — A contact conductor is that part of the distribution system other than the traffic rails, which is in immediate electrical contact with the circuits of the cars or locomotives.

Contact Rails

5003.* Contact Rail. — (a) *General:* A contact rail is a rigid contact conductor.

*(b) *Overhead Contact Rail:* An overhead contact rail is a contact rail which is above the elevation of the maximum equipment line.

(c) *Third Rail:* A third rail is a contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

(c) *Center Contact Rail:* A center contact rail is a contact conductor placed between the track rails, having its contact surface above the ground level.

(e) *Underground Contact Rail:* An underground contact rail is a contact conductor placed beneath the ground level.

(f) *Gage of Third Rail:* The gage of a third rail is the distance, measured parallel to the plane of running rails, between the gage line of the nearest track rail and the inside gage line of the contact surface of the third rail.

(g) *Elevation of Third Rail:* The elevation of a third rail is the elevation of the contact-surface of the third rail, with respect to the plane of the top of running rails.

(h) *Third Rail Protection:* A third rail protection is a guard for the purpose of preventing accidental contact with the third rail.

Trolley Wires

5004. Trolley Wire. — A trolley wire is a flexible contact conductor, customarily supported above the cars.

5005. Messenger Wire or Cable. — A messenger wire or cable is a wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

5006. Classes of Construction. — (a) *General:* Overhead trolley constructions are classed as *Direct Suspension* and *Messenger or Catenary Suspension.*

(b) *Direct Suspension:* A direct suspension is the form of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

(c) *Messenger or Catenary Suspension:* A messenger or catenary suspension is the form of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *Simple Catenary, i.e.,* by primary messengers, or in *Compound Catenary, i.e.,* by secondary messengers.

(5003 b) The maximum equipment line is the contour which embraces cross-sections of all rolling stock under all normal operating conditions.

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5027. Supporting Systems. — (a) *General:* Supporting systems for trolley res shall be classed as follows:

(b) *Simple Cross-Span Systems:* Simple cross-span systems are those having at each support a single flexible span across the track or tracks.

(c) *Messenger Cross-span Systems:* Messenger cross-span systems are those having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

(d) *Bracket Systems:* Bracket systems are those having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

(e) *Bridge Systems:* Bridge systems are those having at each support a rigid member, supported at both sides of the track or tracks.

5030.* Transmission System. — When the current generated for an electric ilway is changed in kind or voltage, between the generator and the cars or omotives, that portion of the conductor system carrying current of a kind or ltage substantially different from that received by the cars or locomotives, nstitutes the *transmission system.*

5031.* Distribution System. — That portion of the conductor system of an ctric railway which carries current of the kind and voltage received by the cars locomotives, constitutes the *distribution system.*

5032. Substation. — A substation is a group of apparatus or machinery hich receives current from a transmission system, changes its kind or voltage, d delivers it to a distribution system.

OPERATION

Temperature Limits

5101.* Railway Motors in Continuous Service. — The following maximum bservable temperatures are permissible in the windings of railway motors, hen in continuous service.

TABLE 501

Temperatures of Railway Motors in Continuous Service

Class of material See § 1004	Temperature	
	By Thermometer See § 1002	By Resistance See § 1002
A	85° C.	110° C.
B	100° C.	130° C.

5120. Railway Substation Machines and Transformers. — Under conditions pecified in § 5201, the windings of railway substation machines and transformers carrying traction loads may have observable temperature rises 5° C. n excess of the limiting observable temperature rises specified in Table 200.

5130.* Automobile Propulsion Machines. — On stand test, the *observable* emperature rises shall not exceed the limits specified in § 5205.

RATING

Ratings of Railway Substation Machinery and Transformers

5201.* Nominal Rating of Railway Substation Machines and Transformers. — The nominal rating of a substation machine or transformer carrying traction

(5030 and 5031) These definitions are identical in sense, although not in words, with [illegible]

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loads shall be the kv-a. output at a stated power factor input, which, having produced a constant temperature in the machine or transformer, may be increased 50 per cent for two hours, without producing temperature rises exceeding by more than 5° C. the limiting values given in Table 200. These machine or transformers should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked "nominal rating."

Ratings of Railway Motors

5202.* Nominal Rating of Railway Motors. — The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90° C. at the commutator, and 75° C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance shall not exceed 100° C. The statement of the nominal rating shall include the corresponding voltage and armature speed.

5203.* Continuous Ratings of Railway Motors. — The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at ⅓, ½ and full voltage respectively, without exceeding the observable temperature rises specified in Table 502, when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

TABLE 502

Stand-test Temperature Rises of Railway Motors

Class of material See § 1004	Temperature rises of windings	
	By Thermometer See § 1002	By Resistance See § 1002
A	65° C.	85° C.
B	80° C.	105° C.

5204. Field-control Railway Motors. — The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

Ratings of Automobile Propulsion Machines

5205. Automobile Propulsion Machines. — The rating of automobile motors and generators shall be based upon temperature rise, on a stand test and with motor covers arranged as in service, fifteen degrees by thermometer or twenty-five degrees by resistance, above those of Table 200.

(5201 and 5202) In the absence of any specification as to the kind of rating the "nominal" rating shall be understood.

(5203) The temperature rise in service may be very different from that on stand-test. See § 5502 for the relation between stand-test and service temperatures as affected by ventilation.

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Ratings of Electric Locomotives

§210. Rating. — Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort and corresponding speeds.

§211. Weight on Drivers. — The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

§212. Nominal Tractive Effort. — The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their nominal (one-hour) rating.

§213. Continuous Tractive Effort. — The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in § 5203.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for ½ or ¾ voltage, but in such cases the voltage shall be clearly specified.

§214. Speed. — The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

TESTS

Efficiency

Losses in D-C. Railway Motors

§337. Losses in Gearing and Axle Bearings. — The losses in gearing and axle bearings for single-reduction single-geared motors, varies with the type, mechanical finish, age and lubrication. The following values, based upon accumulated tests, shall be used in the comparison of single-reduction single-geared motors § 5339.

TABLE 503

Losses in Axle Bearings and Single-reduction Gearing of Railway Motors

Per cent of input at nominal rating	Loses as per cent of input
200	3.5
150	3.0
125	2.7
100	2.5
75	2.5
60	2.7
50	3.2
40	4.4
30	6.7
25	8.5

Note. — Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

§338. Brush Friction, Armature-bearing Friction and Windage. — The brush friction, armature-bearing friction and windage shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. Drive the machine idle as a series motor on low voltage. The product of armature counter-

electromotive-force and amperes at any speed shall be the sum of the above losses at that speed. See § 5339.

5339.* No-load Core Loss, Brush Friction, Armature-bearing Friction and Windage. — The no-load core loss, brush friction, armature-bearing friction and windage shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

The no-load core loss is obtained by deducting from the total losses thus obtained the power required to drive the motor at corresponding speeds as determined under § 5338.

The core loss under load shall be assumed to have the values given in Table 504.

TABLE 504

Core Loss in D-C. Railway Motors at Various Loads

Per cent of input at nominal rating	Loss as per cent of no-load core loss
200	165
150	145
100	130
75	125
50	123
25 and under	122

Note. — With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above table.

5341. Automobile Motors. — When automobile motors are of low voltage, the great influence of brush-contact losses on the efficiency requires that these losses be determined experimentally for the type of brush used.

(5339) In comparing projected railway motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction, single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

TABLE 505

Approximate Losses in D-C. Railway Motors

Input in per cent of that at nominal rating	Losses as per cent of input
100 or over	5.0
75	5.0
60	5.3
50	6.5
40	8.8
30	13.3
25	17.0

The core loss of railway motors may also be determined as specified for other machines.

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CHARACTERISTIC CURVES OF RAILWAY MOTORS

[illegible] General. — The Characteristic Curves of railway motors shall be [illegible]etted with the current as abscissas and the tractive effort, speed and efficiency [illegible]ordinates. In the case of a-c. motors, the power factor shall also be plotted [illegible]ordinates.

[illegible] Voltage. — Characteristic curves of direct-current motors shall be based on full voltage, which shall be taken as 600 volts, or a multiple thereof.

[illegible] Field-Control Motors. — In the case of field-control motors, characteristic curves shall be given for all operating field connections.

SELECTION OF RAILWAY MOTOR FOR SPECIFIED SERVICE

[illegible] Data Required in Selecting Motor. — The following information, relative to the service to be performed, is required, in order that an appropriate motor may be selected.

(a) Weight of total number of cars in train (in tons of 2000 lb.) exclusive of electrical equipment and load.
(b) Average weight of load and durations of same, and maximum weight of load and durations of same.
(c) Number of motor cars or locomotives in train, and number of trailer cars in train.
(d) Diameter of driving wheels.
(e) Weight on driving wheels, exclusive of electrical equipment.
(f) Number of motors per motor car.
(g) Voltage at train with power on the motors—average, maximum and minimum.
(h) Rate of acceleration in miles per hour per second.
(i) Rate of braking (in miles per hour per second).
(j) Speed limitations, if any (including slowdowns).
(k) Distances between stopping points.
(l) Average duration of stops.
(m) Schedule speed, including stops, in miles per hour.
(n) Train resistance in pounds per ton of 2000 pounds at stated speeds.
(o) Moment of inertia of revolving parts, exclusive of electrical equipment.
(p) Profile and alignment of track.
(q) Distance coasted as a percentage of the distance between stopping points.
(r) Duration of layover at end of run, if any.

[illegible] Method of Comparing Motor Capacity with Service Requirements. When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature from the stand-tests.

The essential motor losses affecting temperatures in service are those in the armature windings, core and commutator. The mean service conditions may be assumed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average service.

[illegible]3027] Calculation for comparing motor capacity with service requirements. The rating of a motor should be determined, wherever possible, by testing it in service, or on an equivalent duty-cycle. When the service or equivalent duty-cycle tests are not available, the ratings of the motor may be utilized as follows to determine its temperature rise.

The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current, the latter vary with the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty-cycle which the motor is to perform, and calculate from these the root-mean-square current and the average core loss.

If the calculated r.m.s. service current exceeds the continuous rating, when run with average service core loss and speed, the motor is not sufficiently powerful for the duty-cycle contemplated.

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A stand-test with the current and voltage which will give losses equal to those in service, will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor (§ 4044), well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 per cent (depending upon the character of the service) of the temperature rise obtained on a stand-test with the motor completely enclosed and with the same losses. With a ventilated motor (§ 4045 and § 4047) the temperature rise in service will be 90 to 100 per cent of the temperature rise obtained on a stand-test with the same losses.

In making a stand-test to determine the temperature rise in a specific service it is essential in the case of a self-ventilated motor (§ 4046) to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

CONSTRUCTION

5601.* Standard Height of Trolley Wire on Street and Interurban Railways. — It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 feet (5.5 m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings with steam roads, it is recommended that the trolley wire shall be not less than 21 feet (6.4 m.) above the top of rail, under conditions of maximum sag.

5602. Standard Gage of Third Rails. — The gage of third rails shall be not less than 26 inches (66 cm.) and not more than 27 inches (68.6 cm.).

5603. Standard Elevation of Third Rails. — The elevation of third rails shall not be less than 2¾ inches (7 cm.) and not more than 3½ inches (8.9 cm.).

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(c) If the calculated r.m.s. service current does not exceed the continuous rating, the motor will run with average service core loss and speed, the motor is ordinarily suitable for the service.

In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to compute the equivalent voltage which, with the r.m.s. current, will produce the average core loss. Having obtained this, determine as follows, the temperature rise due to the r.m.s. service current and equivalent voltage:

Let θ_0 = temperature rise
$p_0 = I^2R$ loss, kw.
p_c = core loss, kw.
} with r.m.s. service current, and equivalent service voltage.

θ_s = temperature rise
$P_0 = I^2R$ loss, kw.
P_c = core loss, kw.
} with continuous load current corresponding to the equivalent service voltage.

Then

$$\theta = \theta_s \frac{p_0 + p_c}{P_0 + P_c}, \text{ approximately.}$$

(d) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one-hour test starting at ambient temperature.

(e) Consider any period of peak load and determine the electrical losses in kilowatt hours during that period from the *electrical* efficiency curve. Find the excess of these losses over the losses with r.m.s. service current and equivalent voltage. The excess is divided by the coefficient of thermal capacity, will equal the extra temperature rise during the peak load. This temperature rise added to that due to the r.m.s. service current and equivalent voltage, gives the total temperature rise. If the total temperature rise in such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

(f) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty-cycle.

(5601) A. E. R. A. Standard.

Foreign

Engineering Standards Committee of Great Britain: Standardization Rules Electrical Machinery (exclusive of motors for traction purposes). Standard thod of Specifying the Resistance of Steel Conductor Rails; Standard for ley Groove and Wire.
Verband Deutscher Electrotechniker: Normalien.

CHAPTER VI

STANDARDS FOR TRANSFORMERS AND OTHER STATIONARY INDUCTION APPARATUS

Wherever the General Standards in Chapters II and III apply to transformers r are referred to in the following Chapter by cross references.
Certain rules applying exclusively to railway machinery have, for convenience, n placed in Chapter V with cross references in all case to this Chapter. es in Chapter VI apply to railway machinery except as they are modified he rules in Chapter V.
Note: The word "Transformer" will be used throughout this Chapter as abbreviation of "Transformer or other stationary induction apparatus."

DEFINITIONS

Apparatus

100. Stationary Induction Apparatus. — For the purpose of these Standards, onary induction apparatus is defined as electric apparatus which changes ric energy to electric energy through the medium of magnetic energy, with- mechanical motion. It comprises several forms, as defined in §§ 6001 and 2 to 6015.

101. Transformer. — A transformer is a form of stationary induction appa- s in which the primary and secondary windings are ordinarily insulated one n another.

110. Auto-transformer. — An auto-transformer is one which has a part of urns common to both primary and secondary circuits.

111. Voltage-regulator. — A voltage-regulator is a form of stationary uction apparatus which has turns in shunt and turns in series with the circuit, rranged that the voltage ratio of the transformation, or the phase relation reen the circuit-voltages, is variable at will.

112. Contact Voltage-regulator. — A contact voltage-regulator is a voltage lator in which the number of turns in one or both of the coils is adjustable.

113. Induction Voltage-regulator. — An induction voltage-regulator is one hich the relative position of the primary and secondary coils is adjustable.

114. Magneto Voltage-regulator. — A magneto voltage-regulator is one in h the direction of the magnetic flux with respect to the coils is adjustable.

115. Reactor. — A reactor is a device used primarily because it possesses roperty of reactance. Reactors are used in electric circuits for purposes of ation, protection or control.

Parts of Apparatus

120. High-voltage and Low-voltage Winding. — The terms "high voltage" "low voltage" are used to distinguish the winding having the greater from having the lesser number of turns.

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6021. Primary and Secondary Windings. — The terms "primary" a "secondary" serve to distinguish the windings in regard to energy flow, t primary being that which receives the energy from the supply circuit, and t secondary that which receives the energy by induction from the primary.

6022. Full Capacity Tap.—A full capacity tap is a tap from a transfor winding on which the unit may be operated at rated kv-a. capacity with exceeding the specified temperature rise.

6023. Reduced Capacity Tap.—A reduced capacity tap is one on which t unit may not be operated at full capacity without exceeding the specified tem erature rise.

Properties of Apparatus

6031. Rated Current of a Constant-potential Transformer. — The rated c rent of a constant-potential transformer is that secondary current which, m plied by the rated-load secondary voltage, gives the kv-a. rated output. T is, a transformer of given kv-a. rating must be capable of delivering the r output at rated secondary voltage, while the primary impressed voltag increased to whatever value is necessary to give rated secondary voltage.

6032. Full or Reduced Capacity Taps.—Where transformers are provi with taps from either the high-voltage or low-voltage windings, a definite st ment shall be made as to whether such are full capacity or reduced capacity t

6033. Rated Primary Voltage of a Constant-potential Transformer. — T rated primary voltage of a constant-potential transformer is the rated secon voltage multiplied by the turn ratio.

6034. Ratio of a Transformer. — The ratio of a transformer, unless other specified, shall be the ratio of the number of turns in the high-voltage win to that in the low-voltage winding; *i.e.*, the "turn-ratio."

6035. Voltage Ratio of a Transformer. — The voltage ratio of a transfo the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary te voltage, under specified conditions of load.

6036. Current Ratio of a Transformer. — The current ratio of a tra transformer is the ratio of the r.m.s. primary current to the r.m.s. secon current, under specified conditions of load.

6037. Volt-ampere Ratio of Transformer. — The volt-ampere ratio, w should not be confused with real efficiency, is the ratio of the volt-ampere ou to the volt-ampere input of a transformer at any given power factor.

6050.* Per Cent Resistance Drop. — The per cent resistance drop in a tra former is the ratio of the internal resistance drop at 75° C. to the secon terminal voltage expressed in per cent.

6051.* Per Cent Reactance Drop. — The per cent reactance drop in a tra former is the ratio of the internal reactance drop to the secondary termi voltage expressed in per cent.

6052.* Per Cent Impedance Drop. — The per cent impedance drop in a tra former is the ratio of the internal impedance drop at 75° C. to the secon terminal voltage expressed in per cent.

6053. Regulation of Constant-Potential Transformer. — In constant-po tial transformers, the regulation is the difference between the no-load and fu load values of the secondary terminal voltage at the specified power fa (with constant primary impressed terminal voltage) expressed in per cent rated-load secondary voltage, the primary voltage being adjusted to th value that the apparatus delivers rated output at rated secondary volt See § 6390.

Ambient Temperature. — See § 3000.

(6050-6051-6052) The internal drop in a transformer is the sum of the primary d (reduced to secondary terms) and the secondary drop.

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RATING

General

6201 TABLE 601

Limiting Observable Temperatures and Temperature Rises for Transformers Using Class A* Insulation

	†Air cooled and air blast	Oil cooled	Water cooled
Limiting observable temperature	95° C.	95° C.	80° C.
Standard ambient temperature	40° C.	40° C.	25° C.
Limiting observable temperature rise	55° C.	55° C.	55° C.

* For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of the observable temperature rise shall be 15° C. below the limits fixed for these materials when impregnated.

† For exceptions in the case of Airblast Transformers, see § 6320 (b).

The temperature of the windings of transformers is always to be ascertained by Method 2.

6202. Limiting Observable Temperature of Oil (From § 2232). — The oil in which apparatus is permanently immersed shall, in no part, have a temperature, observable by thermometer, in excess of 90° C.

Permissible Temperatures of Insulations of More than One Class. — See § 2104.

Temperatures of Metallic Parts of Transformers. — See § 2116.

Protection Against Short Circuit. — See § 2120.

Nominal Rating of Railway Substation Transformers. — See § 5201.

Expression of Rating. — See § 2202.

Institute Rating. — See § 2204.

6204.* Rating of Protective Reactors. — Protective reactors shall be rated on the following characteristics:

(a) Kilovolt-amperes absorbed by normal current.

(b) Normal current, frequency and line (delta) voltage.

(c) Current which the device is required to stand under short-circuit conditions.

Ambient Temperature of Reference

Ambient Temperature of Reference for Air. — See § 2211.

Ambient Temperature of Reference for Water-cooled Transformers. — See § 2212.

Transformers Cooled by Other Means. — See § 2213.

Outdoor Transformers Exposed to Sun's Rays. — See § 2214.

Altitude Correction

Altitude. — See § 2215.

6215. Exception to "Altitude." — See § 2215. — Water-cooled oil-immersed transformers are exempt from this reduction.

Units in Which Rating Shall be Expressed

6221. Rating of Transformers. — The rating of transformers shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified frequency and voltage.

6223. Rating of Other Stationary Induction Apparatus. — Other stationary induction apparatus, such as auto-transformers, regulators, reactors, etc., shall have their ratings appropriately expressed. It is also essential to specify the voltage and frequency of the circuits on which the apparatus may be used.

(6204) Reactors shall be so designed as to be capable of withstanding the sudden application, without mechanical injury, of rated current at normal frequency.

Kinds of Rating

Continuous Rating. — See § 2220.
Short-time Rating. — See § 2221.
Duty-cycle Operation. — See § 2222.
Standard Short-time Ratings. — See § 2223.
A. I. E. E. and I. E. C. Ratings. — See § 2224.
Continuous Rating Implied. — See § 2225.

6236. Nominal Ratings. — Nominal ratings are ratings which do not conform with §§ 2220 and 2221. They are sometimes used for railway substation transformers carrying traction loads. Transformers with nominal rating shall be capable of operating under the conditions enumerated in § 5201.

Rating by Temperature Rise

Permissible Temperature Rises for Various Ambient Temperatures above Standard. — See § 2231 (c).

TESTS

Ambient Temperature

Measurement of Ambient Temperatures during Tests of Transformers. — See § 2300.

6300. Measurement of the Ambient Temperature During Tests of Water-cooled Transformers. — The temperature rise of water-cooled transformers shall be based entirely upon the temperature of the cooling water and it is not necessary to take into account the heat carried off by the air, unless it exceeds the amount specified below. If, under assumed standard conditions of water at 25° C., and air at 40° C., the amount of heat which would be carried off by the air is 15 per cent or more of the total, the temperature of the cooling water, during test, should be maintained within 5° C. of that of the surrounding air. Where this is impracticable the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

Oil Cup. — See § 2301.

Transformer Temperatures

Temperature Rise for Any Ambient Temperature. — See § 2310.

Correction for the Duration of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference. — See § 2311.

6311.* Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test of Air-blast Transformers from the Standard Ambient Temperature of Reference. — A correction shall be applied to the observed temperature rise of the windings of air-blast transformers due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i.e.*, the ratio $274.5/(234.5+\theta)$; where θ is the ingoing cooling-air temperature.

Duration of Temperature Test of Transformers for Continuous Service. — See § 2312.

Duration of Temperature Test of Transformer with a Short-time Rating. — See § 2313.

Duration of Temperature Test for Transformer Having More than One Rating. — See § 2314.

Temperature Measurements During Heat Run. — See § 2315.

