Standard Handbook for Electrical Engineers

DONALD G. FINK   Editor-in-Chief

H. WAYNE BEATY   Associate Editor

Eleventh Edition

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DONALD G. FINK *Editor-in-Chief*

*General Manager and Executive Director (Retired), Institute of
Electrical and Electronics Engineers; formerly Vice President—
Research, Philco Corporation, President of the Institute of
Radio Engineers, Editor of the Proceedings of the IRE;
Fellow of the IEEE; Fellow of the IEE (London);
Eminent Member, Eta Kappa Nu; Member of the
National Academy of Engineering*

H. WAYNE BEATY *Associate Editor*

*Senior Editor, Electrical World; Member of the Institute
of Electrical and Electronics Engineers and of the IEEE Power
Engineering Society's Transmission
and Distribution Committee*

Eleventh Edition

Preface to the Eleventh Edition

Since the publication of the preceding edition of this handbook, advances in electrical science and technology have occurred at a pace sharply accelerated by the crisis in energy supply and use. Steeply rising costs of fuel and severe environmental pressures have required new approaches to the design and operation of electrical generating systems. The need for conservation of electrical energy has affected the design of transmission and distribution systems and its use by all consumers.

The rapid pace of electrical engineering in such areas as high-voltage systems, nuclear generation, computer methods and automation, and the newly emerging field of "power electronics" employing arrays of high power semiconductor devices, has rendered obsolete nearly all of the material on these subjects previously published in these pages. Concurrently the adoption of the metric system in the United States has called for the restatement of many formulas and the compilation of extensive tables of conversion factors. Standardization of terms, symbols and concepts has assumed new and critical importance.

The current heavy emphasis on electrical energy sources other than those based on conventional fossil and fissile fuels has generated a new discipline in electrical engineering: the so-called "alternate sources." These are based on such energy supplies as solar and geothermal energy, nuclear fusion, and advanced techniques of fuel-to-energy conversion such as magnetohydrodynamics.

All of this new technology is covered in this edition of the Standard Handbook, which includes many entirely new Sections and others substantially re-written. The result is that this new edition properly reflects the extraordinary pressures and resources that have been at work during the decade since the last edition—a period matched by no other in the history of electrical engineering.

The aim of the Eleventh Edition carries forward the philosophy of the preceding editions: to contain in a single volume all pertinent data within its scope, to be accurate and comprehensive in technical treatment, to be of use in engineering practice (as well as in study in preparation for such practice) and, above all, to be oriented toward practical application, including the impact of economic considerations.

The scope of this Handbook, as of its predecessors, includes the

generation, transmission, distribution, control, conversion and application of electric power. Many phases of the electronic arts are also included in such fields as telecommunications, process automation, computer systems and industrial electronics. But no attempt has been made to provide comprehensive design data on the full range of electronic circuits, equipment and systems. These subjects are extensively covered in a sister volume, the *Electronics Engineers' Handbook*. The two volumes, published under the same editorship, together cover the whole field of electrical and electronics engineering.

The preparation of the Eleventh Edition has involved the contributions of 119 experts in the many special fields it embraces. Together these men and women have produced a volume of 2400 pages, 1645 illustrations, 720 tables, 1950 bibliographic references and over a million words of text matter. The editor gratefully acknowledges their efforts, and particularly the assistance of the Handbook's Associate Editor, Wayne Beaty of *Electrical World*. Together, we have endeavored to produce in this volume another edition that meets the high standard set by the previous editions since 1907.

In a work of such size and complexity it is inevitable that some errors have escaped careful review by the contributors and editors. The undersigned would appreciate their being brought to his attention.

DONALD G. FINK
Editor-in-chief

Contributors to the Eleventh Edition

Michael M. Adibi *Industry Consultant, International Business Machines Corporation* (SEC. 25)

E. J. Allen *Adjunct Associate Professor, University of Florida; formerly, Large Transformer Division, General Electric Company* (SEC. 14)

Roy P. Allen *Manager, Electric Utility Application Engineering, Gas Turbine Division, General Electric Company* (SEC. 6)

H. J. Allison *Professor of Electrical Engineering, Oklahoma State University* (SEC. 11)

John G. Anderson *Manager, High Voltage Laboratory, General Electric Company* (SEC. 27)

S. Annestrand *Head, High Voltage Group, U.S. Department of the Interior, Bonneville Power Administration* (SEC. 15)

R. E. Appleyard *Manager, Engineering and Development, Large Rotating Apparatus Division, Allis-Chalmers Corporation* (SEC. 7)

Jack I. Argersinger *Staff Engineer, Fossil Power Systems, Combustion Engineering, Inc:* (SEC. 5)

G. S. Axelby *Editor, IFAC Journal-Automatica* (SEC. 21)

Joseph Basilesco *Manager, Substations and Communications, Charles T. Main, Inc.* (SEC. 17)