(6311) Thus, a cooling-air room temperature of 30° C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40° C. (274.5° inferred absolute temperature) would be $274.5/264.5 = 1.04$, making the correction factor 1.04; so that an observed temperature rise of say 50° C. at the testing ambient temperature of 30° C. would be corrected to $50 \times 1.04 = 52$° C., this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40° C.

§317. Methods of Loading Transformers for Temperature Tests. — (a) *General:* Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time. The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load. See §§ 2312 to 2314.

An approved method of making these tests is the *loading-back* method. The principal variations of this method are given in § 6317 (b), (c) and (d).

(b) *Loading-back with duplicate single-phase transformers:* Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions while the other may be operating under slightly abnormal conditions.

(c) *Loading-back with one three-phase transformer:* One three-phase transformer may be tested in a manner similar to § 6317 (b) provided the primary and secondary windings are each connected in delta for the test. Normal three-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

(d) *Loading-back with three single-phase transformers:* Duplicate single-phase transformers may be tested in banks of three in a manner similar to that described in § 6317 (c), by connecting both primary and secondary windings in delta, applying normal three-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.

(e) *Other Methods:* Among other methods that have a limited application and can be used only under special conditions may be mentioned:

Applying dead load by means of some form of rheostat.

Running alternately for certain short intervals of time on open circuit and then on short-circuit, alternating in this way until the transformer reaches a steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss as in normal operation.

§320. Method of Temperature Measurement. — (a) *Description:* The temperature of transformer windings shall be measured by their increase in resistance, corrected to the instant of shut-down when necessary, and by thermometers. Whichever measurement yields the higher temperature, that temperature shall be taken as the highest observable temperature by Method 2.

(b) In the case of air-blast transformers, it is important to have the thermometers well distributed and in good contact with the coils, and it is especially important to note the temperature near the air outlet. In measuring the temperature of air-blast transformers, the air supply shall be shut off immediately at the end of the temperature run and the air intake closed to prevent further admission of cooling air. With the above procedure, the observable temperature rise for air-blast transformers may attain a value not in excess of 40° C. as determined by thermometer, although it must not exceed 55° C. as determined by resistance.

(c) *Temperature Correction for Cooling of Transformer Windings after Shut-down:* Since a drop in temperature occurs in a winding between the instant of shut-down and the time of measuring the hot resistance, a correction shall be applied to the temperature determined from this measurement so as to obtain, as nearly as practicable, the temperature at the instant of shut-down. This correction may be determined approximately by plotting a time-temperature curve with temperatures as ordinates and times as abscissas and extrapolating back to the instant of shut-down.

In cases where successive measurements show increasing temperatures after shut-down the highest value shall be taken.

In certain cases, however, other correction factors may be applied as follows:

Oil-Immersed Transformers: For the purpose of simplifying the application of the rule to transformers when the weight of copper in each winding is known and the copper loss as determined by wattmeter measurement does not exceed 10 watts per pound, the extrapolation method has been reduced to the following

under ordinary conditions of testing. The correction in degrees C. shall be the product of the watts loss per pound of copper for each winding multiplied by a factor depending upon the time elapsed between shut-down and the time of the temperature reading as given in the following table:

Time in minutes	Factor
1	0.19
2	0.32
3	0.43
4	0.50

For intermediate times, the value of the factor can be obtained by interpolation.

When the copper loss, measured by wattmeter, does not exceed 7 watts per pound an arbitrary correction of one degree per minute may be used provided the time elapsed between the instant of shut-down and the measurement of the hot resistance does not exceed four minutes.

For determining the copper loss in watts per pound, the total loss in both windings as measured by the wattmeter should be apportioned between the high- and low-voltage windings in the same ratio as their respective I^2R losses.

Air-blast Transformers: An arbitrary correction of one degree per minute may be used provided the time elapsed between the instant of shut-down and the measurement of the hot resistance does not exceed four minutes.

(d) *Covering of Thermometers:* Thermometers used for taking the temperature of air-cooled or air-blast transformers shall have their bulbs covered for protection from air currents. This shall be done by felt pads, approximately 4 cm. × 5 cm. (1½ in. × 2 in.) and 3 mm. (⅛ in.) thick, except that where pads are inconvenient, as in ventilating ducts between coils, grooved wooden strips may be used.

Temperature Coefficient of Copper. — See § 2321.

Efficiency

Efficiencies Recognized. — See § 2331.

Normal Conditions for Efficiency Tests. — See § 2332.

Direct Measurement of Efficiency. — See § 2333.

6334. Classification of Losses. — (a) *General:* Losses are classified as shown below.

(b) *No-load Losses:* No-load losses include the core loss, the I^2R loss due to the exciting current and the dielectric loss in the insulation.

(c) *Load Losses:* Load losses include I^2R losses, and stray load-losses due to eddy-currents caused by fluxes varying with load.

6335. Losses to be Considered in Transformers. — Conventional efficiencies shall be based upon the losses listed in § 6334 and these losses shall be measured as specified in §§ 6336 and 6337.

6336. No-load Losses. — The no-load losses shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated-load conditions.

6337. Load Losses. — The load losses include I^2R and stray load-losses. They shall be measured by applying a primary voltage, at rated frequency, sufficient to produce rated load current in the windings, with the secondary windings short-circuited.

Wave Shape

Standard Wave Shape. — See § 2340.

Tests of Dielectric Strength

Condition of Transformers to be Tested. — See § 2350.

Where High-voltage Tests are to be Made. — See § 2351.

Temperatures at which High-voltage Tests are to be Made. — See § 2352.

Points of Application of Voltage. — See § 2353.

Frequency and Wave Form of Test Voltage. — See § 2354.

Duration of Application of Test Voltage. — See § 2355.

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[illegible]. Standard Test Voltage. — (From § 2356.) *General:* The standard
t voltage for all machines, except as otherwise specified, shall be twice the
mal voltage of the circuit to which the machine is connected plus 1000 volts.
exception § 6361.

360. Transformers for Star Connection. — Transformers which may be
d in star connection on three-phase circuits shall be tested on the basis of the
to line voltage for which they are rated. See § 6361(f).

361.* Exceptions to Standard Test Voltage Given in Section [illegible]. — (a)
tributing Transformers: Transformers for primary pressures from 550 to
volts, the secondaries of which are directly connected to consumer's cir-
s and commonly known as distributing transformers, shall be tested with
00 volts from primary to core and secondary combined. The secondary
dings shall be tested with twice their normal voltage plus 1000 volts.
) *Auto-transformers:* Auto-transformers used for starting purposes, shall
ested with the same voltage as the test voltage of the apparatus to which
are connected.
) *Household Devices:* Transformers taking not over 660 watts and intended
ly for operation on supply circuits not exceeding 275 volts, shall be tested
900 volts.
(d) *Transformers for Use on Circuits of 25 Volts or Lower:* Transformers for
on circuits of 25 volts or lower, such as bell-ringing apparatus, shall be
ed with 500 volts.
) *Alternating-current Transformers Connected to Permanently Grounded Single
e Systems, for use on Permanently Grounded Circuits of more than 300 Volts:*
nsformers used under these conditions shall be tested with 2.73 times the
age of the circuit to ground plus 1000 volts. This does not refer to three-
e transformers operating with grounded neutral.
) *Transformers to be used on Star-connected Three-phase Circuits:* Trans-
ers which may be used in star connection on three-phase circuits shall have
line to line (as distinguished from line to neutral) voltage of the circuits on
h they may be used indicated on the rating plate and the test shall be based
he line to line voltage. See § 6360.
) *Testing Transformers:* Rules do not apply to testing transformers, for
h no definite rule has yet been established.
) *Protective Reactors:* Protective reactors shall be tested from conductors
round with 2000 volts plus 2¼ times the line voltage.

[illegible].* Testing Transformers by Induced Voltage. — Under certain condi-
it is permissible to test transformers by inducing the required voltage in
windings in place of using a separate testing transformer. By "required
ge" is meant a voltage such that the line end of the winding shall receive
t to ground equal to that required by the general rules.

363. Transformers with Graded Insulation. — Where transformers have
ed insulation they shall be so marked. They shall be tested by inducing
required test voltage in the transformer and connecting the successive line
to ground.
ansformer windings permanently grounded within the transformer shall be
d by inducing the required test voltage in such windings. See § 6361.
e of Voltmeter and Spark-gaps in Dielectric Tests. — See § 2359.
e of Spark-gap with Transformers of Low Capacitance. — See § 2360.
e of Spark-gap with Transformers of High Capacitance. — See § 2361.
easurements with Voltmeter. — See § 2362.
easurements with Spark-gap. — See § 2363.

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361 d) This rule does not include bell-ringing transformers of ratio 125 to 6 volts.
362) This test can be made by connecting the windings of two or more transformers
ries, with one end of the series grounded and a voltage impressed such as will give the
from the free end to ground required by the above rule.
391 a) This method is not generally applicable for shop tests, particularly on large
sformers.

Regulation

Conditions for Tests of Regulation. — See § 2390.

6390. Conditions for Test of Regulation. — (a) *Frequency:* The regulation of transformers is to be determined at constant frequency.

(b) *Power Factor:* In transformers, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is, to a load in which the current is in phase with the e.m.f. at the output side of the transformer. See § 2390.

6391.* Tests and Computation of Regulation. — (a) *Method I. By Loading.* The regulation of a constant potential transformer can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power factor.

(b) *Method II. From Impedance Watts and Volts:* The regulation of a constant potential transformer for any specified load and power factor can be computed from the measured impedance watts and impedance volts as follows:

Let P = impedance watts, as measured in the short-circuit test,

E_s = impedance volts, as measured in the short-circuit test,
P_{75} = impedance watts, as measured in the short-circuit test, and corrected to 75° C.,
IX = Reactance Drop in Volts,
I = Rated Primary Current,
E = Rated Primary Voltage,
q_r = per cent drop in phase with current,
q_z = per cent drop in quadrature with current,

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}.$$

$$q_r = 100\frac{P_{75}}{EI}.$$

$$q_z = 100\frac{IX}{E}.$$

Then:

For unity power factor, we have approximately,

$$\text{Per cent regulation} = q_r + \frac{q_z^2}{200}.$$

For *inductive loads* of power-factor m and reactive-factor n,

$$\text{Per cent regulation} = mq_r + nq_z + \frac{(mq_z - nq_r)^2}{200}.$$

CONSTRUCTION

Rating Plates

Marking of Rating Plates. — See § 2401.

Transformer Connections

(These rules do not apply to auto-transformers)

General:

6402.* Scope. — These rules specify the markings of leads brought out of the case but not the markings of winding terminals inside of the case, except that these terminals shall be marked with numbers in any manner that will permit of convenient reference and that cannot be confused with the markings of the leads brought out of the case.

(6402) It is recognized that special cases will arise from time to time that these rules will not cover and that it would be very difficult to cover by any set of general rules. A

TRANSFORMER LEAD MARKINGS SINGLE-PHASE TRANSFORMERS

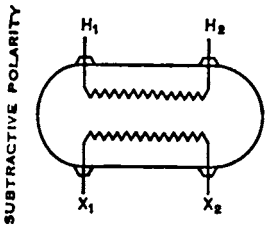


Fig. 6-1

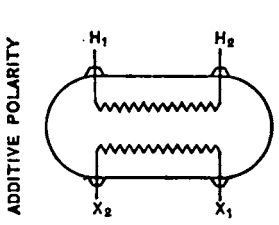


Fig. 6-2

Simple High- and Low-voltage Windings without Taps

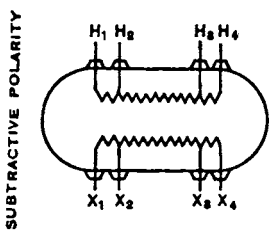


Fig. 6-5

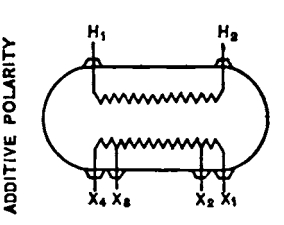


Fig. 6-4

Simple High- and Low-voltage Windings with Taps

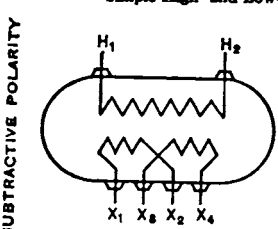


Fig. 6-3

Series Multiple Low-voltage Winding without Taps

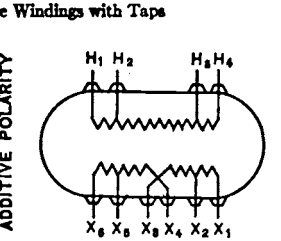


Fig. 6-6

Series Multiple Low-voltage Winding with Taps

lote. — The above figures illustrate the application of the rules on lead markings to nsformers having subtractive and additive polarity.

403.* Markings of Leads. — *(a) *General:* The leads shall be distinguished n one another by marking each lead with a capital letter followed by a nber. The letters to be used are: *H* for high-voltage leads, *X* for low-volt- *leads* and *Y* for tertiary winding leads. The numbers to be used are 1, 2, 3,

403 a) By "tertiary winding" is meant a third winding that, compared with both of other two windings, has smaller kv-a. rating than either or, if the kv-a. rating is the e as one or both of the other two, has lower voltage. *E.g.*, if a transformer has three rate windings, one for 1000 kv-a., 33,000 volts, one for 600 kv-a., 550 volts and one for kv-a. 6,600 volts, the 400 kv-a. winding is the tertiary winding; or, if a transformer three separate windings each with a capacity of 1,000 kv-a., and with voltages of 00, 6,600 and 550 respectively, the 550-volt winding is the tertiary winding. ccording to this definition neither one of two similar windings arranged for series- llel connection is to be classed as a tertiary winding.

*(b) *Neutral Lead:* A neutral lead shall be marked with the proper le followed by *O, e.g., HO, XO.*

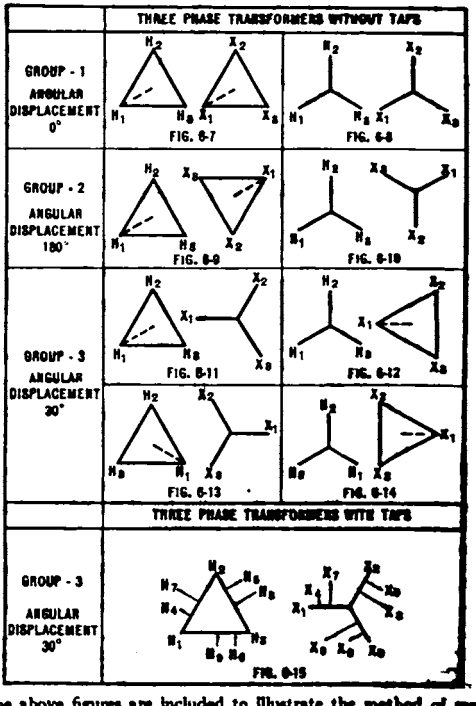
6404. Diagrammatic Sketch of Connections. — The manufacturer sh furnish with each transformer a complete diagrammatic sketch showing the le and internal connections and their markings and the voltages obtainable w the various connections.

This sketch should preferably be on a metal plate attached to the transfor case.

Single-phase Transformers:

6405. Order of Numbering Leads in any Winding. — The leads of any wi ing (high-voltage, low-voltage or tertiary) brought out of case shall be numb 1, 2, 3, 4, 5, etc., the lowest and highest numbers marking the full winding the intermediate numbers marking fractions of winding or taps. All numb shall be so applied that the potential difference from any lead having a l number toward any lead having a higher number shall have the same sig any instant.

TRANSFORMER LEAD MARKINGS AND VOLTAGE VECTOR DIAGR FOR THE USUAL THREE-PHASE TRANSFORMER CONNECTIO



Note. — The above figures are included to illustrate the method of marking t former leads that are brought out of the case and are not intended to standardize nections, vector diagrams or polarity.

(6403 b) A lead brought out from the middle of a winding for some other unit, that of neutral lead, *e.g.*, a 50 per cent starting tap, shall be marked as a tap lead

a winding is divided into two or more parts for series-parallel connections, the leads of these parts are brought out of case, the above rule shall apply be series connection with the addition that the leads of each portion of wind- shall be given consecutive numbers. See Figs. 6-5 and 6-6.

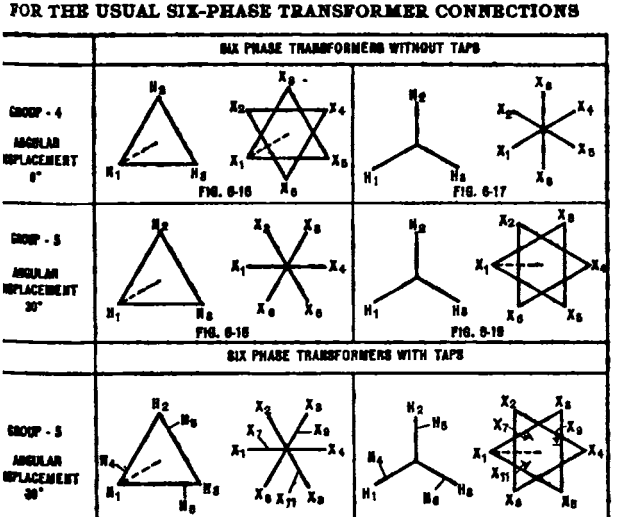
86. Relation of Order of Numbering Leads of Different Windings. — The bering of the high-voltage and low-voltage leads shall be so applied that H_1 and X_1 are connected together and voltage applied to the transformer, voltage between the highest numbered H lead and the highest numbered ad shall be less than the voltage of the full high-voltage winding.
e same relation shall apply between high-voltage and tertiary and low- ge and tertiary winding.

87. Polarity. — When leads are marked in accordance with the above rules, olarity of a transformer is:

ubtractive when H_1 and X_1 are adjacent. See Figs. 6-1, 6-3 and 6-5.
dditive when H_1 is diagonally located with respect to X_1. See Figs. 6-2, nd 6-6.

88. Location of H_1 Lead. — To simplify the work of connecting trans- ers in parallel it is recommended that the H_1 lead shall be brought out on ight-hand side of the case, facing high-voltage side of the case.

NSFORMER LEAD MARKINGS AND VOLTAGE VECTOR DIAGRAMS FOR THE USUAL SIX-PHASE TRANSFORMER CONNECTIONS



e. — The above figures are included to illustrate the method of marking trans- r leads that are brought out of the case and are not intended to standardize con- es, vector diagrams or polarity.

89.[9] Parallel Operation. — Transformers having leads marked in accord- with these rules may be operated in parallel by connecting similarly marked together, provided their ratio, voltages, resistances and reactances are such permit parallel operation.

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[9] In some cases design may be such as to permit parallel operation, although due difference in the number of tap leads, the leads to be connected together may not the same number.

Three-phase Transformers:

6410. Marking of Full Winding Leads. — The three high-voltage leads of the three low-voltage leads which connect to the full-phase windings, shall be marked H_1, H_2, H_3, and X_1, X_2, X_3. The full-phase winding of a tertiary winding shall be marked Y_1, Y_2, Y_3.

6411.* Relation between High-voltage and Low-voltage Windings. — *General:* The markings shall be so applied that if the phase sequence of voltage on the high-voltage side is in the time order H_1, H_2, H_3 it is in the time order of, X_1, X_2, X_3 on the low-voltage side and Y_1, Y_2, Y_3 for a tertiary winding.

*(b) *Angular Displacement:* In order that the markings of lead connections between phases shall indicate definite phase relations, they shall be made in accordance with one of the three three-phase groups as shown. The angular displacement between the high-voltage and low-voltage windings is the angle in each of the voltage vector diagrams (Figs. 6-7 to 6-14 inclusive) between the lines passing from its neutral point through H_1 and X_1 respectively.

6412. Tap Leads. — (a) *General:* Where tap leads are brought out of the case (neutral lead excepted) they shall be marked with the proper letter followed by the numbers, 4, 7, etc., for one phase, 5, 8, etc., for another phase and 6, 9, etc., for the third phase. See Fig. 6-15.

(b) *Delta Connection:* The order of numbering tap leads shall be as follows: 4, 7, etc., from lead 1 toward lead 2; 5, 8, etc., from lead 2 toward lead 3. 6, 9, etc., from lead 3 toward lead 1. See Fig. 6-15.

(c) *Star Connection:* The order of numbering tap leads shall be as follows: 4, 7, etc., from lead 1 towards neutral; 5, 8, etc., from lead 2 towards neutral and 6, 9, etc., from lead 3 towards neutral. See Fig. 6-15.

6413. Interphase Connection Made Outside of Case. — Where the interphase connections are made outside of case, the leads shall be marked with the proper letter followed by the numbers 1, 4, 7, 10, etc., for one phase; 2, 5, 8, 11, etc., for the second phase; and 3, 6, 9, 12, etc., for the third phase.

The markings shall be so applied that when a star connection is made by joining together the highest numbered leads of each phase, all rules have been complied with excepting § 6403 (b) apply.

6414.* Parallel Operation. — Transformers having leads marked in accordance with these rules may be operated in parallel by connecting similarly marked leads together provided their angular displacements are the same and provided also their ratios, voltages, resistances, and reactances are such as to permit satisfactory parallel operation.

6415. Location of H1 Lead. — To simplify the work of connecting transformers in parallel it is recommended that the $H1$ lead shall be brought out on the right-hand side of the case, facing the high-voltage side of the case.

Three-Phase to Six-phase Transformers:

6416. Rules that are Applicable for Three-Phase Transformers. — Sections 6411 (b) and 6413 shall apply to three-phase to six-phase transformers. Rules 6410 and 6412 shall apply to three-phase windings but not to six-phase windings.

6417. Markings of Six-phase Leads. — The six leads which connect to the full-phase windings shall be marked $X1$, $X2$, $X3$, $X4$, $X5$, $X6$. See Figs. 6-16 to 6-19 inclusive.

6418. Relation between Three-phase and Six-phase Windings. — *General:* The markings shall be so applied that if the phase sequence of voltage

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(6411 b) Any three-phase transformer having a delta-Y connection may be represented by voltage vector diagram either in accordance with Fig. 6-11 or Fig. 6-13. A three-phase transformer having Y-delta connection may be represented by voltage vector diagram either in accordance with Fig. 6-12 or Fig. 6-14. Since these voltage vector diagrams are equivalent, it is recommended that the terminal markings for three-phase transformers having delta-Y connection be always made in accordance with Fig. 6-13 and that the terminal markings for three-phase transformers having Y-delta connection be always made in accordance with Fig. 6-12.