K. J. Bell *Professor of Chemical Engineering, Oklahoma State University* (SEC. 11)

Robert W. Bergamann *Technical Director, Electrical Engineering, Marion Power Shovel Company, Inc.* (SEC. 21)

J. L. Blackburn *Consulting Engineer, Relay-Instrument Division, Westinghouse Electric Corporation* (SEC. 16)

Warren B. Boast *Anson Marston Distinguished Professor Emeritus of Electrical Engineering, Iowa State University* (SEC. 2)

B. P. Boehle *Switchgear Division, Brown Boveri & Company* (SEC. 10)

Robert W. Bohl *Professor, Metallurgy and Nuclear Engineering, University of Illinois* (SEC. 4)

Henry S. Borkovitz *Director of Engineering, Sola Basic Industries* (SEC. 10)

William F. Brown *Senior Sales Application Engineer, Mine Hoist Department, Rexnord, Inc.* (SEC. 21)

H. Russell Brownell *Technical Consultant* (SEC. 3)

A. M. Bruning *Vice President, Engineering, A. B. Chance Company* (SEC. 10)

John F. Cachat *Vice President and General Manager, Tocco Division, Park-Ohio Industries, Inc.* (SEC. 21)

Harold E. Campbell *Senior Engineer, Power Distribution Systems Engineering Operation, General Electric Company* (SEC. 18)

Nathan Cohn *Consultant; formerly Executive Vice President, Leeds & Northrup Company* (SEC. 16)

E. J. Croop *Insulation and Chemical Technology Department, Westinghouse Research Laboratories* (SEC. 4)

T. W. Dakin *Insulation and Chemical Technology Department, Westinghouse Research Laboratories* (SEC. 4)

Edward F. Eaton *Manager, Marine Applications Engineering, General Electric Company* (SEC. 23)

Å. Ekström *High Voltage Direct Current Department, ASEA* (SEC. 15)

Charles Emerson *American Machinist* (SEC. 21)

J. C. Engel *Member of the Technical Staff, Westinghouse Research Laboratories* (SEC. 13)

P. G. Engström *Director, Semiconductor and Electronics Division, ASEA* (SEC. 15)

K. Eriksson *High Voltage Direct Current Department, ASEA* (SEC. 15)

Daniel M. Forman *Project Engineer, Automatic Machinery Division, Babcock & Wilcox* (SEC. 21)

Donald G. Fink *Executive Director, retired, Institute of Electrical and Electronics Engineers* (SECS. 1 AND 11)

R. X. French *Head, Electrical Analysis Division, Sargent and Lundy. Engineers* (SEC. 12)

Larry Givens *Editor, Automotive Engineering* (SEC. 23)

Jolal Gohari *Senior Engineer, Electrical Engineering Division, American Electric Power Service Corporation* (SEC. 16)

R. B. Greklla   *Insulation and Chemical Technology Department, Westinghouse Research Laboratories* (SEC. 4)

L. Gyugyl   *Member of the Technical Staff, Westinghouse Research Laboratories* (SEC. 13)

Harry W. Hale   *Professor of Electrical Engineering, Iowa State University* (SEC. 2)

Donald H. Hall   *Senior Engineer, Medium Steam Turbine Department, General Electric Company* (SEC. 6)

B. Hammarlund   *High Voltage Direct Current Department, ASEA* (SEC. 15)

Charles A. Harper   *Systems Development Division, Westinghouse Electric Corporation* (SEC. 4)

Forest K. Harris   *Consultant, Electricity Division, National Bureau of Standards* (SEC. 3)

T. M. Heinrich   *Member of the Technical Staff, Westinghouse Research Laboratories* (SEC. 13)

S. W. Herwald   *Vice President, Strategic Resources, Westinghouse Electric Corporation* (SEC. 21)

G. Hjalmarsson   *High Voltage Direct Current Department, ASEA-KABEL* (SEC. 15)

F. N. Houser   *Manager, Railroad Research Information Service, National Research Council* (SEC. 23)

John F. Hower   *Manager, Maintenance, Lehigh Portland Cement Company* (SEC. 21)

William L. Hughes   *Director, Engineering Energy Laboratory and Clark Dunn Professor of Engineering, Oklahoma State University* (SEC. 11)

Daniel Jackson, Jr.   *Associate Editor, Coal Age* (SEC. 21)

A. Johansson   *High Voltage Direct Current Department, ASEA* (SEC. 15)

Loering M. Johnson   *Section Manager, Standards, Nuclear Power Systems, Combustion Engineering, Inc.* (SEC. 5)

Edwin C. Jones, Jr.   *Professor of Electrical Engineering, Iowa State University* (SEC. 2)

A. S. Judd   *Engineering Associate, Imperial Oil Enterprises, Ltd.* (SEC. 21)

John E. Kaufman   *Technical Director, Illuminating Engineering Society of North America* (SEC. 22)