(6414) In some cases designs may be such as to permit parallel operation although due to a difference in the number of tap leads, the leads to be connected together are not similarly marked.

the three-phase side is in the time order $H1$, $H2$, $H3$, it is in the time order $X1$, $X2$, $X3$, $X4$, $X5$, $X6$ on the six-phase side.

b) *Angular Displacement:* In order that the markings of lead connections ween phases shall indicate definite phase relations, they shall be made in ordance with one of the four six-phase groups shown in Figs. 6-16 to 6-19 usive. The angular displacement between the high-voltage and low-tage windings is the angle in each of the voltage vector diagrams from its tral through $H1$ and $X1$ respectively.

419.* **Tap Leads.** — (a) *General:* Where tap leads from low-voltage wind- are brought out of the case (neutral lead excepted), they shall be marked llows:

) *Diametrical Connection:* Diametrical connection tap leads shall be ked from the two ends of each phase winding towards the middle or neutral t in the following order; $X7$, $X13$, etc., from $X1$ towards neutral; $X8$, , etc., from $X2$ towards neutral; $X9$, $X15$, etc., from $X3$ towards neutral; $X16$, etc., from $X4$ towards neutral; $X11$, $X17$, etc., from $X5$ towards tral; $X12$, $X18$, etc., from $X6$ towards neutral. See Fig. 6-20.

ap from the middle point of any phase winding, not intended as a neutral, l be given a number determined by counting from $X1$, $X2$ or $X3$ and not $X4$, $X5$, or $X6$; *e.g.*, if the only taps brought out are 50 per cent starting , they shall be numbered $X7$, $X8$, and $X9$.

c) *Double Delta Connection:* Tap leads shall be marked in the following r; $X7$, $X13$, etc., from $X1$ towards $X3$; $X8$, $X14$, etc., from $X2$ towards $X9$, $X15$, etc., from $X3$ towards $X5$; $X10$, $X16$, etc., from $X4$ towards $X11$, $X17$, etc., from $X5$ towards $X1$; $X12$, $X18$, etc., from $X6$ towards See Fig. 6-21.

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CHAPTER VII

STANDARDS FOR SWITCHING, CONTROL AND PROTECTIVE APPARATUS

he A. I. E. E. Standards for Switching Control and Protective Apparatus the General Standards shown in Chapters II and III and the Standards in r Chapters which are applicable to the devices involved, together with the ifications and extensions given in this Chapter.

419 c) For starting purposes it is generally customary to bring out only two taps one delta and start three-phase.

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DEFINITIONS

Devices—General

7000.* Switching and Control Apparatus. — For the purpose of these Standardization Rules switching and control apparatus is defined as electric apparatus whose function is primarily to control or protect in some predetermined manner electric apparatus to which it is connected.

7001. Switch. — A switch is a device for making, breaking or changing connections in an electric circuit.

7002. Master-switch. — A master-switch is a switch which serves to govern the operation of contactors and auxiliary devices of an electric controller.

7003. Control Switch. — A control switch is a switch for controlling electrically-operated switches and circuit breakers.

7004. Auxiliary Switch. — An auxiliary switch is a switch actuated by a main device, for signalling, interlocking, etc.

7005. Circuit Breaker. — A circuit breaker is a device (other than a fuse) constructed primarily for the interruption of a circuit under *infrequent* abnormal conditions.

7006. Contactor. — A contactor is a device for repeatedly establishing and interrupting an electric circuit under normal conditions.

7007.* Electric Controller. — An electric controller is a device, or group of devices, which is designed to control in some predetermined manner the operation of the apparatus to which it is connected.

7008.* Motor-starter. — A motor-starter is an electric controller designed for accelerating a motor to normal speed in one direction of rotation.

7009. Automatic Motor-starter. — An automatic motor-starter is a motor-starter designed to automatically control the acceleration of a motor.

7010. Auto-transformer Motor-starter. — An auto-transformer motor-starter is a motor-starter having an auto-transformer to furnish a reduced voltage for starting. The device includes the necessary switching mechanism, and is frequently called a Compensator or Auto-starter.

7015.* Fuse. — A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

7016. Electric Protective Relay.—An intermediate device, equipped with contacts to open or close an auxiliary circuit, by means of which one circuit is indirectly controlled by a change in conditions in the same or other circuits.

7017. Rheostat. — A rheostat is a resistor which is provided with means for readily varying its resistance. See § 3064.

7018. Protective Reactor. — A protective reactor (See § 3078) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short-circuit conditions.

(7000) The "National Electrical Code" of the National Fire Protection Association deals with certain circuit breakers up to 550 volts rating and switches and fuses of 600 volts rating fuses.

(7007) A switch (see § 7001) should not be called a controller.

(7008) A device designed for starting a motor in either direction of rotation but not a controller (see § 7007).

(7015) Any terminals, tubes, etc., integral with this element are included as part of the fuse.

Fuses may be divided into two classes:

(a) Those designed to protect the circuit and apparatus both against short-circuits and against definite amounts of overload (*e.g.* fuses of the National Electric Code which blow on overload in excess of 10 per cent).

(b) Those designed to protect the system only against short-circuits; (*e.g.*, expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

7019.* **Lightning Arrester.** — A lightning arrester is a device for protecting cuits and apparatus against lightning or other abnormal potential rises of ort duration.

7020. Under-voltage or Low-voltage Release Switching and Control Appara- — Under-voltage or low-voltage release switching and control apparatus is paratus which, on the reduction or failure of voltage, operates to cause the erruption of power to the main circuit, but which does not prevent the re-ablishment of the main circuit on return of voltage.

7021. Under-voltage or Low-voltage Protection Switching and Control paratus. — Under-voltage or low-voltage protection switching and control paratus is apparatus which, on the reduction or failure of voltage, operates to se and maintain the interruption of power to the main circuit.

7022. Phase-failure Protection Switching and Control Apparatus. — Phase-ure protection switching and control apparatus is apparatus which, on the re of power in one wire of a polyphase circuit, operates to cause and main-the interruption of power on the circuit.

7023. Phase-reversal Protection Switching and Control Apparatus. — Phase-rsal protection switching and control apparatus is apparatus which, on the rsal of the phase relations in a polyphase circuit, operates to cause and main-the interruption of power on the circuit.

Electric Protective Relays—Classified According to Functions

7026. Directional Relay.—Any relay which functions in conformance with ction of power or voltage or current or phase rotation, etc.

7027. Power-Directional Relay.—Any relay which functions in conformance h direction of power.

NOTE.—This includes both unidirectional relays with single-throw contacts duodirectional relays with double-throw contacts. The reason this name is erred to "reverse power" is that the device is frequently used to function er normal direction of power. Furthermore, in some cases, the normal dition of the system may permit power to flow in either direction. Relays se in either alternating or direct-current circuits are to be classed as power-ctional relays.

7028. Polarity-directional Relay.—Any relay which functions by reason of a ge of the direction of polarity.

7029. Phase-rotation Relay. — Any relay which functions by reason of a nge of the direction of phase rotation.

7030. Current Relay. — Any relay which functions at a predetermined value the current. These may be either over-current relays or under-current ys.

7031. Voltage Relays. — Any relay which functions at a predetermined ue of the voltage. These may be either over-voltage relays or under-voltage ys.

7032. Power Relay. — Any relay which functions at a predetermined value the power. These may be either over-power relays or under-power ys.

7033. Frequency Relay. — Any relay which functions at a predetermined ue of the frequency. These may be either over-frequency relays or under-quency relays.

7034. Temperature Relay. — Any relay which functions at a predetermined mperature in the apparatus protected.

7035. Open-phase Relay. — Any relay which functions by reason of the ening of one phase of a polyphase circuit.

7019) Lightning arresters may be divided into two classes:
a) Those intended to discharge for a very short time.
b) Those intended to discharge for a period of several minutes.

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7036. Differential Relay. — Any relay which functions by reason of the difference between two quantities, such as current or voltage, etc.

NOTE.—This term includes relays heretofore known as "ratio balance relays," "biased," and "percentage differential relays."

Electric Protective Relays—Classified According to Applications

7040. Locking Relay. — Any relay which renders some other relay or other device inoperative under predetermined values of current or voltage, etc.

7041. Trip-free Relay. — Any relay which prevents holding in an electrically operated device, such as a circuit breaker, while an abnormal condition exists on the circuit.

7042. Auxiliary Relay. — Any relay which assists another relay in the performance of its function and which operates in response to the opening or closing of its operating circuit.

7043. Signal Relay. — An auxiliary relay which operates an audible or a visible signal.

Electric Protective Relays—General Qualifying Terms

7050. Notching. — A qualifying term applied to any relay, indicating that a number of separate impulses are required to complete operation.

7051. Inverse Time. — A qualifying term applied to any relay indicating that there is purposely introduced a delayed action, which delay decreases as the operating force increases.

7052. Definite Time. — A qualifying term applied to any relay indicating that there is purposely introduced a delayed action, which delay remains substantially constant regardless of the magnitude of the operating forces. If the forces slightly above the minimum operating value, the delay may be inverse.

7053. Instantaneous. — A qualifying term applied to any relay indicating that no delayed action is purposely introduced.

7054. Use of Terms. — Where relays operate in response to changes in more than one condition, all functions should be mentioned.

Characteristics of Devices—General

7060. "Air" as a Prefix. — The prefix "air" applied to a device which interrupts an electric circuit indicates that the interruption occurs in air.

7061. "Oil" as a Prefix. — The prefix "oil" applied to a device which interrupts an electric circuit indicates that the interruption occurs in oil.

7062. Fume-resisting. — Fume-resisting switching and control apparatus is apparatus so constructed that it will not be readily injured by the specified fume.

7063.* Drip-proof. — Drip-proof switching and control apparatus is apparatus so protected as to exclude falling moisture or dirt.

7064. Dust-proof. — Dust-proof switching and control apparatus is apparatus so constructed or protected that the accumulation of dust within or without the device will not interfere with its successful operation.

7065. Dust-tight. — Dust-tight switching and control apparatus is apparatus so constructed that the dust will not enter the enclosing case.

7066. Explosion-proof. — Explosion-proof switching and control apparatus is apparatus so constructed that explosions of gas within the casing will not injure it or ignite inflammable gas outside it.

7067. Gas-proof. — Gas-proof switching and control apparatus is apparatus so constructed or protected that the specified gas will not interfere with successful operation.

(7063) Drip-proof apparatus may be either open or semi-enclosed, if it is provided with suitable protection integral with the apparatus, or so enclosed as to exclude effectively falling solid or liquid material.

7068. Gas-tight. — Gas-tight switching and control apparatus is apparatus constructed that the specified gas will not enter the enclosing case.

7069. Moisture-resistant. — Moisture-resistant switching and control apparatus is apparatus so constructed or treated that it will not be readily injured by moisture. (Such apparatus shall be capable of operating in a very humid atmosphere, such as found in mines, evaporating rooms, etc.).

7070. Splash-proof. — Splash-proof switching and control apparatus is apparatus so constructed or protected that external splashing will not interfere with its successful operation.

7071. Submersible. — Submersible switching and control apparatus is apparatus so constructed that it will operate successfully when submerged in water under specified conditions of pressure and time.

7072. Sleet-proof. — Sleet-proof switching and control apparatus is apparatus so constructed or protected that the accumulation of sleet will not interfere with its successful operation.

Parts of Devices—General

7080. Conducting Parts. — Conducting parts of switching and control apparatus are those designed to carry current or which are conductively connected therewith.

7081. Contact. — A contact is a surface common to two conducting parts, held by pressure, for the purpose of carrying current.

7082. Magnet Brake. — A magnet brake is a friction brake controlled by electro-magnetic means.

7083. Grounded Parts. — Grounded parts are those parts which may be considered to have the same potential as the earth.

Properties of Devices—General

7090. Interrupting Rating. — Interrupting (breaking or rupturing) rating is a rating based upon the r.m.s. current at normal voltage which the device can interrupt under prescribed conditions at stated intervals a specified number of times.

OPERATION

Temperature Limits

7101.* **Circuit Breakers, Relays and Switches.** — The maximum observable temperature rises of the various parts of circuit breakers, relays and switches shall not exceed the following limits for ambient temperatures up to and including 40° C. not greater than 40° C. See § 7301.

Contacts in air when clean and bright	30° C.
Contacts in oil	30° C.
Oil	40° C.
Potential Coils, Class O insulation	35° C.
Series Coil, Class O insulation	50° C.
Series and Potential Coils, Class A insulation	50° C.
Series and Potential Coils, bare or Class B insulation	70° C.
All other parts	70° C.

7102. Magnetic Contactors. — The maximum observable temperature rises of the various parts of magnetic contactors shall not exceed the following limits

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7101) The Institute calls attention to the inherent decrease in current which can be carried by switch and circuit-breaker contacts in air, due to oxidization of the contact surfaces. The rating of air switches and circuit breakers is, therefore, based on sufficient maintenance to keep the temperature rise within the specified limits. Relays which form part of controllers are to have the temperature limits specified in § 7102.

for ambient temperatures up to and including but not greater than 40° C. § § 7302.

Laminated contacts	65° C.
Operating coils	70° C.
Solid contacts	100° C.
Current-carrying parts insulated with asbestos or other fireproof material	150° C.

7105.* **Fuses.** — The maximum observable temperature rise of coils or wi ings, measured by thermometer, shall not exceed the following limits for ambi temperatures up to and including but not greater than 40° C.

If insulation is of unimpregnated fibrous material	35° C.
If insulation is of fibrous material treated to withstand heat	50° C.
If insulation is of asbestos, mica or similar heat-resisting material with a cotton binder	70° C.

7106. Cast Grid Resistors. — The maximum observable temperature rise cast grids used as resistors shall not exceed 350° C. for ambient temperatures to and including but not greater than 40° C.

RATING

Expression of Rating

7201. Rating of Circuit Breakers and Switches. — The rating of a circ breaker or switch shall include the following items:

(a) the normal r.m.s. current which it is designed to carry.

(b) the normal r.m.s. voltage of the circuit on which it is intend to operate.

(c) the normal frequency of the current.

(d) the interrupting rating of the device. See § 7060.

7202. Continuous Current-carrying Capacity of Fuses. — Fuses shall be constructed that they will carry continuously 110 per cent of their rated curr

7205. Rating of Lightning Arresters. — The rating of a lightning arre shall be the voltage of the circuit on which it is to be used.

TESTS

Heat Tests

7301. Circuit Breakers, Relays and Switches. — The rated current of circ breakers, relays and switches at rated frequency shall be applied continuou until the temperature becomes constant. The temperature rises measured thermometer or thermocouple (Method No. 1) placed on the surface of the to be measured shall not exceed the limits specified in § 7102.

The ambient temperature shall be determined by taking the average of readings of three thermometers placed as follows:

One 12 inches above;

One 12 inches below;

One midway but 12 inches from the breaker as installed.

7302. Magnetic Contactors. — The rated current of magnetic contactor rated frequencies shall be applied continuously or until the temperature becom constant when continuous duty is specified. It shall be applied for the specif length of time when given a short time rating. The temperature rises measu by thermometer shall not exceed the limits specified in § 7102.

Tests of Dielectric Strength

7322.* **Standard Test Voltage.** — (a) *Apparatus rated at 600 volts or l* The standard test voltage for all switching and control apparatus rated at volts or less shall be twice the normal voltage of the circuit to which the ap ratus is to be connected plus 1000 volts.

(7105) Coils or windings such as accompany fuses of the magnetic blow-out type.

(7323) This assumes a precipitation of 1/10th inch (2.54 mm.) per minute at an an of 45° from the perpendicular with water having a resistivity as low as 7000 ohm-cen meters.

) *Apparatus rated above 600 volts:* Apparatus rated above 600 volts shall be ed at 2½ times rated voltage, plus 2000 volts, at a specified altitude.
As a supplementary test, devices for outdoor use should be capable of withding for 10 seconds a dielectric wet test at twice rated voltage plus 1000 volts.
) *Auto-Transformers for Motor-starters:* Auto-transformers for motor-starters l be tested with the same voltage as the test voltage of the apparatus to ch they are to be connected.

Tests of Lightning Arresters.

171. Resistance. — The resistance of the arrester at double potential and at normal potential, shall be determined by observing the discharge currents ugh the arrester.

172. Arrester with Gap. — In the case of any arrester using a gap, a test shall nade of the spark potential on either direct-current or 60 cycle a-c. excitation.

173. Equivalent Sphere Gap. — The equivalent sphere gap under disruptive harge shall be measured, using a considerable quantity of electricity.

174. Continuous Surges. — The endurance of the arrester to continuous es shall be tested.

175. Dielectric Strength. — See §§ 2355 and 7323.

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CHAPTER VIII

STANDARDS FOR METERS, INSTRUMENTS AND INSTRUMENT TRANSFORMERS

he A.I.E.E. Standards for Meters, Instruments and Instrument Transers are the General Standards shown in Chapters II and III, and the Standin other Chapters which are applicable to the devices involved, together with modifications and extensions given in this Chapter.

DEFINITIONS

900.* Meter. — A meter is a device which registers through a totalising hanism, the integral, with respect to time, of the electrical quantity to which sponds. (This definition does not preclude the general use of " meter " as a r, or in compound words, to mean a " measuring device.")

901.* Instrument. — An instrument is a device which indicates or records present value of the quantity under observation.

902. General Nomenclature. — In general, the names of meters and instrus are self-defining. The following names are preferred to others some-

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900 and 8001) While the word "instrument" is a general term which may properly ude indicating, integrating and recording devices, there is a tendency to restrict its o indicating devices and to recording (graphic or curve drawing) devices. Integrating ces are then denoted by the word "meter." This distinction gives rise to the above ral definitions.

times used for the same devices: Reactive-factor Meter, Power-factor Meter, Watthour Meter, Reactive Volt-Ammeter (or Reactive Volt-ampere Indicator) etc.

8003. Recording Instruments. — Recording ammeters, voltmeters, wattmeters, etc., are instruments which record graphically, upon time charts, the values of the quantities they measure.

8004.* Crest Voltmeter. — A crest voltmeter is a voltmeter depending for its indications upon the crest, or maximum value of the voltage of the system to which it is connected. Crest voltmeters shall be marked in true crest volts and also in the r.m.s. value of the sinusoidal wave having the same crest value. (See § 2362.)

8005. Synchronoscope (also called a Synchroscope or Synchronism Indicator). — A synchronoscope is a device which indicates synchronism between two machines, and in addition shows whether the incoming machine is fast or slow.

8006. Line-drop Voltmeter Compensator. — A line-drop voltmeter compensator is a device used in connection with a voltmeter which causes the latter to indicate the voltage at some distant point of the circuit.

8007. Demand-meter. — (a) *General:* A demand-meter is a device which indicates or records the demand or maximum demand. In practise, two types are recognized. See §§ 3454, 3458, 3460 and 3464.

(b) *Integrated-Demand-Meter:* An integrated-demand-meter is a demand meter which indicates or records the maximum demand obtained through integration.

(c) *Lagged-Demand-Meter:* A lagged-demand-meter is a demand-meter in which the indication of maximum demand is subject to a characteristic time lag.

8020.* Period of an Instrument. — The period of an instrument, sometimes called the "periodic time," is the time taken for the pointer to make one complete oscillation (two consecutive swings). A swing is a complete movement in either direction.

8030. Instrument Transformer. — An instrument transformer is a transformer suitable for use with measuring instruments; that is, one in which the conditions of phase and of current or potential in the primary circuit, are represented with acceptable accuracy in the secondary circuit. An instrument transformer may be either an instrument current transformer or an instrument potential (voltage) transformer.

8031.* Secondary Burden. — The secondary burden of a current transformer is an expression in ohms and henrys of the resistance and inductance of the external circuit connected to the secondary of that transformer.

8032. Voltage Ratio of Instrument Transformer. — The voltage ratio of an instrument potential transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified secondary burden.

8033. Current Ratio of Instrument Transformer. — The current ratio of an instrument current transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified secondary burden.

8034. Marked Ratio of Instrument Transformer. — The marked ratio of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage or current, frequency, load and secondary burden.

(8004) Corona voltmeter (see Transactions of the A. I. E. E., Volume XXXIX, page 1057) is recognized as a satisfactory form of crest voltmeter.

(8020) In strongly damped instruments, the period is influenced by the amplitude of the movement.

(8031) Considerable uncertainty of meaning has been occasioned by the use of the terms, load, secondary load, and secondary connected load for this quantity, and such use is discouraged.

OPERATION

8101. Permissible Temperature in Shunts. — (a) *General:* The limiting observable temperature of shunts measured by Method I shall not exceed 120° C. (b) *Exceptions:* The above rule shall not apply to shunts having no soldered joint and made of material which is not permanently changed in resistance if continuously subjected to a higher temperature.

8110. Grounding of Meters and Instruments. — The covers of meters and instruments, which are used with current and potential transformers, shall be connected to the grounded sides of the secondary circuits of such transformers in all cases where the indications of the instrument are liable to be influenced by electrostatic action.

8111. Instrument Current Transformers on Open Secondary Circuit.— Under conditions of open secondary circuit, current transfomers shall be capable of carrying continuously rated primary current without damage to the primary insulation and without interruption of service.

8112. Instrument Current Transformers on Closed Secondary Circuit. — Under conditions of closed secondary circuit, current transformers shall withstand 40 times rated current applied for 1 second, without injury.

RATING

8200. General. — The rating of a meter is a designation assigned by the manufacturer to indicate its operating limitations. The full scale marking of an instrument does not necessarily correspond to its rating, but if the rating differs from the full scale marking, the rating shall be marked on the instrument.

8201. Standard Ambient Temperature.— For purposes of rating meters and instruments, the standard ambient temperature shall be 40° C. See §§ 8301 and 2211.

8202. Rating Limitation of the Circuits of Meters and Instruments. — No circuit of a meter or instrument shall be given a rating higher than that corresponding to the maximum current or voltage to which it may be continuously subjected.

8203.* Temperature Rise of Meter and Instrument Windings. — The permissible temperature rises in meters and instruments shall be based upon the temperatures specified in § 1005 and the standard ambient temperature of 40° C.

8204. Temperature Rise in Shunts. — Shunts shall be rated in accordance with their observable temperature rise by Method 1, assuming the ultimate temperatures specified in § 8101 and an ambient temperature specified in § 8201.

TESTS

8300. Measurement of Temperature Rise of Shunts. — Observable temperature shall be measured in such a manner as not to cause local change of temperature.

8301. Standard Temperature of Reference for Meter and Instrument Characteristics. — The standard temperature of reference for meter and instrument characteristics shall be 20° C. See §§ 8201, 2211.

8302. Damping. — The pointer being at zero before any load is applied, damping shall be measured by suddenly applying and maintaining a load which will give a steady deflection of one-half full angular scale, and observing the following quantities:

(a) The number of swings taken by the pointer in coming to rest.

(8203) Heating is frequently an immaterial consideration in determining the rating of meters and instruments. Losses, impairment of accuracy and other factors often determine the rating.

(b) The time, in seconds, required for the pointer to come to rest.
(c) The overshooting, in per cent of the angular displacement due to the disturbance.

Dielectric Strength of Instrument Transformers.

8310. Test Voltage Instrument Potential Transformers. — The test voltage for instrument potential transformers shall be twice the normal voltage of the circuit to which it is connected plus 1000 volts.

8311. Test Voltage of Instrument Current Transformers. — The test voltage of instrument current transformers shall be 2½ times the rated voltage plus 2000 volts.

8312. Test Voltage for Meters and Instruments. — Meters and instruments which have a potential circuit shall withstand a test of twice potential of the circuit plus 1000 volts. Instruments without a potential circuit shall withstand a test of 1000 volts.

SPECIFICATION OF CHARACTERISTICS

8500. Errors of Indicating Instruments. — In specifying the accuracy of an indicating instrument, the error at any point on the scale shall be expressed as a percentage of the full scale reading.

8501. Torque. — The torque of meters and instruments shall be expressed in millimeter-grams.

8502. Damping. — The damping of an instrument shall be expressed in terms of the quantities enumerated in § 8302, all three of which are essential to a complete description.

8503.* Marking of Switchboard Shunts. — The marking of switchboard shunts shall include the rating in amperes, the drop in volts at that rating and the serial number of any instrument in connection with which the shunt may be calibrated. When shunts are designed to be used with devices taking sufficient current to be an appreciable proportion of the whole, this fact shall be indicated.

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(8503) For example, if with 100 amperes rated load in the main circuit, a measuring device takes 10 amperes, leaving 100 less 10 amperes in the shunt with a drop of 0.05 volts, the shunt shall be marked: Volts 0.050. Amperes 100 less 10.

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CHAPTER IX

STANDARDS FOR WIRES AND CABLES

DEFINITIONS

9000.* Wire. — A wire is a slender rod or filament of drawn metal.

9001.* Conductor. — A conductor is a wire or combination of wires not sulated from one another, suitable for carrying a single electric current.

9002.* Stranded Conductor. — A stranded conductor is a conductor com-sed of a group of wires, or of any combination of groups of wires.

9003. Strand. — A strand is one of the wires, or groups of wires, of any randed conductor.

9004.* Cable. — A cable is either a stranded conductor (single-conductor ble), or a combination of conductors insulated from one another (multiple-nductor cable).

9005.* Stranded Wire. — A stranded wire is a group of small wires, used as ingle wire.

9006.* Cord. — A cord is a small, flexible, insulated cable.

9007. Concentric Strand. — A concentric strand is a strand composed of a ntral core surrounded by one or more layers of helically-laid wires or groups wires.

9008. Concentric-lay Cable. — A concentric-lay cable is a single-conductor ble composed of a central core surrounded by one or more layers of helically-d wires.

9009.* Rope-lay Cable. — A rope-lay cable is a single-conductor cable com-sed of a central core surrounded by one or more layers of helically-laid groups wires.

9000) The definition restricts the term to what would ordinarily be understood by the m "solid wire." In the definition, the word "slender" is used in the sense that the gth is great in comparison with the diameter. If a wire is covered with insulation, it roperly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be derstood to include the insulation.

9001) The term "conductor" is not to include a combination of conductors insulated m one another, which would be suitable for carrying several different electric currents. ded conductors (such as bus-bars) are, of course, conductors, but are not considered der the terminology here given.

9002) The wires in a stranded conductor are usually twisted or braided together.

9004) The first kind of cable is a single conductor, while the second kind is a group of eral conductors. The component conductors of the second kind of cable may be her solid or stranded, and this kind of cable may or may not have a common insulating ering. The term "cable" is applied by some manufacturers to a solid wire heavily ulated and lead-covered; this usage arises from the manner of the insulation, but such onductor is not included under this definition of "cable." The term "cable" is a eral one, and in practise, it is usually applied only to the larger sizes. A small cable is led a "stranded wire" or a "cord," both of which are defined below. Cables may be re or insulated, and the latter may be armored with lead, or with steel wires or bands.

9005) A wire has been defined as a slender rod or filament of drawn metal. If such a ment is subdivided into several smaller filaments or strands, and is used as a single re, it is called a "stranded wire." There is no sharp dividing line of size between a stranded wire" and a "cable." If used as a wire, for example in winding inductance ls or magnets, it is called a stranded wire and not a cable. If it is substantially insu-ed, it is called a "cord," defined below.

(9006) There is no sharp dividing line in respect to size between a "cord" and a able," and likewise no sharp dividing line in respect to the character of insulation tween a "cord" and a "stranded wire." Rubber is used as the insulating material r many classes of cords.

(9009) This kind of cable differs from the preceding in that the main strands are them-ves stranded.

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9010.* N-conductor Cable. — An N-conductor cable is a combination of N conductors insulated from one another.

9011.* N-conductor Concentric Cable. — An N-conductor concentric cable is a cable composed of an insulated central conductor with (N-1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

9012.* Duplex Cable. — A duplex cable is a cable composed of two insulated stranded conductors twisted together.

9013. Twin Cable. — A twin cable is a cable composed of two insulated stranded conductors laid parallel, having a common covering.

9014. Twin Wire. — A twin wire is a cable composed of two small insulated conductors laid parallel, having a common covering.

9015.* Triplex Cable. — A triplex cable is a cable composed of three insulated single-conductor cables twisted together.

9016.* Twisted Pair. — A twisted pair is a cable composed of two small insulated conductors, twisted together, without a common covering.

9017.* Sector Cable. — A sector cable is a multiple-conductor cable in which the cross-section of each conductor is substantially a sector, an ellipse, or a figure intermediate between them.

9018. Round Conductor. — A round conductor is either a solid or stranded conductor of which the cross-section is substantially circular.

9019.* Split Conductor. — A split conductor is a conductor which is divided into two or more parts, separated from one another by insulation which is thin compared with the insulation around the conductor.

9030. Factor of Assurance. — The factor of assurance of wire or cable insulation is the ratio of the voltage at which it is tested to that at which it is used.

9031. Insulation Resistance. — The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

9032.* Circular Mil. — A circular mil is a unit of area equal to $\frac{\pi}{4}(=0.7854\ldots)$ of a square mil. The cross-sectional area of a circle in circular mils is therefore equal to the square of its diameter in mils. A circular inch is equal to a million circular mils.

9033.* Lay. — The lay of any helical element of a cable is the axial length of a turn of the helix of that element.

9034. Direction of Lay. — The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

(9010) It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable" etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in § 9004 above).

(9011) This kind of cable usually has only two or three conductors. Such cables are used particularly for alternating currents. The remark on the expression "N-conductor" given for the preceding definition also applies here.

(9012) They may or may not have a common insulating covering.

(9015) They may or may not have a common insulating covering.

(9016) The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

(9017) Sector cables are used in order to obtain decreased overall diameter and thus permit the use of larger conductors in a cable of given diameter.

(9019) The term split conductor usually designates a conductor in two parts or splits which may be either concentric or external to one another.

(9032) A mil is the one-thousandth part of an inch. There are 1974 circular mils in a square millimeter.

(9033) Among the helical elements of a cable may be each strand in a concentric-lay cable, or each insulated conductor in a multiple-conductor cable.

ANNEALED COPPER STANDARD

10.* Standard Annealed Copper. (a) *General:* The following shall be taken rmal values for standard annealed copper.

Resistance: At a temperature of 20° C., the resistance of a wire of stand- nnealed copper one meter in length and of a uniform section of 1 square neter is $1/58$ ohm $= 0.017241 \ldots$ ohm.

Density: At a temperature of 20° C., the density of standard annealed er is 8.89 grams per cubic centimeter.

Temperature Coefficient of Resistance: At a temperature of 20° C., the stant mass " temperature coefficient of resistance of standard annealed r, measured between two potential points rigidly fixed to the wire, is $93 = 1/254.45 \ldots$ per degree centigrade.

Resistance of Standard Annealed Copper at 20° C.: As a consequence, it ws from (b) and (c) that, at a temperature of 20° C. the resistance of a of standard annealed copper of uniform section, one meter in length and ing one gram, is $(1/58) \times 8.89 = 0.15328 \ldots$ ohm.

OPERATION

Temperature Limits

20.* Maximum Temperatures. — The temperature of the insulation of a or cable at the surface of the conductor shall not be allowed to exceed the wing values.

t t = maximum safe temperature.

E = r.m.s. operating electromotive force in kilovolts between conductors,

Impregnated paper, $t = 85 - E$

Varnished cambric, $t = 75 - E$

Rubber insulation, $t = 60 - \frac{E}{4}$.

DESIGNATION

100. Designation of Wires by Diameter or Gage Number. — The sizes of s shall be stated by their diameters in mils, the American Wire Gage (Brown harpe) sizes being taken as standard. For brevity, in cases where the t careful specification is not required, the sizes of wires may be stated by the number in the American Wire Gage.

101. Designation of Cables by Cross-sectional Area. — The sizes of nded conductors shall be stated by their cross-sectional area in circular or circular inches, except in the case of flexible stranded conductors, for

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(050) See I. E. C. Publication No. 28, "International Standard of Resistance for per," March, 1914.

aragraphs (b) and (c) define what are sometimes called "Volume Resistivity" and ass Resistivity," respectively. This may be expressed in other units as follows:

olume Resistivity = 1.7241 microhms-cm. (microhms in a centimeter cube) at 20° C.

lass Resistivity = 875.20 ohms (mile, pound) at 20° C.

or detailed specifications of commercial copper see the Standard Specifications of the erican Society for Testing Materials.

(0100) For example: At a working pressure of 3.3 kv., the maximum safe limiting mperature at the surface of the conductor, or conductors, in a cable would be as follows:

For impregnated paper 81.7° C.
For varnished cambric 71.7° C.
For rubber insulation 59.2° C.

The life of the insulation of a cable depends in a great measure upon the actual temp- ture attained by the insulation. The result of operating at temperatures in excess of safe limit is to shorten the life of the insulating material. When the safe limits are eeded, deterioration is rapid and permanent, the damage increasing with the length of e that the excessive temperature is maintained and with the amount of excess tempera- e until finally the insulation breaks down.

Some of the older types of cable for voltages above 7500 have a dielectric loss that is so h that it may add considerably to the heating that would otherwise result. In such es the dielectric loss is a material factor in determining the safe load to be carried by cable, and the safe operating temperature will be determined by the temperature at ich cumulative heating occurs under the conditions of service, if this occurs at a lower mperature than that at which the insulation deteriorates.

which see § 9402. The cross-sectional area of a cable shall be considered to be the sum of the cross-sectional areas of its component wires, when measured perpendicular to their axes. The sizes of stranded conductors smaller than 250,000 circular mils (*i.e.*, No. 0000 A. W. G. or smaller) may be stated by means of the gage number of a solid wire having the same cross-sectional area.

9202.* Conductivity. — The conductivity of the metal of wires shall be expressed in terms of the conductivity of the Annealed Copper Standard, as defined in § 9050.

9203.* Copper-wire Tables. — The copper-wire tables published by the Bureau of Standards in Circular No. 31 are adopted. Table VI therein gives the values of diameters and cross-sections of A. W. G sizes to four significant figures. These tables are based upon the Annealed Copper Standard described in § 9050.

TESTS

General

9300. Cable Lengths Tested. — Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

9301. Immersion in Water. — (a) *General:* The outer surface of the insulation of complete insulated wires and cables shall be grounded while being electrically tested. If the insulation is not provided with a conducting covering, and if the covering is not liable to injury by water, the ground shall be obtained by immersing the insulated wire or cable in water for at least twelve hours and testing at the end of that period while immersed. If the outer covering is susceptible to injury by immersion, the insulated conductor shall be tested before the application of such covering.

Dry core paper insulated lead covered cables, such as telephone and telegraph cables, for use in water, shall be tested after at least twelve hours immersion.

(b) *Multiple-conductor Cable:* In the case of multiple-conductor cable without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

Tests of Dielectric Strength

9310. Object of Tests. — High-voltage tests are intended to detect weak spots in the insulation and to determine whether its dielectric strength is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

9311. Nature of Tests. — High-voltage tests shall be made at the factory by subjecting the insulation to an alternating voltage. The initially applied voltage must not be greater than the working voltage, and the rate of increase shall be approximately uniform and not over 100 per cent in 10 seconds, and not less than 100 per cent in 60 seconds.

9312.* Magnitude and Duration of the Test Voltage. — (a) *General:* Wires and cables shall be tested at the place of manufacture for five consecutive minutes, except as provided in § 9312 (b) and (f).

(b) *Rubber Insulation, National Electrical Code:* Rubber covered wires and cables for working pressures up to 600 volts alternating, insulated in accordance with the requirements of the National Electrical Code, shall be tested in accordance with that Code.

(9202) For any given wire, let

k = conductivity, in per cent of Annealed Copper Standard;
l = length, meters;
R = resistance, ohms;
W = weight, grams;
θ = temperature, degrees centigrade.

Then the conductivity may be derived from the following formula:

$$k = \frac{15.328}{\frac{WR}{l} + 0.000597\,(20 - \theta)}.$$

(9203) For detailed specifications of commercial copper, see the Standard Specifications of the American Society for Testing Materials.

c) *Thirty per cent to 40 per cent Hevea Rubber Insulation for Pressures up to Volts, a-c.:* Wires and cables for working pressures up to 600 volts alternat- insulated with 30 per cent to 40 per cent Hevea rubber compound, unless insulation thickness is less than specified in § 9405, shall be tested in accord- e with Table 901.

TABLE 901

High-voltage Tests for Rubber Insulated Wires and Cables

per cent to 40 per cent Hevea Rubber Insulation for working pressures up to 600 Volts a-c.)

n A. W.G. or Cir. Mils.	Size Sq. mm.	Test-pressure kilovolts
14–8	2.081– 8.366	3.0
7–0000	10.55 –107.2	3.5
250,000 and larger	127 and larger	4.0

f) *Thirty per cent to 40 per cent Hevea Rubber Insulation for Pressures over Volts, a-c.:* Wires and cables insulated with 30 per cent Hevea rubber com- nd for working pressures over 600 volts alternating, shall be tested with one volt per 64th inch of thickness (2.53 kv., per mm.) up to 10/64th inch 6 mm.). Above 10/64ths inch, (3.96 mm.), the test pressure shall be 10 volts plus 1.5. kilovolts per 64th inch (3.79 kv. per mm.) additional up to 64ths inch (11.89 mm.). Where the insulation thickness is 16/64ths inch 4 mm.) or over, this rule shall apply only to conductors over 26,000 cir. mils 2 sq. mm.) area.

g) *Varnished Cambric and Impregnated Paper Insulation:* Varnished cambric impregnated paper insulated wires or cables shall be tested in accordance h Table 902.

TABLE 902

High-voltage Tests for Varnished Cambric or Impregnated Paper Insulated Cables

(Minimum Values)

Operating kv.	Test kv.	Operating kv.	Test kv.
Below 0.5	2.5*	5	14
0.5	3	7.5	19.5
1	4	10	25
2	6.5	over 10	2½ times operating pressure
3	9		
4	11.5		

* The minimum thickness of insulation shall be 1/16 in. (1.6 mm.).

or intermediate working voltages, the test voltage shall be interpolated.

) *Telephone, Telegraph and Annunciator Wires and Cables:* Section 9312 l not apply to wires and cables for telephone, telegraph, annunciator and lar devices.

913. Frequency of Test Voltage. — The frequency of the test voltage shall exceed 100 cycles per second, and should approximate as closely as possible sine wave. The source of energy should be of ample capacity.

914. Dielectric Strength Tests. — Ultimate dielectric strength tests, when ured, shall be made on samples not more than 6 meters (20 ft.) long. The

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9312 c) Hevea rubber is rubber from the Hevea Brasiliensis tree. Compounds con- ing 30 to 40 per cent of Hevea rubber have electrical and mechanical properties rior to compounds insulated in accordance with the requirements of the National trical Code.

9312 e) Different engineers specify different thickness of insulation for the same king voltages. Therefore, at the present time the test kv. corresponding to working given in Table 902, are based on the *minimum* thickness of insulation specified by neers and operating companies.

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maximum allowable temperature, at which the test is made, for the particular type of insulation and the particular working pressure, shall be not greater than the temperature limits given in § 9100.

9315. Multiple-conductor Cables. — If a multiple-conductor cable is designed for the same operating voltage between conductors and sheath or water as between conductors, each conductor shall be tested against the other conductors connected together and to the sheath or water. If the cable is designed for an operating voltage between conductors and ground different from that between conductors, the test between conductors and the sheath or water shall be made separately and shall be based on the normal operating voltage between conductors and sheath or water as prescribed in § 9312.

Insulation Resistance

9320.* Expression of Insulation Resistance. — Insulation resistance shall be expressed in megohms. Linear insulation resistance, or the insulation resistance of unit length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet, and shall be corrected to a temperature of 15.5° C., using a temperature coefficient determined experimentally for the insulation under consideration.

9321. Megohms Constant. — The megohms constant of an insulated conductor shall be the factor K in the following equation:

$$R = K \log_{10} \frac{D}{d},$$

where R = insulation resistance, in megohms, for a specified unit length,
D = outside diameter of insulation,
d = diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

9322. Measurement of Insulation Resistance. — The apparent insulation resistance should be measured after the high-voltage test, measuring the leakage current after a one-minute electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained negative to the sheath or water.

9323. Insulation Resistance of Multiple-conductor Cables. — The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from each conductor to all the other conductors in multiple with the sheath or water.

Capacitance or Electrostatic Capacity

9330.* Expression of Capacitance. — Capacitance shall be expressed in microfarads. Linear capacitance, or the capacitance of unit length, shall be expressed in microfarads per unit length (kilometer, or mile, or one thousand feet), and shall be corrected to a temperature of 15.5° C., using a temperature coefficient determined experimentally for the insulation under consideration.

9331. Microfarads Constant. — The microfarads constant of an insulated conductor shall be the factor K in the following equation:

$$C = \frac{K}{\text{Log}_{10} \frac{D}{d}}$$

where C = capacitance in microfarads per unit length,
D = outside diameter of insulation,
d = diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

(9320) In the case of dry-core paper-insulated cables, the temperature coefficient of insulation resistance cannot be closely determined on account of variations in design and manufacture. Therefore no temperature corrections shall be applied to insulation resistance tests. Tests should be made at a temperature of 15.5° C. or higher.

(9330) In the case of dry-core paper-insulated cables, the temperature coefficient of capacitance cannot be determined closely on account of variations in design and manufacture. Therefore no temperature corrections shall be applied to capacitance tests. Tests should be made at a temperature of 15.5° C. or higher.

TABLE 903

Proposed Standard Cables

This table is offered for consideration but will not be recommended for fi
tion until ratified by other societies interested.)

Number and size. See Note 4	Strands: Individual wires: Nominal diameter mils	Strands: Individual wires: Nominal circular mils	Total nominal cross-section circular mils	Total diameter, inches
37 No. 8	128.5	16,510	2,097,000	1.671
37 No. 9	114.4	13,090	1,662,000	1.487
91 No. 8	128.5	16,510	1,502,000	1.414
91 No. 9	114.4	13,090	1,191,000	1.258
61 No. 8	128.5	16,510	1,007,000	1.157
-121 mils	121.0	14,641	893,100	1.089
61 No. 9	114.4	13,090	798,500	1.030
-107 mils	107.0	11,449	698,400	.963
61 No. 10	101.9	10,380	633,200	.917
-116 mils	116.0	13,456	497,900	.812
37 No. 10	101.9	10,380	384,100	.713
-97 mils	97.0	9,409	348,100	.679
37 No. 11	90.74	8,234	304,700	.635
19 No. 9	114.4	13,090	248,700	.572
-107 mils	107.0	11,449	217,500	.535
19 No. 11	90.74	8,234	156,400	.454
19 No. 12	80.81	6,530	124,100	.404
19 No. 13	71.96	5,178	98,380	.360
19 No. 14	64.08	4,107	78,030	.320
7 No. 10	101.9	10,380	72,660	.306
7 No. 11	90.74	8,234	57,640	.272
7 No. 12	80.81	6,530	45,710	.242
7 No. 14	64.08	4,107	28,750	.192
7 No. 16	50.82	2,583	18,080	.152
7 No. 18	40.30	1,624	11,370	.121
7 No. 20	31.96	1,022	7,154	.096
7 No. 22	25.35	642.4	4,497	.076
7 No. 24	20.10	404.0	2,828	.060

ote 1. — Nominal diameters and circular mils of the individual wires are taken fr
e VI, circular No. 31 of the Bureau of Standards.
ote 2. — The variation of the mean diameter of any wires shall not exceed 1 per c
e or below the nominal diameter.
ote 3. — The variation of the total cross-section of the cable shall not exceed 1 p
above or below the nominal cross-section.
ote 4. — Sizes are expressed as A. W. G. numbers except where diameters are giv
ils.

332. Measurement of Capacitance. — The capacitance of cable shall
sured with alternating current by comparison with a standard condens
s preferable that the measurement be made either at a frequency appro
ing that of operation or at a frequency giving results approximating the
esponding to the operating frequency or frequencies.

333. Capacitance of Paired Cables. — The capacitance of paired cables sh
measured between the two conductors of any pair, the other wires being co
ted to the sheath or ground.

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9384. Capacitance of Multiple-conductor Cables (not paired). — The capacitance of multiple-conductor (not paired) cables shall be measured between conductors, and also between each conductor and the other conductors connected to the sheath or ground.

CONSTRUCTION

Stranding

9400.* Proposed Standard Cables. — Insulated cables not requiring special flexibility shall be made of the number and size strands specified in Table 903.

9401. Cables not Requiring Special Flexibility. — Cables not requiring special flexibility and not made in accordance with § 9400 shall be stranded in accordance with Table 904.

TABLE 904

Standard Stranding of Concentric-Lay Cables

Size (see Note 1)	Square mm.	Number of Wires (See note 2.	
		A Bare, insulated or weatherproof cables for aerial use	B Insulated cables for other than aerial use
2.0 Cir. Inches	1013	91	127
1.5 "	760	61	91
1.0 "	507	61	61
0.6 "	304	37	61
0.5 "	253	37	37
0.4 "	203	19	37
0000 A. W. G.	107	19 or 7 (See note 3)	19
00 "	67.4	7	19
2 "	33.6	7	7
7 and smaller	10.5	..	7

Note 1. — For intermediate sizes, use stranding for next larger size.
Note 2. — Conductors of 0000 A. W. G. and smaller are often made solid and this table of stranding should not be interpreted as excluding this practice.
Note 3. — Class A cable, sizes 0000 and 000 A. W. G., is usually made of 7 strands when bare and 19 strands when insulated or weatherproof.

9402.* Flexible Cables. — Conductors of special flexibility should ordinarily be made with wires of regular A. W. G. sizes, and rated by the number and size of wires. The stranding of flexible cables is given in Table 905.

(9400) The basis of this rule is the use of strands of American Wire Gage sizes. To meet existing operating conditions, four sizes of strands other than American Wire Gage sizes have been deemed necessary and their diameters are shown in mils.

(9402) Where necessary to closely approximate a regular size cable, the strands may be made of half-size wires from No. 15 to No. 30 A. W. G.

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TABLE 908

Stranding of Flexible Cables

irest W. G. ze Note 1)	Circular mils (see Note 2)	Diam. of cable, mils	No. of wires	Size of each wire		Construction (see Note 3)
				A. W. G.	Diam., mils.	
..	2,039,000	1885	703	15.5	53.9	37 X 19
..	1,816,000	1779	"	16.0	50.8	"
..	1,617,000	1679	"	16.5	48.0	"
..	1,440,000	1584	"	17.0	45.3	"
..	1,284,000	1496	"	17.5	42.7	"
..	1,103,000	1372	427	16.0	50.8	61 X 7
..	874,600	1222	"	17.0	45.3	"
..	693,600	1088	"	18.0	40.3	"
..	550,000	969	"	19.0	35.9	"
..	436,200	863	"	20.0	32.0	"
..	345,900	768	"	21.0	28.5	"
..	274,300	684	"	22.0	25.3	"
..	264,600	671	259	20.0	32.0	37 X 7
00	209,800	598	"	21.0	28.5	"
00	171,300	538	133	19.0	35.9	19 X 7
00	135,900	479	"	20.0	32.0	"
0	107,700	427	"	21.0	28.5	"
1	82,780	332	91	20.5	30.2	Concentric
2	65,650	295	"	21.5	26.9	"
3	52,060	263	"	22.5	23.9	"
4	39,190	228	61	22.0	25.3	"
5	31,080	203	"	23.0	22.6	"
6	24,650	181	"	24.0	20.1	"
8	17,410	152	"	25.5	16.9	"
10	10,560	118	37	25.5	16.9	"
12	6,640	94	"	27.5	13.4	"
14	4,176	74	"	29.5	10.6	"
iller	.....	....	To equal Required Size	30.0	.....	Bunched

1. — The A.W.G. cross-sectional areas except for 61 strands, are approximated per cent. In the case of 61 strand cables the approximation is 6 per cent.
2. — Circular mils are based on theoretical diameters of A. W. G. sizes, which ove or below values given in table by less than 0.1 mil.
3. — "61X7" in the rating of a rope-lay cable signifies 61 strands of 7 wires each.

* **Correction for Lay.** — Two per cent shall be taken as the standard nt of resistance and of mass, due to stranding. In cases where the lay itely known, the increment should be calculated and not assumed.

) The resistance and mass of a stranded conductor are greater than in a solid or of the same cross-sectional area, depending on the lay (*i.e.*, the pitch of the the wires).

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Thickness of Insulation

9405. Thickness of Insulation for Rubber Insulated Wires and Cables. — Unless special conditions warrant departures from this rule, the thickness of insulation for rubber compounds containing from 30 to 40 per cent of Hevea rubber, shall be in accordance with Table 906.

TABLE 906

Thickness of Insulation

30 to 40 per cent Hevea Rubber Compound

Recommended Walls of Insulation, 64ths. Inch

Size A. W. G. or Cir. Mils	Square mm.	Working pressure, volts alternating										
		600 or less	1500	2500	3500	5000	6000	7000	8000	9000	10000	11000
14–8	2.08–8.37	3	6	8	10	12	14	16	18	20	22	24
7–2	10.6–33.6	4	7	9	10	12	14	16	18	20	22	24
1–0000	42.4–107	5	8	10	10	12	14	16	18	20	22	24
250,000–500,000	127–253	6	9	10	11	12	14	16	18	20	22	24
550,000–1,000,000	279–507	7	10	10	12	12	14	16	18	20	22	24
1,250,000–2,000,000	633–1013	8	10	10	12	14	16	18	18	20	22	24

Notes. — In multiple-conductor cables, the thickness of insulation on each conductor shall be based on the highest r.m.s. voltage between the conductor and the outside of this insulation. The above table is based upon alternating voltages of commercial frequencies. For voltages over 600, the insulation thickness for direct-current cables has not been established. For intermediate sizes the insulation thickness should be the same as for the next larger sizes.

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CHAPTER X

STANDARDS FOR STORAGE BATTERIES

DEFINITIONS

10001. Battery. — A group of cells electrically connected. Storage batteries e conveniently divided in two groups: stationary batteries and portable tteries. Stationary batteries include line batteries, load-regulating batteries, ak-load batteries, oil switch and exciter-reserve batteries, stand-by batteries, sphone exchange batteries and farm light batteries. Portable batteries lude starting and lighting batteries, vehicle batteries, car lighting batteries, ctric locomotive batteries, mine-lamp batteries, and ignition batteries.

10002. Cell. — A single element with electrolyte and container.

10003. Element. — The positive and negative groups with separators assem-d.

10004. Group. — Assembly of a set of positive or a set of negative plates for : cell.

10005. Jar or Tank. — The container for a cell.

NOTE. — The term tank is generally confined to lead containers supported wood.

10006. Separator. — A device for preventing metallic contact between the tes of opposite polarity within the cell.

10007. Electrolyte. — A solution of sulphuric acid for lead batteries and of tain hydroxides for nickel-iron batteries.

10008. Positive Plate. — The grid and active material from which the cur-t flows to the external circuit when the battery is discharging.

10009. Negative Plate. — The grid and active material to which the current vs from the external circuit when the battery is discharging.

10010. Grid. — A metallic framework for conducting current and holding active material or active material units of the plate.

10011. Active Materials. — Substances reacting chemically to produce :trical energy during discharge of the cell, but subject to oxidation or reduc-1 when on charge in the reverse direction, transforming electrical energy into mical energy. In the charged condition, these are lead peroxide on the itive plates and sponge lead on the negative plates of lead-acid cells, but for kel-iron cells they are nickel peroxide in the positive tubes and iron in the ative pockets.

10012. Couple. — One positive and one negative plate connected together a unit for adjacent cells.

10013. Counter Cells. — Cells of practically no capacity used to oppose the : voltage.

10014. End Cells. — Those cells of a battery which may be cut in or out of : circuit for adjusting the voltage.

10015. Terminals. — Fittings to provide electrical connections to storage ls or batteries.

10016. Pilot Cell. — A selected cell whose temperature, voltage and gravity : assumed to indicate the state of charge of the entire battery.

MISCELLANEOUS

10020. Ampere-hour Capacity. — The number of ampere-hours which can delivered by a cell or battery under specified conditions as to temperature, te of discharge and final voltage.

10021. Ampere-hour Efficiency. — The ratio of the ampere-hours output of a ll or battery under specified conditions of temperature, rate of discharge and al voltage, to the ampere-hours of input required for complete charge. See efficiency."

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10032. Average Voltage. — The average value of the voltage during the period of charge or discharge. It is conveniently obtained from the time integral of the voltage curve.

10033. Boost Charge. — A partial charge, usually at a high rate for a short period.

10034. Charge. — The restoration of the active materials in a battery by passing a direct current through it in the opposite direction to that of the discharge.

10035. Charging Rate. — The current, expressed in amperes, at which a battery is charged.

10036. Closed Circuit Voltage. — The voltage at a cell or terminals of the battery when current is flowing.

10037. Constant-current Charge. — A charge in which the current is maintained at constant value. For portable lead batteries this usually involves two rates called the starting and the finishing rates.

10038. Constant-potential Charge. — A charge in which the voltage at the terminals of the battery is held at a constant value. A modified constant potential system is one in which a fixed resistance is inserted in the charging circuit to limit the initial current.

10039. Discharge. — The conversion of the chemical energy of the battery into electrical energy.

10040. Efficiency. — The ratio of the useful output to the required input. The efficiency from an electro-chemical standpoint is the ampere-hour efficiency. It represents the ratio of the quantity of electricity delivered by the battery to the quantity required for a complete recharge, expressed in ampere-hours. The energy efficiency is the watt-hour efficiency. It represents the ratio of the energy delivered by the battery to the energy expended in charging it, expressed as watt-hours measured at the terminals of the battery. If the measurements are made at the busses, the watt-hour efficiency of the installation may be obtained. The so-called volt efficiency is the ratio of the average voltage on discharge to the average voltage on charge. The watt-hour efficiency of the battery is customarily taken as the product of the ampere-hour efficiency and the volt efficiency.

10041. Final Voltage. — The prescribed voltage upon reaching which the discharge is considered complete. The final voltage is usually chosen so that the useful capacity of the cell is realized. Final voltages vary with the kind of battery and the rate of the discharge.

10042. Equalizing Charge. — A charge given to a lead battery to insure the complete reduction of the lead sulphate. The equalizing charge is ordinarily at the finishing rate or less.

10043. Finishing Rate. — The rate of charge expressed in amperes to which the charging current for lead batteries is reduced near the end of charge to prevent excessive gassing.

10044. Gassing. — The evolution of oxygen or hydrogen, or both.

10046. Polarity. — An electrical condition determining the direction in which current tends to flow. By common usage the discharge current is said to flow from the peroxide plate or position through the external circuit. In a nickel iron battery the positive plate is that containing nickel peroxide.

10047. Reversal. — Change in normal polarity of a storage cell.

10048. Specific Gravity. — The ratio of the weight of a given volume of the liquid electrolyte to the weight of the same volume of water at a specified temperature. It is usually measured in storage battery work by a hydrometer.

10049. Trickle Charge. — A continuous charge at low rate for batteries in wet storage. It is approximately 1 per cent of the finishing rate.

10050. Volt Efficiency. — The ratio of the average voltage of the cell or battery on discharging to the average voltage on charge. See "efficiency."

10051. Watt-hour Capacity. — The ampere-hour capacity multiplied by the average voltage during discharge. It may, however, be measured directly.

2. Watt-hour Efficiency. — The ratio of the watt-hours of useful output watt-hours of input expended in charging. See "efficiency."

TEMPERATURE

1. The capacity obtained from a storage battery on discharge varies with nperature of the electrolyte. In order to compare various batteries, d reference temperatures are necessary; the following standard reference atures are established:

r. The temperature of electrolyte at beginning of discharge shall be ° C. (77° F.).

». The ambient temperature on discharge shall be from 5° C. to 8° C. er than the temperature of the electrolyte, on the beginning of discharge. e ambient temperature shall be kept constant throughout the discharge.

. (a) No limit is placed on the temperatures obtained by the electrolyte discharge.

n lead acid batteries, the limit of temperature of electrolyte permitted on depends upon the specific gravity of the electrolyte, higher temperatures ermitted on low gravity electrolyte. In general, it is desirable that the ature of the electrolyte on charge shall not exceed 45° C. (113° F.).

RATINGS

General

1. The capacities of storage batteries for different classes of service are ectly comparable. The capacity depends upon the discharge rate, e temperature of electrolyte (which has been standardized as 25° C.), gravity of electrolyte, and final voltage allowed.

1. Storage batteries shall be rated in accordance with the following ed capacity specifications:

(a) Ampere-hour capacity.
(b) Discharge rate.
(c) Reference temperature of discharge—25° C.
(d) Specific gravity of electrolyte at 25° C.
(e) Final voltage limit per cell on discharge.

1. The tabulated data required by the capacity specifications shall either n on a name-plate attached to battery, or, where this is not practicable, furnished separately.

TESTS

General

1. Batteries shall be tested as required, to determine if the rated capacity ned under the conditions as given in capacity specifications.

BATTERIES FOR SPECIAL SERVICE

). In certain definite classes of service, some or all of the variables given capacity specifications (No. 10202) can be definitely stated and stand-

CHAPTER XI

STANDARDS FOR ILLUMINATION

chapter consists of extracts from the Report of the Committee on clature and Standards of the Illuminating Engineering Society. It is cluded by permission.

General

0. Radiant flux, ϕ, is the rate of flow of radiation evaluated with refer- energy, and is expressed in ergs per second or in watts.

1.* Luminous flux is the rate of flow of radiant energy evaluated with

)1), (11006), (11007), (11008), (11010), (11011) These are the International ons as agreed on at the Paris meeting of the International Commission on Illumi- in 1921.

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reference to visual sensation. Although luminous flux must strictly be defined as above, it may be regarded for practical photometric purposes as an entity, since the rate of flow is for such purposes invariable.

11002. Visibility, K_λ, of radiation of a particular wave-length is the ratio of the luminous flux at that wave-length to the corresponding radiant flux.

Defining equation: $$K_\lambda = \frac{F_\lambda}{\Phi_\lambda}.$$

11003.* The mechanical equivalent of light is the ratio of radiant flux to luminous flux for the wave-length of maximum visibility, and is expressed in ergs per second per lumen, or in watts per lumen. It is the reciprocal of the maximum visibility.

11004. Luminosity of a particular wave-length is the product of the visibility of that wave-length and the corresponding ordinate of the spectral curve of radiant flux, and is represented by the ordinate of the spectral curve of luminous flux. This curve is called the spectral luminosity curve and is different with different sources.

11006. The **Luminous efficiency** of any source is the ratio of the luminous flux to the radiant flux from the source and is expressed in lumens per watt.

11006.* Luminous intensity of a point source in any direction is the flux per unit solid angle (one steradian) emitted by the source in that direction. (The flux from any source of dimensions which are negligibly small by comparison with the distance at which it is observed, may be treated as if it were emitted from a point.)

11007*. Illumination at any point of a surface is the luminous flux density at that point, or when the illumination is uniform, the flux per unit of intercepting area.

11008.* International Candle. — The unit of luminous intensity is the International Candle, such as has resulted from international agreement between the three national standardizing laboratories of France, Great Britain and the U. S. A. in 1909.

This unit has been conserved since then by means of incandescent lamps in the laboratories which continue (or remain) charged with conservation.

11009. Candlepower, cp., is luminous intensity expressed in candles.

11010.* Lumen. — The unit of luminous flux is the lumen. It is equal to the flux emitted in a unit solid angle by a uniform point source of one international candle.

11011.* Lux, Phot, Foot-candle. — The practical unit of illumination is the lux. It is equal to one lumen per square meter, or it is the illumination at the surface of a sphere of one meter radius due to a uniform point source of one international candle placed at its center.

As a consequence of certain recognized usages, the illumination can also be expressed by means of the following units:

Using the centimeter as the unit of length, the unit of illumination is one lumen per square centimeter, and is called the phot. Using the foot as the unit of length, the unit of illumination is one lumen per square foot, and is called the foot-candle.

11012. Brightness of an element of a luminous surface may be expressed in either of two ways: (a) in terms of intensity, I, (b) in terms of flux, F.

(a) Brightness in terms of the luminous intensity I (or candle-power) per unit of projected area of the surface (candlepower brightness) corresponds to

defining equation, $$bI = \frac{dI}{dS \cos\theta}$$

where θ is the angle between the normal to the surface and the line of sight.

(b) Brightness in terms of the flux, F, proceeding from a unit area of the sur-

---

(11003) This term has been used in a variety of senses. As here defined it refers only to the minimum mechanical equivalent of light. The reciprocal of this quantity is sometimes called the luminous equivalent of radiation.

(11010) A uniform source of one candlepower emits 4π lumens.

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, on the assumption that the surface is a perfect diffuser; *i.e.*, that it obeys cosine law of emission or reflection, (lumen brightness) corresponds to the

$$\text{defining equation, } b_F = \frac{dF}{dS}$$

fect diffusion assumed).
he units in which brightness is measured according to (a) and (b) differ only umerical value. See § 11013.

1013. Lambert, *L*, is the unit of brightness in the lumen system. The bert is the brightness of a perfectly diffusing surface emitting or reflecting lumen per square centimeter. For most purposes the **millilambert,** 0.001 bert, is the preferable practical unit.
o say that the brightness of a surface as viewed from a given point is *n* berts, signifies that its brightness is the same as that of a perfectly diffusing ace emitting or reflecting *n* lumens per square centimeter.
n practice no surface obeys exactly the cosine law of emission or reflection; ce the brightness of a surface generally is not uniform but varies somewhat the angle at which it is viewed.
perfectly diffusing surface emitting one lumen per square foot will have a htness of 1.076 millilamberts.
rightness expressed in candles per square centimeter may be reduced to berts by multiplying by $\pi = 3.14$.
rightness expressed in candles per square inch may be reduced to lamberts multiplying by $\pi/6.45 = 0.487$.

Surfaces and Media Modifying Luminous Flux

1020. Diffusing surfaces and media are those which break up the incident and distribute it more or less in accordance with the cosine law, as for mple, white plaster and opal glass.

1021. Redirecting surfaces and media are those which change the direction he luminous flux in a definite manner; as for example, a mirror or a lens.

1022. Scattering surfaces and media are those which redirect the luminous and break it up into a multiplicity of separate pencils; as for example, le glass, reflecting or transmitting.

1023.* Reflection factor, of a body ρ, is the ratio of the flux reflected by the y to the flux incident upon it. The reflection from a body may be regular, use or mixed. In regular reflection the flux is reflected at an angle of reflec- equal to the angle of incidence. In diffuse reflection the flux is reflected in directions. In perfectly diffuse reflection, the distribution of the reflected is in accordance with Lambert's cosine law. In most practical cases, there superposition of regular and diffuse reflection.

1024.* Absorption factor, of a body a, is the ratio of the flux absorbed by the y to the flux incident upon it.

1025.* Transmission factor, of a body τ, is the ratio of the flux transmitted the body to the flux incident upon it.

$$\rho + a + \tau = 1.$$

Illumination

1030. Unidirectional illumination on a surface is that produced by a single t source of relatively small dimensions. It is characterized by the fact that mall opaque object placed near the illuminated surface casts a sharp shadow.

1031. Multidirectional illumination on a surface is that produced by several arated light sources of relatively small area. It is characterized by the fact t a small opaque object placed near the illuminated surface casts several dows.

11023) (11024) (11025) These terms are introduced to replace the more commonly d terms, Coefficient of reflection, Coefficient of absorption, Coefficient of transmission, ich latter terms refer to the specific properties of materials rather than to the behavior bodies under specified conditions, such as angle of incidence, etc.

11032. Diffused illumination is that produced either by primary or secondary light sources having dimensions relatively large with respect to the distance from the point illuminated, and scattering light in all directions. It is characterized by relative lack of shadow. **Diffused illumination** may be derived principally from a single direction as in the light from a skylit window or from directions as in the open air. Perfectly diffused illumination on a surface is shadowless.

In any practical case of illumination on a surface there is usually a mixture of the above types.

11033. Coefficient of utilization of an illumination installation on a given plane is the total flux received by that plane divided by the total flux from the lamps illuminating it. When not otherwise specified, the plane of reference is assumed to be a horizontal plane 30 inches (76 cm.) from the floor.

11034. Variation factor of an illumination installation is the ratio of either the maximum or minimum illumination on a given plane to the average illumination on that plane.

11035. Variation range of illumination on a given plane is the ratio of the maximum illumination to the minimum illumination on that plane.

11036. Hemispherical ratio for a given lighting unit is the ratio of the luminous flux in the upper hemisphere to that in the lower hemisphere.

11037. Brightness ratio is the ratio of the brightness of any two surfaces. When the two surfaces are opposed, the brightness ratio is commonly called the "brightness contrast."

Illuminants

11040. The output of all illuminants should be expressed in **lumens.**

11041. Illuminants should be rated upon a lumen basis rather than a candle power basis.

11042. Lamp efficiency is the ratio of the luminous flux output to the power input.

11043. The lamp efficiency or **specific output of electric lamps** should be stated in terms of lumens per watt and that of illuminants depending upon combustion should be stated in lumens per British thermal unit per hour.

11044. The power consumption of **auxiliary devices** which are necessarily employed in circuit with a lamp should be included in the input of the lamp. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

11045. The specific consumption of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes watts per mean horizontal candle.

11046. Life Tests. — **Electric incandescent lamps of a given type** may be assumed to operate under comparable **conditions only when their lumens per** watt consumed are the same. Life test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

11047. In comparing different luminous sources not only should their candle power be compared, but also their relative form, **brightness,** distribution of illumination and character of light.

Lamp Accessories

11048. A reflector is an appliance the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

11049. A shade is an appliance the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

11050. A globe is an enclosing appliance of clear or diffusing material the chief use of which is either to protect the lamp or to diffuse its light.

Photometry

1060. **Performance curve** is a curve representing the behavior of a lamp in particular (candlepower, consumption, etc.) at different periods during its

1061. **Characteristic curve** is a curve expressing a relation between two ible properties of a luminous source, as candlepower and volts, candlepower rate of fuel consumption, etc.

1062. **Mean horizontal candlepower** of a lamp is the average candlepower e horizontal plane passing through the luminous center of the lamp. is here assumed that the lamp (or other light source) is mounted in the l manner, or, as in the case of an incandescent lamp, with its axis of sym- y vertical.

1063. **Mean spherical candlepower** of a lamp is the average candlepower of a in all directions in space. It is equal to the total luminous flux of the lamp mens divided by 4π.

1064. **Mean hemispherical candlepower** of a lamp (upper or lower) is the ge candlepower of a lamp in the hemisphere considered. It is equal to the luminous flux emitted by the lamp in that hemisphere divided by 2π.

1065. **Mean zonal candlepower** of a lamp is the average candlepower of a over the given zone. It is equal to the total luminous flux emitted by the in that zone divided by the solid angle of the zone.

1066.* **Spherical reduction factor** of a lamp is the ratio of the mean spherical e mean horizontal candlepower of the lamp.

TABLE 1100

Photometric Units and Abbreviations

otometric quantity	Name of unit	Symbols and defining equations	Abbreviation for name of unit
uminous flux	Lumen	$F.\psi$	l.
aminous intensity.	Candle	$I=\frac{dF}{d\omega}$, $\Gamma=\frac{d\psi}{d\omega}$	cp.
llumination	Phot, foot-candle, lux	$E=\frac{dF}{dS}=\frac{I}{r^2}\cos\theta$	ph. fc.
xposure	Phot-second	Et	
	Micro phot-second		phs. μ phs.
rightness	Apparent candle per sq. cm.	$b_l=\frac{dI}{dS\cos\theta}$	
	Apparent candle per sq. in.		
	Lambert	$b_l=\frac{dF}{dS}$	L. mL.
eflection factor		ρ	
bsorption factor		α	

ransmission factor	τ
lean spherical candlepower	scp.
lean lower hemispherical candlepower	lcp.
lean upper hemispherical candlepower	ucp.
lean zonal candlepower	zcp.
lean horizontal candlepower	mhc.

066) In the case of a uniform point-source, this factor would be unity, and for a ht cylindrical filament obeying the cosine law it would be $\pi/4$.
erfect diffusion assumed.

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14. 1 lumen is emitted by 0.07958 spherical candlepower.
15. 1 spherical candlepower emits 12.57 lumens.
16. 1 lux = 1 lumen incident per square meter = 0.0001 phot = 0.1 milliphot.
17. 1 phot = 1 lumen incident per square centimeter = 10,000 lux = 1,000 milliphots = 1,000,000 microphots.
18. 1 milliphot = 0.001 phot = 0.929 foot-candle.
19. 1 foot-candle = 1 lumen incident per square foot = 1.076 milliphots = 10.76 microphots.
20. 1 lambert = 1 lumen emitted per square centimeter of a perfectly diffusing surface.
21. 1 millilambert = 0.001 lambert.
22.*1 lumen, emitted, per square foot = 1.076 millilamberts.
23.*1 millilambert = 0.929 lumen, emitted, per square foot.
24. 1 lambert = 0.3183 candle per square centimeter = 2.054 candles per square inch.
25. 1 candle per square centimeter = 3.1416 lamberts.
26. 1 candle per square inch = 0.487 lambert = 487 millilamberts.

CHAPTER XII

STANDARDS FOR TELEPHONY AND TELEGRAPHY

Many of the following definitions are tentative and not yet fully established. Criticisms and suggestions, addressed to the Secretary of the Standards Committee, will be welcomed. Some of the definitions are specific to telephony and differ in detail from similar definitions appearing in other parts of the rules.

DEFINITIONS

Line Circuits

12000. Ground-return Circuit. — A ground-return circuit is a circuit consisting of one or more metallic conductors in parallel, with the circuit completed through the earth.

12001. Metallic Circuit. — A metallic circuit is a circuit of which the earth forms no part.

12002. Two-wire Circuit. — A two-wire circuit is a metallic circuit formed by two parallel conductors insulated from each other.

12003. Superposed Circuit. — A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

12004. Phantom Circuit. — A phantom circuit is a superposed circuit, the two sides of which consists of the two conductors of a two-wire circuit in parallel.

12005. Side Circuit. — A side circuit is a two-wire circuit forming one side of a phantom circuit.

12006. Non-phantomed Circuit. — A non-phantomed circuit is a two-wire circuit, which is not arranged for use as the side of a phantom circuit.

12007. Simplexed Circuit. — A simplexed circuit is a two-wire telegraph circuit, arranged for the superposition of a single ground-return signalling circuit operating over the wires in parallel.

12008. Composited Circuit. — A composited circuit is a two-wire telegraph circuit, arranged for the superposition on each of its component metallic conductors of a single independent ground-return signalling circuit.

12009. Quadded or Phantomed Cable. — A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

12010. Simplex Circuit. — A simplex circuit in telegraphy is one arranged for operation in one direction at one time.

12011. Duplex Circuit. — A duplex circuit in telegraphy is one arranged for simultaneous operation in opposite directions.

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012. Diplex Circuit. — A diplex circuit in telegraphy is one arranged for simultaneous transmission of two messages in the same direction.

013. Quadruplex Circuit. — A quadruplex circuit in telegraphy is one ged for the simultaneous transmission of two messages in each direction.

014. Multiplex Circuit. — A multiplex circuit in telegraphy is one arranged he simultaneous transmission of one or more messages in both directions. duplex and quadruplex are examples of multiplex whereas diplex is not.

015. Linear Electrical Constants. — The linear electrical constants of a re the electrical constants per unit length of the line, *e.g.*, linear resistance, nductance, etc.

016. Smooth Line. — A smooth line is a line whose electrical elements are ntinuously and uniformly distributed throughout its length.

017.* Periodic Line. — A periodic line is a line consisting of successive r sections in each of which one or more electric elements are not distributed rmly. As examples of periodic lines are (1) loaded lines and (2) artificial consisting of successive similar sections of lumped constants.

018. Equivalent Smooth Line. — An equivalent smooth line of a periodic s a smooth line having the same electrical behavior as the periodic line, at a single frequency, when measured at terminals or at corresponding section ions.

019. Equivalent Periodic Line. — An equivalent periodic line of a smooth is a periodic line having the same electrical behavior, for an assumed single ency, as the smooth line, when measured at terminals or at corresponding n junctions. The terms conjugate smooth line and conjugate periodic re also sometimes used.

020. Composite Line. — A composite line is a line consisting of a plurality ccessive sections having different linear electrical constants, as in the case e an underground cable section is joined to an overhead open-wire section.

021. Loaded Line. — A loaded line is one in which the normal reactance of circuit has been altered for the purpose of increasing its transmission effi- y.

023. Series Loaded Line. — A series loaded line is one in which the normal ance has been altered by reactance serially applied.

025. Shunt Loaded Line. — A shunt loaded line is one in which the normal ance of the circuit has been altered by reactance applied in shunt across ircuit.

024. Continuous Loading. — A continuous loading is a series loading in h the added inductance is uniformly distributed along the conductors.

025.* Coil Loading. — A coil loading is one in which the normal inductance ered by the insertion of lumped inductance in the circuit at intervals.

Circuit Constants and Characteristics

050. Damping of a Circuit. — The damping at a given point in a circuit which the source of energy has been withdrawn, is the progressive diminu- in the effective value of electromotive force and current at that point ting from the withdrawal of electrical energy.

051.* Damping Constant. — The damping constant of a circuit is a measure

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017) The term periodic in this definition refers to the line constants and not to time ons.

025) This lumped inductance may be applied either in series or in shunt. commonly understood, coil loading is a series loading, in which the lumped induct- is applied at uniformly spaced recurring intervals.

051) Applied to the admittance of a condenser or other simple circuit having capacity ance, the damping constant for a harmonic electromotive force of given frequency is atio of the conductance G, of the condenser or simple circuit at that frequency to the capacitance, C, of the condenser at the same frequency. $(G/2C)$.

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of the ratio of the dissipative to the reactive component of its admittance impedance.

12052.* Mutual Impedance. — The mutual impedance for single frequ alternating currents, between a pair of terminals and a second pair of term of a network, under any given condition, is the negative ratio of the electromo force produced between either pair of terminals on open circuit to the cu flowing between the other pair of terminals.

12053.* Self-impedance. — The self-impedance between a pair of term of a network, under any given condition, is the ratio of the electromotive f applied across the terminals to the entering current.

12054.* Characteristic Impedance. — The characteristic impedance of a is the ratio of the applied electromotive force to the resulting steady-state c rent upon a line of infinite length and uniform structure, or of periodic recur structure.

12055.* Sending-end Impedance. — The sending-end impedance of a is the ratio of the applied electromotive force to the resulting steady-state cu at the point where the electromotive force is applied.

12056.* Propagation Constant. — The propagation constant of a uni line, or section of a line of periodic recurrent structure, is the natural logar of the ratio of the steady-state currents at various points separated by unit in a uniform line of infinite length, or at successive corresponding points in of recurrent structure of infinite length. The ratio is determined by div the value of the current at the point nearer the transmitting end by the va the current at the point more remote.

12057. Attenuation Constant. — The attenuation constant for a single quency is the real part of the propagation constant taken at that frequency.

12058. Wave-length Constant. — The wave-length constant is the imagin part of the propagation constant.

12059. Standard Cable. — A standard cable is an ideal uniform line in ter of which the attenuation of a line or network may be specified. It is ch acterized by the following constants: Linear resistance, 88 ohms per loop m (54.7 ohms per loop km.). Linear capacitance between wires 0.054 microfa per loop mile (0.03355 microfarad per loop km.). Linear inductance and in leakance, 0.

Equivalent Circuits

12102.* Equivalent Circuit. — An equivalent circuit is a simple network series and shunt impedances, which, at a given frequency, is the approxim electrical equivalent of a complex network.

12103.* "T" Equivalent Circuit. — A "T" equivalent circuit is a th star or "Y" connection of three impedances externally equivalent to a com network. See Fig. 12-1 for symbol.

(12052) A receiving-end impedance is an example of a mutual impedance.

Single-frequency voltages and currents are here supposed to be represented by com numbers. Their ratio is therefore a complex number.

(12053) Single-frequency voltages and currents are here supposed to be represe by complex numbers. Their ratio is therefore a complex number.

(12054) In practise, the terms (1) line impedance, (2) surge impedance, (3) iter impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final s ing-end impedance, (7) natural impedance and (8) free impedance, have apparently b more or less indefinitely and indiscriminately used as synonyms with what is here de as "characteristic impedance."

Single-frequency voltages and currents are here supposed to be represented by com numbers. Their ratio is therefore a complex number.

(12055) See note under "Characteristic Impedance." In case the line is of infi length of uniform structure or of periodic recurrent structure, the sending-end impeda and the characteristic impedance are the same.

Single-frequency voltages and currents are here supposed to be represented by comp numbers. Their ratio is therefore a complex number.

(12056) Single-frequency voltages and currents are here supposed to be represe by complex numbers. Their ratio is therefore a complex number.

(12102 to 12106 Incl.) As ordinarily considered, the simple networks, as defined, are

4.* "*I*" **Equivalent Circuit.** — An "*I*" equivalent circuit is a connec- five impedances in the form shown in Fig. 12-2, which is externally lent to a complex network. It differs from the "*T*" equivalent circuit the impedances are arranged symmetrically on the two sides of the circuit, is often desirable in connection with practical problems, as indicating e circuit is balanced with respect to ground.

5.* "Π" **Equivalent Circuit.** — A "Π" equivalent circuit is a delta tion of three impedances externally equivalent to a complex network. so called a "*U*" equivalent circuit. See Fig. 12-3 for symbol.

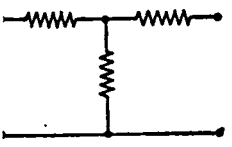


Fig. 12-1

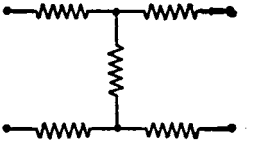


Fig. 12-2

6.* "*O*" **Equivalent Circuit.** — An "*O*" equivalent circuit is a connec- four impedances in the form shown in Fig. 12-4, externally equivalent to lex network. It differs from the Π equivalent circuit in that the impedre arranged symmetrically on the two sides of the circuit, which is often e in connection with practical problems, as indicating that the circuit is d with respect to ground.

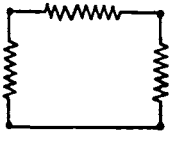


Fig. 12-3

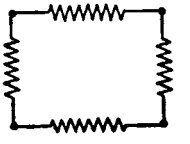


Fig. 12-4

Telephony

). **Manual Telephone System.** — A manual telephone system is one in he calling party gives his order to an operator who completes the call by hand, either with or without the assistance of one or more additional rs.

. **Automatic or Full Mechanical Telephone System.** — An automatic or chanical telephone system is one in which the calling party is enabled to te a call by remote-control switches without the aid of an operator.

. **Semi-automatic or Semi-mechanical Telephone System.** — A semitic or semi-mechanical telephone system is one in which the calling party is order to an operator who completes the call through remote-control s.

. **Telephone Exchange.** — A telephone exchange consists of one or more offices with associated plant, by means of which telephone service is d in a specified local community.

. **Telephone Exchange Area or District.** — A telephone exchange area ict is the area or district served by a telephone exchange.

. **Central Office (British "Exchange").** — A central office is a switching or inter-connecting lines terminating therein.

. **Toll Central Office.** — A toll central office is one in which toll and long e lines terminate.

. **Local Central Office.** — A local central office is one in which subscriber's rminate.

12206. Private Branch Exchange (Generally Abbreviated "P. B. X."). — A private branch exchange is a telephone system generally installed on the premises of a subscriber, including a switchboard and extension sets, and connected to a central office, affording intercommunication between the extension sets and also between these sets and the central office.

12209. Private Exchange. — A private exchange is one which serves a business organization or individual, and is not connected to a central office.

12210. Private Automatic Exchange. — A private automatic exchange is an automatic exchange which serves one business organization or individual, and not connected to a central office.

12211. Subscriber Set (Often Abbreviated to "Subset"). — A subscriber set is an assembly of apparatus for sending and receiving telephone calls.

12212. Subscriber Station (Often Abbreviated to "Substation"). — A subscriber station is an installed subscriber set connected to a central office for the purpose of sending and receiving telephone calls.

12213. Pay Station (British "Public Call Office"). — A pay station is a subscriber station available for the use of the public on the payment of a fee. The fee may be either deposited in a coin box or paid to an attendant.

12214. Toll Station. — A toll station is a pay station located outside of a local service area and affording toll and long distance service only.

12215. Subscriber Line or Subscriber Loop. — A subscriber line or subscriber loop is the wire connection between a subscriber station and the central office.

12216. Subscriber Line Circuit. — A subscriber line circuit is a subscriber line with its associated individual central office apparatus.

12217. Individual Line (British "Direct Line"). — An individual line is a subscriber line which connects one subscriber station to a central office, though it may have one or more extension sets.

12218. Party Line. — A party line is a subscriber line which connects two or more subscriber stations to a central office.

12219. Tip Side or Tip Wire, Ring Side or Ring Wire. — The tip side or wire, or the ring side or wire, is that conductor of a circuit which is associated with the corresponding member of a jack.

12220. Negative Side or Negative Wire, Positive Side or Positive Wire. — The negative side or wire, or the positive side or wire, is that conductor of a circuit which is normally connected to the corresponding pole of a battery.

12221. Main Distributing Frame. — A main distributing frame is a structure for terminating the permanent inside and outside wires of a central office and effecting flexible junctions between them. It generally carries central office protective devices and functions as a test point between line and office.

12222. Intermediate Distributing Frame. — An intermediate distributing frame is a structure for terminating permanent inside wires of a central office and for effecting flexible junctions between them.

12223. Switchboard. — A switchboard is an assemblage of apparatus for coordinate structure for switching talking and signaling circuits.

12224. Switchboard Section. — A switchboard section is an element or unit one or more of which constitutes a complete manual switchboard.

12225. Operating Room. — An operating room is a room which contains a manual switchboard and associated apparatus.

12226. Combination Current. — A combination current consists of two or more currents of different characteristics in the same circuit. As ordinarily used the term refers to currents whose characteristics are steadily maintained, as for example, a combination of direct current and an alternating current.

12227. Manual Ringing. — Manual ringing is ringing which is effected and continues with the operation of a key.

12228. Machine Ringing. — Machine ringing is intermittent and is caused to act periodically by the apparatus itself.

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12229. Superimposed Ringing Current. — A superimposed ringing current is a mbination current for ringing, consisting of a direct and an alternating current.

12230. Pulsating Ringing Current. — A pulsating ringing current is a current r ringing in which the succeeding impulses are separated by intervals approxi- tely equal to those of the impulses themselves.

12231. Harmonic Selective Signaling. — Harmonic selective signaling employs vices tuned mechanically or electrically to the frequency of the ringing current, that each device will not operate when receiving current intended to operate other device.

12232. Multiple Harmonic Signaling. — Multiple harmonic signaling employs quencies which are integral multiples of the lowest frequency.

12233. Non-multiple Harmonic Signaling. — Non-multiple harmonic signal- employs frequencies which are not integral multiples of the lowest frequency.

12234. "To Call." — "To call" is to originate a telephone call.

12235. "To Dial." — "To dial" a number is to use a dial type of calling vice in order to control automatic switches.

12236. "To Set Up." — "To set up" a number is to use a key type or multiple r type of calling device in order to control automatic switches.

12237. Calling Device. — A calling device is an apparatus by means of which omatic switches are controlled for the purpose of establishing a connection.

12238. Calling Party. — A calling party is a person who originates a telephone

12239. Called Party. — A called party is the person who answers when a tion is called.

12240. Reverting Call. — A reverting call is one between two stations on the ne subscriber line.

12241. Telephone Traffic. — Telephone traffic is the aggregate volume of nmunication handled in a given time.

12242. "Busy." — "Busy" is the condition of a line or an apparatus when n in use.

12243. Free. — Free is the condition of a line or an apparatus when it is not se. Free is the opposite of busy.

12244. "To Make Busy." — "To make busy" is to cause a line or an appa- us to appear to be busy.

12245. "To Release" or to "Disconnect." — "To release" or "to discon- t" is to terminate a telephone connection by disengaging the apparatus.

12246. "To Clear." — "To clear" is to restore a line or an apparatus to the t condition.

12247. Trunk. — A trunk is the wire connection between switching devices central offices.

12248. Trunk Circuit. — A trunk circuit is a trunk with its associated indi- ual apparatus.

12249. Trunked Call. — A trunked call is one which employs an inter-office nk or a trunk between two switchboard positions.

12250. Relay. — A relay is a device by means of which contacts in one circuit operated by a change in conditions in the same circuit or in one or more ociated circuits. (See Rule 7016.)

12251. Polar Relay. — A polar relay is a relay which operates in response to hange in the direction of the current in the controlling circuit.

12252. Quick Operating Relay. — A quick operating relay is one which erates its contacts within a specified brief time limit.

12253. Quick Release Relay. — A quick release relay is one which releases contacts within a specified brief time limit.

12254. Quick Acting Relay. — A quick acting relay is one which has the roperties of both a quick operating and a quick release relay.

12255. Slow Operating Relay. — A slow operating relay is one which does not operate until after a specified delay.

12256. Slow Release Relay. — A slow release relay is one which when operated will not release until after a specified delay.

12257. Slow Acting Relay. — A slow acting relay is one which has the properties of both a slow operating and a slow release relay.

12258. Line Relay. — A line relay is one whose coil is normally in the line circuit.

12259. Cut-off Relay. — A cut-off relay is one which when operated disconnects from a line apparatus normally connected to it.

12260. Relay Coil Section. — A relay coil section is one of two or more windings of a coil on one and the same core. The several sections may be concentric or placed side by side on the core.

12261. Tension Spring. — A tension spring is one which functions through mechanical pressure but does not carry an electrical current.

12262. Contact Spring. — A contact spring is one which takes an electrical part in switching a circuit.

12263. Main Contact Spring. — A main contact spring is one which directly switch a circuit between two or more other contact springs.

12264. Armature Spring. — An armature spring is the first of a group to be moved by the armature. It may or may not be a main contact spring.

12265. Plunger Spring. — A plunger spring is the first of a group to be moved by the plunger.

12266. Impulse Springs. — Impulse springs are those which act to make and break a circuit for the purpose of sending impulses.

12267. Make-Before-Break Contact Springs (Abbreviation "M. B. B." — Make-before-break contact springs are those in which the main spring touches the front contact before it breaks away from the back contact. Also called continuity preserving contact.

12268. Back Contact Spring. — A back contact spring is one against which the main contact spring rests when in the normal position.

12269. Front Contact Spring. — A front contact spring is one against which the main contact spring rests when in the operated position.

12270. Automatic Signaling. — Automatic signaling is effected without the aid of an operator.

12271. Automatic Switch. — An automatic switch is a remote control device for controlling talking or signaling circuits.

12272. Finder Switch. — A finder switch is a switch connected to one of a smaller number of circuits and which finds automatically a circuit out of a larger number of circuits from whence the signal comes.

12273. Line Switch. — A line switch is a switch connected to one of a larger number of circuits from which a signal comes and which finds automatically the circuit out of a smaller number of circuits.

12274. Selector Switch. — A selector switch is a switch whose duty is to select a particular group of trunks and one trunk of the group selected. In particular cases, one of these functions may be omitted.

12275. Connector Switch or Final Selector. — A connector switch or final selector is a switch whose duty is to establish a connection with the called line. It is usually operated by the last digit or digits of the call number.

12276. Switch Frame. — A switch frame is a structure for mounting the assembly of switching apparatus which may be integral therewith.

12277. Section of Switches. — A section of switches, considered from a mounting standpoint, is a group of adjacent switches whose banks are multiplied together.

12278. Switchroom. — A switchroom is a room which contains an assembly of automatic switches and associated apparatus.

Bank Wires. — Bank wires are those wires which multiple adjacent banks to each other.

Bank Cable. — A bank cable is one which connects a switch bank to a rack.

Multiple Cable. — A multiple cable is one which multiples together more sections of switch banks by connecting together their terminals.

Impulse. — An impulse is any sudden change of brief duration pro- the current of a circuit.

Make Impulse. — A make impulse is an impulse due to a temporary current.

Break Impulse. — A break impulse is an impulse due to a temporary tion of current.

Impulse Frequency. — The impulse frequency is the number of occurring per second. The reciprocal of this is the impulse period.

Impulse Period. — The impulse period is the period of time included the corresponding points in periodically recording impulses. It thus ds to the period of alternating current.

Impulse Ratio. — Impulse ratio is the ratio of duration of an impulse pulse period.

Impulse Circuit. — An impulse circuit is one through which impulses mitted.

Telephone Impulse Repeater. — A telephone impulse repeater is a r repeating impulses from one line circuit into another and for perform- r duties.

Supervisory Signal. — A supervisory signal is a device for attracting a of an attendant to a duty in connection with switching apparatus or sories. This includes cord supervisory lamps on a manual switchboard supervisory lamps in an automatic exchange which indicates that a as been occupied but has not completed its function.

Tell-tale Signal. — A tell-tale signal is a device for locating the f some apparatus; for example, the blowing of a fuse, the continued of heavy current by apparatus intended to receive only momentary etc.

Alarm Signal. — An alarm signal is a sound-producing device for g attention to either a supervisory or a tell-tale signal.

Amplifier. — See § 13040.

Telephone Repeater. — A telephone repeater is a device for ampli- oice current from one line circuit into another line circuit.

Telephone Receiver. — A telephone receiver is an electrically oper- ice designed to produce sound waves or vibrations which correspond to romagnetic waves or vibrations actuating it.

Microphone. — A contact device designed to have its electrical resist- ectly and materially altered by slight differences in mechanical pressure.

Telephone Transmitter. — A telephone transmitter is a sound-wave- or vibration-operated device designed to produce electromagnetic vibrations which correspond to the sound waves or vibrations actuat-

* **Coefficient of Coupling of a Transformer.** — The coefficient of coup- transformer at a given frequency is the ratio of the mutual impedance the primary and secondary of the transformer, to the square root of uct of the self-impedances of the primary and of the secondary.

Repeating Coil. — A term used in telephone practice meaning the transformer, and ordinarily a transformer of unity ratio.

Single-frequency voltages and currents are here supposed to be represented ex numbers. Their ratio is therefore a complex number.

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12305.* **Retardation Coil.** — A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which flow at different rates.

12306. Manual Switchboard. — A manual switchboard is one in which switching operations are performed by hand.

12307. Multi Office Exchange (British "Multi Exchange System"). — A multi office exchange is one which is composed of more than one office.

12308. Trunk Hunting. — Trunk hunting is the operation of an automatic switch in moving its wipers or brushes to an idle set of terminals or contacts in a chosen group of terminals or contacts.

12309. Wiper. — A wiper is that portion of the moving member of a switch which engages with a bank contact.

12310. Bank. — A bank is an assembly of fixed contacts with which the moving members of a selector engage. Banks are usually multiplied.

Telegraphy

12500. Relay. — A relay is a device by means of which contacts in one circuit are operated by a change in conditions in the same circuit or in one or more associated circuits.

12501. Polar Relay. — A polar relay is a relay which operates in response to a change in the direction of the current in the controlling circuit.

12502. Non-polar Relay, or Neutral Relay. — A non-polar relay is a relay which operates in response to a change in the strength of the current in the controlling circuit, irrespective of the direction of the current.

12503. Neutral Relay. — See non-polar relay.

12504. Selector. — A selector is a device which performs certain functions such as causing an electric lamp to light, or an electric bell to sound, in response to a definite signal or group of successive signals received over a control circuit.

12505. Direct-point Repeater. — A direct-point repeater is a repeater in which the receiving relay controlled by the signals received over a line repeats these signals into another line or lines without the interposition of any telegraph repeating or transmitting apparatus.

12506. Concentrator. — A concentrator is a traffic distributing device by means of which a number of telegraph or telephone lines, and connected operating instruments are brought together at one point to facilitate their interconnection at such times as signals or messages are to be transmitted from one to the other.

12507. Transmitter. — A transmitter is a device for effecting electrical changes in a controlled circuit. The term transmitter is commonly applied principally to devices which in response to a controlling means effects in a main line telegraph circuit electrical changes necessary to send signals over the line.

12508. Synchronous System. — A synchronous system of telegraphy is one in which the proper transmission and reception of signals is dependent upon the synchronous operation of similar commutators or other devices located at the sending and receiving stations of a circuit.

12509. Differential Duplex. — A differential duplex is a duplex system in which at each station one of two portions of the receiving instrument is connected in series with the line wire and the other in series with an artificial line of such electrical characteristics that the effects upon the receiver of currents passing through the main and artificial lines, as a result of outgoing signals, are neutralized.

12510. Bridge Duplex. — A bridge duplex is a duplex system in which the receiving instruments at each station are connected across two impedances

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(12305) In telephone and telegraph usage, the terms "impedance coil," "inductance coil," "choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

ies with the line wire and the other in series with the artificial line in such ner that no electrical change in the receiver circuit is effected by outgoing ls.

111. **Half-set Repeater.** — A half-set repeater is a repeater used for con- ng together a simplex circuit and a duplexed circuit converting them into quivalent of a single simplex circuit.

112. **Intermediate Current Supply.** — An intermediate current supply is an anded source of current connected in series with a line wire at a station than a terminal on a ground return telegraph circuit.

113. **Phantoplex Circuit.** — A phantoplex circuit is a superposed circuit ated by alternating current over a simplex, duplex or quadruplex circuit ated from direct-current sources.

114. **Spark Condenser.** — A spark condenser is a condenser, with or without ated non-inductive resistance, connected with a pair of instrument contact s for the purpose of diminishing sparking at these points.

115. **Current Margin.** — In a non-polar simplex system, the difference en the current flowing through a receiving instrument when operated, to lo- ing when not operated.

116. **Margin Ratio.** — In a non-polar simplex system, the ratio of the cur- lowing through a receiving instrument when operated, to that flowing when perated.

117. **Percentage Margin.** — In a non-polar simplex, the current margin ured as a percentage of the current flowing through the relay when operated.

118. **Main Circuit.** — A main circuit is a major electrical circuit of a tele- system and includes both transmitting and receiving devices.

119. **Local Circuit.** — A local circuit is a circuit, within the limits of the n, usually controlled by a receiving instrument in a main circuit or con- ng a transmitter effecting changes in a main line circuit.

CHAPTER XIII

STANDARDS FOR RADIO COMMUNICATION

General

s chapter has been mainly abstracted from the report of the Standardisa- Committee of the Institute of Radio Engineers, and is here included by ssion, until further revised. For full particulars, see the I. R. E. Stand- ion Committee report.

120. **Acoustic Resonance Device.** — One which utilizes, in its operation, nce to the audio frequency of the received signals.

121. **Antenna.** — A system of conductors designed for radiating or absorb- f energy of electromagnetic waves.

122. **Atmospheric Absorption.** — That portion of the total loss of radiated due to atmospheric conductivity.

123. **Audio Frequencies.** — Frequencies corresponding to the normally e vibrations. These are assumed to lie below 10,000 cycles per second.

124. **Capacitive Coupler.** — An apparatus which, by electric fields, joins rs of two radio-frequency circuits, and which is used to transfer electrical between these circuits through the action of electric forces.

125. **Coefficient of Coupling (Inductive).** — The ratio of the effective l inductance of two circuits to the square root of the product of the ve self-inductances of each of these circuits.

126. **Direct Coupler.** — A coupler which magnetically joins two circuits a common conductive portion.

18007. Counterpoise. — A system of electrical conductors forming a portion of a radiating oscillator, the other portion of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

18008. Damped Alternating Current. — A damped alternating current is an alternating current whose amplitude progressively diminishes.

18009. Damping Factor. — The damping factor of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let I_0 = initial amplitude,
I_t = amplitude at the time t,
e = base of Napierian logarithms,
a = damping factor.

Then $I_t = I_0 e^{-at}$.

18010. Detector. — That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a source contained or separate indicator, translates the radio-frequency energy into a form suitable for operation of the indicator. This translation may be effected either by the conversion of the radio-frequency energy, or by means of the control of local energy by the energy received.

18015. Electromagnetic Wave. — A periodic electromagnetic disturbance progressing through space.

18016. Forced Alternating Current. — A current, the frequency and damping of which are equal to the frequency and damping of the exciting electromotive force.

18017. Free Alternating Current. — The current following any electromagnetic disturbance in a circuit having capacitance, inductance, and less than the critical resistance.

18018. Critical Resistance of a Circuit. — That resistance which determines the limiting condition at which the oscillatory discharge of a circuit passes into an aperiodic discharge.

18019. Group Frequency. — The number per second of periodic changes of amplitude or frequency of an alternating current.

Note 1. Where there is more than one periodically recurrent change of amplitude or frequency, there is more than one group frequency present.

Note 2. The term "group frequency" replaces the term "spark frequency."

18020. Inductive Coupler. — An apparatus which, by magnetic forces, links portions of two radio-frequency circuits and is used to transfer electrical energy between these circuits, through the action of these magnetic forces.

18025. Logarithmic Decrement. — The logarithmic decrement of an exponentially damped alternating current is the logarithm of the ratio of successive current amplitudes in the same direction.

Note: Logarithmic decrements are standard for a complete period or cycle.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction.

d = logarithmic decrement.

Then: $$d = \log_e \frac{I_n}{I_{n+1}}.$$

18026. Radio Frequencies. — The frequencies higher than those corresponding to the normally audible vibrations, which are generally taken as 10,000 cycles per second. See also Audio Frequencies.

Note: It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience.

18027. Resonance. — Resonance of a circuit to a given exciting alternating e.m.f. is that condition due to variation of the inductance or capacity in which the resulting effective current (or voltage) in that circuit is a maximum.

1935. Standard Resonance Curve. — A standard resonance curve is a curve ordinates of which are the ratios of the square of the current at any frequency he square of the resonant current, and the abscissas are the ratios of the corponding wave length to the resonant wave length; the abscissas and ordis having the same scale.

1936. Sustained Radiation. — Sustained radiation consists of waves radiated n a conductor in which an alternating current flows.

1936. Tuning. — The process of securing the maximum indication by nting the time period of a driven element. (See Resonance.)

1938. Wave-Meter. — A wave-meter is a radio-frequency measuring instrut, calibrated to read wave lengths.

1934. Decremeter. — An instrument for measuring the logarithmic decret of a circuit or of a train of electromagnetic waves.

1937. Attenuation, Radio. — The decrease with distance from the radiating ce, of the amplitude of the electric and magnetic forces accompanying (and ituting) an electromagnetic wave.

1938. Attenuation, Coefficient of (Radio). — The coefficient which, when tiplied by the distance of transmission through a uniform medium, gives the ral logarithm of the ratio of the amplitude of the electric or magnetic forces ial distance, to the initial value of the corresponding quantities.

1939. Coupler. — An apparatus which is used to transfer radio-frequency gy from one circuit to another by associating portions of these circuits.

1940. Amplifier. — An amplifier is an instrument which modifies the effect local source of energy in substantial accordance with the wave-form of the ived energy, and gives out a wave of greater amplitude than that which it ives.

1941. Phase Angle Defect. — The phase angle defect of a condenser is the arture from quadrature of the phase difference between potential and current erminals. This is sometimes called the phase angle of a condenser: although ctly speaking the phase angle of a condenser is 90° less the phase angle defect, is therefore exactly 90° when the phase angle defect is zero.

1942. Impulse E.m.f. — An e.m.f. the effective value of which becomes small pared with its maximum value in a time which is short compared with the ition of the current which it causes.

1944. Directive Coefficient. — The directive coefficient of a transmitting nna at a given distance therefrom on the surface of the earth or sea, for a n wave length, is the ratio of average field intensity within an angle of stated es centered about the direction of maximum radiation, to the average field sity in all directions.

1945. Directional Selectivity. — The directional selectivity of a receiving nna at a given wave length is the ratio of the average e.m.f. induced in that nna for waves of equal intensity coming from directions comprised within an e of stated degrees centered about the direction of best reception, to the age e.m.f. induced in the antenna for waves of equal intensity coming from irections.

1946. Radiation Efficiency. — The radiation efficiency of an antenna at a n wave length is the ratio of radiation resistance to the antenna resistance.

1947. Selectivity. — The (overall) selectivity of a receiving system is the uct of the several selectivities of that system.

1948. Average Selectivity. — The average selectivity of a receiving system e nth root of the product of the n selectivities of that system.

1949.* Radio-Frequency Selectivity. — The radio-frequency selectivity of a le element * of a receiving system is the ratio of resonant response (in terms fective voltage or current measured at the indicator) to the non-resonant

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CHAPTER XIV

STANDARDS FOR PRIME MOVERS AND GENERATOR UNITS

General

14000. Regulation of Steam Engines, Steam Turbines and Internal Combustion Engines. — In steam engines, steam turbines and internal combustion engines, the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed, to the rated-load speed in passing slowly from rated-load to no-load (with constant conditions at the supply).

14001. Fluctuation of Steam Engines, Steam Turbines and Internal Combustion Engines. — The percentage fluctuation of a steam engine, steam turbine or internal combustion engine, is the immediate percentage speed regulation corresponding to a sudden change from rated-load to no-load.

14002. Regulation of Hydraulic Turbines. — In a hydraulic turbine or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation in speed in passing slowly from rated-load to no-load (at constant head of water), to the rated-load speed.

14003. Regulation of Generator Units. — In a generator unit, consisting of a generator combined with a prime mover, the speed or voltage regulation shall be based upon constant conditions of the prime mover; *i.e.*, constant steam-pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

14010.* Variation in Prime Movers. — The variation in prime movers which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 degrees. See § 4088.

14011. Pulsation in a Prime Mover, or in the Alternator Connected Thereto. — The pulsation in a prime mover, or in the alternator connected thereto, is the ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

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(14010) If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct connected, and p n times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

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CHAPTER XV

STANDARDS FOR TRANSMISSION LINES AND DISTRIBUTION LINES

Note: For flash-over tests of insulators, see foot-note to § 2361.

General

§ 2360. **Regulation of Transmission Lines, Feeders, etc.** — The regulation of transmission lines, feeders, etc., is the change in the voltage at the receiving end between rated non-inductive load and no-load, with constant impressed voltage at the sending end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

CHAPTER XVI

MISCELLANEOUS STANDARDS

HEATING DEVICES

§ 2361. **Value of A-C. Test Voltage for Household Devices.** — Heating devices taking not over 660 watts, intended solely for operation on supply circuits not exceeding 275 volts, shall be tested with 500 volts at operating temperature.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

I. E. C. RULES FOR ELECTRICAL MACHINERY

VOLUME I

(Adopted at the Plenary Meeting, held in London, October, 1919)

These rules apply to rotating machines of which the terminal pressure do not exceed 5000 volts or of which the rated output does not exceed 750 kv or of which the stator cores do not exceed 50 cm. in length axially, and t transformers which are not water-cooled.

PART I. GENERAL

I. Scope of Rules

1. *Rotating Machines.* — The rules of the I. E. C. contained in this publicat apply to rotating machines, of which the terminal pressure does not exce 5000 volts or of which the rated output does not exceed 750 kv.-a., or of wh the stator cores do not exceed 50 cm. in length axially.

2. *Transformers.* — These rules also apply to all transformers which are n water-cooled. (For water-cooled transformers, *see* Appendix II.)

3. *Altitude.* — In the absence of any information in regard to the heig above sea level at which the machine is intended to work in ordinary servi this height is assumed not to exceed 1000 meters. If the machine is intend to work at an altitude above 1000 meters a correction to the temperature s should be applied. The value for this correction has not yet been fixed by t I. E. C.

4. *Temperature.* — In the absence of any information to the contrary, it i assumed that the temperature of the cooling air shall not exceed 40° C.

II. Definitions

5. *Rating.* — (See Appendix IV.)

6. *Use of the Term "Machine."* — The term "machine" is used in the rules in its most general sense, so as to avoid the constant repetition of th words "machines, transformers and other electromagnetic induction apparatus"

7. *Use of the Term "Power."* — It is usual to speak of a machine by i *power*. It is necessary to note that the term "power" should be used in th following way:

(a) For direct-current generators, the electric power at the terminals expres in watts (w.) or kilowatts (kw.).

(b) For alternators, the apparent power at the terminals, expressed in volt amperes (v.-a.) or kilovolt-amperes (kv.-a.).

(c) For motors, the mechanical power available at the shaft, expressed i watts (w.) or kilowatts (kw.).

(d) For transformers, apparent output at the secondary terminals, expresse in volt-amperes (v.-a.) or kilovolt-amperes (kv.-a.).

III. I. E. C. Rating

8. *Test Rating.* — The I. E. C. rating has been established as a *test* rating which will enable an exact comparison to be made between machines of differe makes.

9. *Classes of Rating.* — There are two classes of I. E. C. rating:

(a) The I. E. C. continuous rating (*see* Clause 10).

(b) The I. E. C. short-time rating or limited-time rating (*see* Clause 12).

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o. *Continuous Rating.*—The I. E. C. continuous rating is the load which be carried on test, under the conditions of that rating, for an unlimited iod without the limits of the I. E. C. rules, as regards temperature rise, ig exceeded.

1. *Service Thermally Equivalent to the Continuous Rating.* — Any machine nded for continuous service on fluctuating load may be given for test pur- es a thermally equivalent I. E. C. continuous rating, provided that the rice for which it is intended shall not cause, in any of its parts, temperatures temperature rises in excess of those allowed by the I. E. C. rules when the chine is tested under the conditions of its continuous rating.

General Note re Classes of Fluctuating Load Service, inserted by the Editing mittee. — It is desirable to distinguish between two kinds of fluctuating load ice:

(i) *That in which the overload peaks can be sustained by a machine of ordinary construction, without modification, and without exceeding the limits of temperature rise allowed by these rules for the machine when tested under its I. E. C. continuous rating.*

(ii) *That in which the overload peaks involve special provisions in design or construction either for mechanical or for electrical reasons.*

To designate this second class of service it is customary in Great Britain and the United States of America to employ the term "duty cycle rating," and the word "cycle" in this case signifies a period of time sufficiently long to include all the variations of load which might influence either the electrical construction or the mechanical construction of the machine.

12. *Short-time Rating.*—The I. E. C. short-time rating is the load which can carried on test for the time specified in the rating, the test being started with machine cold and carried out under all the conditions of the rating, without limits fixed by these I. E. C. rules, as regards temperature rise, being exceeded.

13. *Service Thermally Equivalent to the Short-time Rating.* — Any machine ended for service on loads which vary considerably may be given for test rposes a thermally equivalent I. E. C. short-time rating, provided that the vice for which it is intended shall not occasion, in any of its parts, tem- ratures or temperature rises in excess of those allowed by these rules when machine is tested under the conditions of its short-time rating.

PART II. INFORMATION TO BE GIVEN WITH ENQUIRIES AND ORDERS FOR ELECTRICAL MACHINES

IV. General Information

Note. — The term *machine* is used in these rules in its most general sense so to avoid the constant repetition of the words *machines, transformers* and other *tromagnetic induction apparatus.*

14. *General Information.* — The enquiry or order for an electrical machine ould give the following general information:

(a) The service output.

(b) The class of service required.

In the absence of any indication to the contrary, continuous service is understood.

(c) The maximum temperature of the cooling air in which the machine is ended to work when it exceeds 40° C.

In the absence of any definite information, it is understood that the temperature of the cooling air will not exceed 40° C.

(d) The altitude of the place where the machine is intended to work, if it ceeds 1000 meters. In regard to altitude, *see* Clause 3.

(e) Any special requirements, if necessary, with regard to windings, methods connection, neutral points and special tapping points, etc.

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(f) When the apparatus is intended to operate in parallel with other apparatus, the fact should be stated.

(g) Any special requirements in regard to electrical and mechanical details such as protective devices, cooling arrangements, etc.

(Specific recommendations regarding these details will be made at a later date by the I. E. C.)

V. Supplementary Information

15. *Supplementary Information.* — The above general information should be completed by the following supplementary information in regard to the particular machine forming the subject of the order:

16. *Direct-current Generator.*
- Output at the terminals, in watts (w.) or kilowatts (kw.).
- Pressure between terminals, in volts.
- Current, in amperes.
- Speed, in revolutions per minute.
- Method of excitation.

17. *Direct-current Motor.*
- Output at the shaft, in watts (w.) or in kilowatts (kw.).
- Pressure between terminals, in volts.
- Current, approximate, in amperes.
- Speed at rated output, approximate, in revolutions per minute.
- Method of excitation.

18. *Alternating-current Transformer.*
- Frequency, in periods per second.
- Number of phases.
- Output, in voltamperes (v.-a.), or in kilovoltamperes (kv.-a.).
- Primary pressure between terminals, in volts.
- Secondary pressure between terminals, in volts, at no-load and at rated output with statement as to the power factor of the circuit fed by the secondary. If the power factor is not specified it shall be taken as 0.8.
- Secondary current, in amperes.
- For transformers intended to work in parallel, the primary pressure, current, and power factor on short-circuit test, shall also be stated.
- For three-phase transformers the method of connection shall also be indicated in accordance with the vector diagrams (*see* Appendix I).
- Any special requirements as to the accessibility of neutral points or special tapping points shall be indicated.

Note. — Whatever may be the nature of the transformers (step-up or step-down) the primary terminals are those which are connected to the source of electrical energy and the secondary terminals those which receive the electrical energy.

19. *Synchronous Alternator for Alternating Currents, Single or Polyphase.*
- Frequency, in periods per second.
- Number of phases.
- Output between terminals, in volt-amperes (v.-a.) or kilovolt-amperes (kv.-a.).
- Pressure between terminals, in volts, corresponding to the rated output.
- Power factor of the system to be supplied. If this is not specified it shall be taken as 0.8.
- Current, in amperes.
- Speed, in revolutions per minute.
- Excitation pressure, in volts (if the alternator is not provided with a special exciter).
- Maximum exciting current available, in amperes (if the alternator is not provided with a special exciter).

20. *Synchronous Motor for Alternating Currents, Single or Polyphase.*
Frequency, in periods per second.
Number of phases.
Mechanical output at the shaft, in watts (w.) or in kilowatts (kw.).
Current, approximate, in amperes.
Pressure, in volts, of supply available.
Speed, in revolutions per minute.
Unless otherwise specified, the motor must be capable of giving its rated mechanical output at unity power factor.
If the motor is required to act as a device for improving the power factor, the value of the reactive power required shall be stated.
Excitation pressure, in volts (if the motor is not provided with a special exciter).
Method of starting to be employed and source of power available for this purpose.
Maximum exciting current available, if limited.

21. *Non-synchronous Motor for Alternating Currents, Single or Polyphase.*
Frequency, in periods per second.
Number of phases.
Mechanical power at the shaft, in watts (w.) or in kilowatts (kw.).
Pressure between terminals, in volts.
Current, approximate, in amperes.
Speed, in revolutions per minute, approximate, at the rated output.
Rotor, whether wound or squirrel cage.
Method of starting.
Unless otherwise specified it is assumed that the stator receives the supply current.
Starting torque in kilograms at one meter.
Ratio of the starting current to the current corresponding to the rated output.
Ratio of the starting torque to the torque corresponding to the rated output.
The last three items are to be stated for the motor with its starting accessories.

PART III. CONDITIONS TO BE FULFILLED BY ELECTRICAL MACHINERY

VI. General Remarks

22. *General.* — This section deals with the conditions to be fulfilled by a machine purporting to comply with the I. E. C. Rules.

VII. Limits of Temperature and Temperature Rise

Temperature Limits

23. *Table of Temperature Limits.* — The following table gives the limits for the observable temperatures and temperature rises of windings and of certain parts of machines.

The permissible temperature limits are indicated in Column 1 of the table. The permissible limits of temperature rise are given in Column 2. The temperature rises measured on any machine which has worked for the specified time at the output corresponding with its I. E. C. rating shall not exceed in any of its parts the limiting values given in Column 2 of the table. The highest permissible temperature given in Column 1 and the temperature rises given in column 2 of the table should never be exceeded by a machine operating in service. (For exception *see* Clause 27.)

Temperature Limits

Item No.	Nature of the insulation of the winding or name of part.	Column 1 Highest permissible observable temperature	Column 2 Highest permissible observable temperature rise for the purpose of fixing the international rating
		Degrees C.	Degrees C.
1	Cotton, paper or silk, non-impregnated	80	40
2	Cotton, paper or silk, impregnated (*see* Clause 24)	95	55
3	Cotton, paper or silk, immersed in oil	95	55
4	Enamelled wire (*see* Clause 25)	95	55
5	Mica, asbestos, glass, porcelain, micanite and similar compositions	115	75
6	Insulated windings permanently short-circuited	100	60
7	Non-insulated windings permanently short-circuited	110	70
8	Oil (for temperature limits, *see* Appendix II).	..	..
9	Commutators, slip rings (*see* Cl. 27)	90	50
10	Bearings	80	40
11	Iron core immersed in oil	95	55
12	Iron core in contact with windings	Same as the windings	
13	Iron core not in contact with windings nor immersed in oil. The temperature and temperature rise shall not exceed that allowed for the windings themselves, and in no case shall the temperature and temperature rise exceed 110° C. and 70° C. respectively.		
14	Single layer windings: An increase of 5° C. above the temperatures given for items 1, 2 and 4 shall be permitted in the case of coils, revolving or stationary, with single layer windings when not immersed in oil.		

24. *Impregnated Cotton, Paper or Silk.*—An insulation is considered to be "impregnated" when a suitable substance replaces the air between its fibers, even if this substance does not completely fill the spaces between the insulated conductors. The impregnating substance, in order to be considered suitable, must have good insulating properties; must entirely cover the fibers and render them adherent to each other and to the conductor; must not produce interstices within itself as a consequence of evaporation of the solvent or through any other cause; must not flow during the operation of the machine at full working load at the temperature limit specified; must not deteriorate under prolonged action of heat.

25. *Enamelled Wire.* — When employing the temperature limits in the table for enamelled wire the maker must satisfy himself that the enamel employed is of good quality.

26. *Compound Insulations Made Up of Different Materials.* — When the insulation consists of layers of several different materials, the lowest of the temperatures permitted for the different insulating materials employed (see Clause 23) is to be adopted as the limiting temperature. The insulating material, even when forming the support, shall always be assumed as forming part of the winding.

27. *Commutators and Slip Rings.* — The observable temperature and temperature rise of commutators and slip rings may exceed the values given in Item 9 of the table, provided that the above [illegible]

a) The temperatures of the insulating materials in the commutator and the adjoining windings shall not exceed those allowed in the table for the ılating materials of those parts.
b) The manufacturer shall give a special guarantee that the high temature attained shall not impair the commutation.
c) The temperature shall not be so high as to affect the quality of the soldered ıts and the connections.

Reference Temperature of Cooling Medium

8. *Reference Temperature of Cooling Medium.* — (a) *Temperate Climates.* — the absence of any indication to the contrary the maximum temperature of air in which the machine is intended to operate in service shall be deemed e 40° C.
) *Cold Climates.* — In cold climates, when the actual temperature of the in which the machine is intended to operate in service is not much different n 40° C. it is recommended that this conventional reference temperature of C. should be adopted.
) *Tropical Climates.* — The question of a reference temperature for cooling for machines intended to operate in service in tropical climates will be dealt ı by the I. E. C. at a later date.
l) *Water Cooling* (*see* Appendix II).

Permissible Limits for Temperature Rise

9. *Permissible Limits for Temperature Rise.* — The limits permitted for perature rise are deduced from the values allowed for the highest permissible ervable temperature (*see* Clauses 23–27) by subtracting therefrom 40° C. : value assumed as that of the maximum cooling air temperature of the e in which the machine may be required to work in service (*see* Clause 28).

Temperature Measurements

). *Value of Temperature of Cooling Medium.* — A machine may be tested ny convenient cooling air temperature less than 40° C., but whatever be the ıe of this cooling air temperature the permissible rises of temperature shall exceed those given in Column 2 of the table (*see* Clause 23).
orrections for variations in the cooling air temperature are not considered ssary within the limits of cooling air temperature obtaining in general tise.
ı the case of cooling by means of forced ventilation, the temperature of the measured where it enters the machine, shall be considered as the cooling air perature.
or all machines cooled by other means, special rules will be necessary. (For er cooling, *see* Appendix II).

r. *Measurement of Cooling Air Temperature During Tests.* — The cooling temperature shall be measured by means of several thermometers placed lifferent points around and half-way up the machine at a distance of one to meters, and protected from all heat radiation and draughts.
he value to be adopted for the temperature of the cooling air during a shall be the mean of the readings of the thermometers (placed as mentioned ve), taken at equal intervals of time during the last quarter of the duration he test.
n order to avoid errors due to the time lag between the temperature of e machines and the variations in the cooling air, all reasonable precautions ll be taken to reduce these variations and the errors arising therefrom.

Methods of Measurement of the Temperatures of Machines

2. *Measurement of the Temperatures of Machines.* — Two methods of deterıing the temperature of windings and other parts of machines are recogıd:

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(a) Thermometer method.
(b) Resistance method.*

33. *Thermometer Method.* — In this method the temperature is determined by thermometers applied to the accessible surfaces of the completed machine. The term "thermometer" also includes thermocouples and resistance-thermometers.

34. *Resistance Method.* — In this method the temperature rise of the winding is determined by the increase in the resistance of the windings themselves as checked by thermometers applied to the accessible surfaces of the windings to ascertain whether there is any higher local temperature. The highest of the temperatures thus found shall be taken as the observable temperature.

35. *Temperature of Windings.* — The temperature of windings, as a rule, shall be measured by the resistance method. The thermometer method also is permitted in the following cases:

(a) When it is not practicable to determine the temperature rise by the resistance method, as for example with low resistance commutating coil and compensating windings, and in general in the case of low resistance windings, especially when the resistance of joints and connections forms a considerable portion of the total resistance. In this case the temperature limits given in the table apply without correction.

(b) Single layer windings, revolving or stationary, when not immersed in oil. In this case an increase of 5° C. above the limits of temperature and of temperature rise given in the table is permitted.

(c) When, for reasons of manufacturing in quantity, the thermometer method is used alone, although the resistance method would be possible. In this case the value of the highest permissible observable temperature and temperature rise given in the table shall be reduced by five degrees except in the case of stationary field coils, when the values given in the table shall be reduced by the difference between resistance and thermometer measurements as determined on similar machines, but in no case shall such reduction be less than 5° C.

36. *Corrections of Measurements Taken after the Machine Has Shut Down.* — If the temperature is measured only after shut-down, the highest temperature attained while running shall be deduced by extrapolation on the time-temperature curve.

37. *Measuring Temperature of Direct-current Generators and Motors.* — The temperature of field windings shall be measured in the manner described in Clauses 35 and 36.

The temperature of the armature shall be determined as a rule by thermometers placed on the windings at the hottest accessible parts, and when this method is employed the value of the highest permissible observable temperature and temperature rise shown in the table shall be reduced by 5° C.

38. *Measuring Temperature of Transformers.* — The temperature of transformer windings shall always be ascertained by resistance.

39. *Measuring Temperature of Synchronous Alternators and Motors.* — The temperature of the field windings shall always be ascertained by resistance. The temperature of stator windings shall be ascertained either by resistance or by thermometer in the manner described in the preceding clauses.

40. *Measuring Temperature of Non-synchronous Motors without Commutators.* — The temperatures of the stator and rotor shall be ascertained in the same manner as those of the stator of a synchronous alternator (*see* Clause 39), except in the case of a permanently short-circuited winding, when the thermometer method shall be employed.

41. *Coefficients of Variation of Resistance of Copper with Temperature.* — In the case of resistance measurements, the temperature coefficient of copper shall be taken from the values stated in the accompanying table, which have been

* Note. — With a view to brevity, the expression "method of variation of resistance of the winding" is replaced by the term "resistance method," or simply "by resistance."

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duced from the formula $1/(234.5+t)$. Thus, at an initial temperature $t = 30°$ C. e temperature coefficient or increase in resistance per degree Centigrade rise $1/(264.5) = 0.00378$.

Temperature of the windings in degrees C., at which the initial resistance is measured.	Copper—increase in resistance per ohm per degree C.
0	0.00427
5	0.00418
10	0.00409
15	0.00401
20	0.00393
25	0.00385
30	0.00378
35	0.00371
40	0.00364

42. When the temperature of a winding is to be determined by resistance, e temperature of the winding before the test measured by thermometer shall ot differ much from that of the cooling air.

43. *Duration of Temperature Test for Continuous Rating.* — For machines ith I. E. C. continuous rating, the temperature test shall be continued until is evident that the maximum temperature rise attained would not exceed the mits given in the table (*see* Clause 23), if the test were to be prolonged until ie final steady temperature were attained. If possible, the temperature hall be measured both while running and after shut-down.

44. *Duration of Temperature Test for Short-time Rating.* — For machines ith I. E. C. short-time rating the duration of the temperature test shall be iat corresponding to the short-time test rating as indicated upon the rating late.

At the commencement of the test the temperature of the machine must be actically that of the cooling air.

VII. Dielectric Tests

(*See* Appendix III for proposals.)

IX. Mechanical Tests

(Not yet prepared.)

X. Commutation

(Not yet prepared.)

PART IV. MARKINGS

XI. Rating Plates

45. *Rating Plate.* — Every machine shall bear the information necessary define the limitations of the service for which it is intended.

For this purpose it shall have, in all cases, a rating plate and also ich diagrams and terminal markings as may be necessary.

46. *Information on Rating Plate.* — The rating plate of a machine complying ith the I. E. C. rules shall have a distinctive special sign and give the following formation:

(a) The name of the maker.
(b) The maker's machine number.

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(c) The class of rating or the necessary information if the machine is intended to operate under more than one class of rating.

(d) The altitude at which the machine is intended to work if such altitude exceeds 1000 meters.

(e) The following technical information, according to the character of the machine:

In the absence of any indication in regard to the class of rating it is understood that the machine is intended for continuous service.

47. *Direct-current Generator.*

Generator — Direct-current.
Output, in watts (w.) or in kilowatts (kw.), with statement as to the class of rating.
Pressure between terminals, in volts.
Current, in amperes.
Speed, in revolutions per minute.

48. *Direct-current Motor.*

Motor — Direct-current.
Output, in watts (w.) or in kilowatts (kw.), with statement as to the class of rating.
Pressure between terminals, in volts.
Current, approximate, in amperes.
Speed, in revolutions per minute.

49. *Transformer.*

Frequency, in periods per second.
Number of phases.
Apparent output at the secondary, in volt-amperes (v.-a.) or in kilovolt-amperes (kv.-a.), with statement as to the class of rating.
Primary pressure between terminals, in volts.
Secondary pressure, in volts, at no load and at rated load, with statement as to the power factor.
Short-circuit pressure, in volts.
Secondary current, in amperes.
In addition, for three-phase transformers, a vector diagram indicating the method of connection of the windings in accordance with the figures. (*See* Appendix I.)

50. *Alternator.*

Frequency, in periods per second.
Number of phases.
Apparent output, in volt-amperes (v.-a.) or kilovolt-amperes (kv.-a.), with statement as to the class of rating.
Pressure between terminals, in volts, corresponding to the rated output.
Current, in amperes.
Power factor corresponding to the rated output.
Speed, in revolutions per minute.
Excitation pressure, in volts.
Maximum exciting current, in amperes.

51. *Synchronous Motor.*

Frequency, in periods per second.
Number of phases.
Mechanical output, in watts (w.) or in kilowatts (kw.), with statement as to the class of rating.
Pressure between terminals, in volts, corresponding to the rated output.
Current, approximate, in amperes.
If the motor is intended to work with a power factor different from unity, the necessary information to be given.
Speed, in revolutions per minute.
Excitation pressure, in volts.
Maximum exciting current, in amperes.

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2. *Non-synchronous Motor.*

Frequency, in periods per second.
Number of phases.
Mechanical output, in watts (w.) or in kilowatts (kw.), with statement as to the class of rating.
Pressure between terminals, in volts.
Current, approximate, in amperes.
Speed, in revolutions per minute, at rated output.
Maximum pressure between slip rings, in volts.

APPENDIX I

t the meeting of the Advisory Committee on Rating held in September,), the question of terminal marking and vector diagrams was referred to srs. Everest and la Cour. The following rules were forwarded to the tral Office, but as they have not been submitted to the National Committees, Editing Committee decided to include them as an Appendix only. They therefore, be submitted to the next Plenary Meeting for ratification.

Terminal Markings for Transformers

Single-phase Transformers. — The terminals of all single-phase transers shall be marked with the letter T for the high-pressure side and *t* for the pressure side.

The neutral terminal, if provided, shall be marked by N or *n*.

The letters T and *t* should be accompanied by subscripts 0, 1, 2, etc., arranged in order of progression in the same direction as the electromotive force in each circuit at the same instant, as shown in the diagram.

If the transformer has two or more windings intended to be coupled in series or in parallel, the subscripts shall be single numbers for the first of such windings (1, 2, etc.), double numbers for the second windings (11, 22, etc.), and so on.

Polyphase Transformers. — The terminals of all polyphase transformers be marked as follows:

) Phase Identification. The terminals of the high-pressure and low-ure windings of any one phase shall be marked with the same letter, using al letters on the high-pressure terminals and small type letters on the low-ure terminals.

The letters A, B, C, *a*, *b*, *c* shall be used.

The neutral terminal, if provided, shall be marked N or *n*.

) Polarity Identification. The relative polarity of the corresponding pressure and low-pressure windings in each phase shall be indicated by the ion of subscripts (0) and (1) after the phase letters, so placed that at the nt when (in, for instance, phase A) the high-pressure terminal marked A_1 itive to terminal A_0, the low-pressure terminal a_1 shall be simultaneously ive to that marked a_0.

Vector Diagrams for Polyphase Transformers

Polyphase Transformers Connected Together. — When two or more polyphase formers are to be grouped together with their windings connected to the primary and secondary systems, it is essential that the transformers shall spond, not only as regards the pressures for which they are intended, lso as regards the exact phase relation of the secondary winding to the ary winding.

Scope of Vector Diagrams. — All polyphase transformers shall bear a vector am which shows accurately the phase relation between primary and dary terminals. To secure the correctness of such a diagram the following rements shall be complied with:

The identification of each phase of the secondary winding with the corre-ling phase of the primary winding shall be clearly indicated by the same inal marks (*see* Paragraph 2 above).

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(b) To avoid error arising from differences in methods of winding, the relative instantaneous polarity of primary and secondary windings in each phase shall be indicated at the terminals of the various phase windings (*see* Paragraph 3 above).

5. *Vector Diagrams.* — The vector diagram of connections shall show the phase letter and the polarity marking for each phase of the windings, and shall show correctly how the various phases are connected together. Because to avoid the complexity of marking both phase letter and polarity mark at each end of every winding vector, it shall be sufficient to show the phase letter connected together with an arrow head to indicate polarity, the arrow head in every case pointing away from that end of the phase which has the polarity mark (or at its terminal.

6. The following are some typical vector diagrams which embody the principles laid down in these rules:

APPENDIX II

This Appendix contains proposals prepared by the Advisory Committee on Rating for submission to the National Committees, but not yet presented to a Plenary Meeting for ratification.

1. *Temperature Limits for Oil.*

Temperature limit for oil (measured by thermometer)...	90° C.
Temperature limit for the windings (measured by the increase of resistance) and other parts immersed in oil..	95° C.

Note. — The adoption of these temperatures implies the employment of a good oil of which the quality may be verified by ascertaining the flash point and measuring the deposit produced by heating.

The I. E. C. has not yet sufficient data to fix limiting values for the flash point or to prescribe the methods of measurement of the deposit.

2. *Reference Temperature of Cooling Water.* — For water-cooled apparatus in the absence of any indication to the contrary, the maximum temperature of the cooling water in service shall be deemed to be 25° C. at the point of entry.

3. *Temperature Limits for Water-cooled Transformers.* — In the case of oil immersed water-cooled transformers, the limits of highest permissible observed temperature given in the table are to be reduced by 10° C.; therefore the corresponding limits of temperature rise shown in the table may be increased by

APPENDIX III

Dielectric Tests

This Appendix contains proposals in regard to Dielectric Tests prepared by the Advisory Committee on Rating, for submission to the National Committees but not yet presented to the Plenary Meeting for ratification.

Dielectric Tests. — The high-pressure test shall be applied between the winding and the frame, with the core connected to the frame and to the windings not under test, and shall be applied only to a new and completed machine with all its parts in place under conditions equivalent to normal working conditions and, unless otherwise specified, the test shall be carried out at the maker's works at the conclusion of the temperature test of the machine.

The test pressure shall be alternating, preferably of sine wave form.

The test shall be commenced at a pressure of less than one-third the test pressure and shall be increased to the full test pressure as rapidly as is consistent with its value being correctly indicated by the measuring instrument. The full test pressure shall then be maintained for one minute in accordance with the values as indicated in the following table:

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Machine or part	Test pressure (R. M. S.)
Rotating machines of size less than 1 kw.	500 volts + twice the rated pressure.
Rotating machines of size 1 kw. to 3 kw.	1000 volts + twice the rated pressure.
Rotating machines of size above 3 kv.-a.	1000 volts + twice the rated pressure with minimum, 2000 volts.
Field windings for synchronous generators when the excitation pressure does not exceed 750 volts.	10 times the excitation pressure. Minimum, 2000 volts. Maximum, 3500 volts.
Field windings for synchronous motors:	
(a) When intended to be started up with the field windings short-circuited.	10 times the excitation pressure. Minimum, 2000 volts. Maximum, 3500 volts.
(b) When intended to be started up with the field windings separated by a break-up switch.	5000 volts.
(c) When intended to be started up with the fields on open circuit and without a break-up switch.	5000 volts when the excitation pressure is less than 275 volts. 8000 volts when the excitation pressure is equal to or exceeds 275 volts.
Exciter	Not yet decided.
Transformers in general	1000 volts + twice the rated pressure.
Transformers for primary pressures over 550 volts, the secondaries of which are for direct connection to public or private distribution systems or public or private consumers (i.e., secondary pressures less than 550 volts).	Primary windings: 1000 volts + twice the rated primary pressure with minimum, 10,000 volts (adopted as a protection to human life). Secondary windings: 1000 volts + twice the rated secondary pressure.
Secondary (rotor) windings of induction motors not permanently short-circuited.	For non-reversing motors: 1000 volts + twice the maximum pressure which could be induced between the slip rings. For reversing motors: 1000 volts + 4 times the pressure between the slip rings at standstill on open circuit with full primary pressure applied to stator windings.
Alternating-current apparatus connected to a single-phase system of more than 300 volts pressure permanently earthed.	Not yet decided.
Assembled apparatus	When the test is made on an assembled group of several pieces of new apparatus each one of which has previously passed its high pressure test, the test on such assembled group shall not exceed 85 per cent. of the lowest test pressure appropriate for any part of the group.

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APPENDIX IV

Definitions dealing with the subject of "Rating":

Great Britain. — The rating of an electrical machine is the output assigned to it by the maker, together with the associated conditions, all of which are marked on the Rating Plate.

Note. — A machine may have a test rating or a service rating, or both assigned to it, and marked on the rating plate.

United States of America. — The rating of a machine is the output marked on the Rating Plate and shall be based on, but shall not exceed the maximum load which can be taken from the machine under prescribed conditions of test. This is also called the Rated Output.

(The term "maximum load" does not refer to loads applied solely for mechanical, commutation, or similar tests.)

France. — The rating of a machine is determined by the conditions of working such as speed, pressure, current, power factor, etc., as indicated on the Rating Plate.

Italy. — The output of a machine is the normal or average output, that is to say, the load at which the machine can work under normal conditions.

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