James A. Keeley   *The Miami Herald* (SEC. 21)

Daniel E. Klion   *Assistant Engineering Manager, Stone & Webster Engineering Corporation* (SEC. 5)

W. Thomas Knipe   *Technical Manager, Development and Engineering, Leeds & Northrup Company* (SEC. 16)

Alexander Kusko   *President, Alexander Kusko Inc. Consulting Engineers* (SEC. 20)

J. Lapp   *Senior Engineer, Research and Development, McGraw Edison Company* (SEC. 10)

Robert E. Larson   *Manager, Overhead Conductor Engineering, Alcoa Conductor Products Company* (SEC. 4)

Enrico Levi   *Professor of Electrical Engineering, Polytechnic Institute of New York; Senior Technical Advisor, Energy Research and Development Administration* (SEC. 23)

David Linden   *Chief, Power Sources Technical Area, U.S. Army Electronics Command* (SEC. 11)

E. M. Lindheimer   *Manager, Research and Development Contracts, Nuclear Division, Combustion Engineering, Inc.* (SEC. 5)

G. Liss   *High Voltage Direct Current Department, ASEA* (SEC. 15)

Frederick A. Lowenheim   *Retired, formerly Research Coordinator, M8T Chemicals, Inc.* (SEC. 24)

John Lusti   *Vice President, Corporate Technical Department, Otis Elevator Company* (SEC. 21)

Duane E. Lyon   *Assistant Professor, Forest Products Laboratories, Mississippi State University* (SEC. 4)

Charles T. Main, II   *Associate, Charles T. Main, Inc.* (SEC. 21)

H. Mårtensson   *Chief Engineer, High Voltage Direct Current Department, ASEA* (SEC. 15)

Norman W. Mather   *Professor of Electrical Engineering, Princeton University* (SEC. 11)

J. F. McPartland   *Editorial Director, Electrical Construction and Maintenance* (SEC. 19)

Julius E. Miklosy   *Assistant Superintendent, Engineering Department, Inland Steel Company* (SEC. 21)

H. F. Minter   *Insulation and Chemical Technology Department, Westinghouse Research Laboratories (retired)* (SEC. 4)

Lawrence R. Mizen   *Senior Engineer, Medium Steam Turbine Department, General Electric Company* (SEC. 6)

J. A. Moran   *Senior Engineer, Underground Cable Systems, Power Technologies, Inc.* (SEC. 14)

P. M. Moretti   *Professor of Mechanical Engineering, Oklahoma State University* (SEC. 11)

J. W. Motto   *Member of the Technical Staff, Westinghouse Research Laboratories* (SEC. 13)

E. F. Myers   *Consultant, Large Motor Engineering, Westinghouse Electric Corporation* (SEC. 8)

A. H. Myles   *Chief Engineer, retired, Square D Company* (SEC. 21)

Frederick R. Nelson   *Head, Communications Section, American Electric Power Service Corporation* (SEC. 16)

W. E. Newell (deceased)   *formerly Member of the Technical Staff, Westinghouse Research Laboratories* (SEC. 13)

A. Nilsson   *High Voltage Direct Current Department, ASEA* (SEC. 15)

R. M. Oates   *Member of the Technical Staff, Westinghouse Research Laboratories* (SEC. 13)

M. J. Offenheiser   *Technical Journalist* (SEC. 21)

T. B. Owen   *retired, formerly Missiles and Space Systems Division, Douglas Aircraft Company* (SEC. 23)

Jerald D. Parker   *Professor of Mechanical Engineering, Oklahoma State University* (SEC. 11)

B. R. Pelley   *European Applications Engineering Manager, International Rectifier, England* (SEC. 13)

Wendell E. Phillips *Consulting Engineer* (SEC. 28)

P. F. Pittman *Member of the Technical Staff, Westinghouse Research Laboratories* (SEC. 13)

Barry M. Pressman *Power Products Manager, Rochester Instrument Systems* (SEC. 16)

R. Ramakumar *Professor of Electrical Engineering, Oklahoma State University* (SEC. 11)

Robert W. Rex *President, Republic Geothermal Company* (SEC. 11)

Richard A. Road *Vice President-Engineering (retired), Duncan Electric Company* (SEC. 3)

L. T. Rosenberg *Consultant, Allis-Chalmers Corporation* (SEC. 7)

Dan Rossiter *Vice President, Macro Corporation* (SEC. 16)

Eugene C. Sakshaug *Manager, Surge Arrester Engineering, General Electric Company* (SEC. 27)

R. N. Sampson *Insulation and Chemical Technology Department, Westinghouse Research Laboratories* (SEC. 4)

W. J. Schmitt *Switchgear Division, Brown Boveri & Company* (SEC. 10)

Norman R. Schultz (deceased) *Manager, Power Distribution Systems Operation, General Electric Company* (SEC. 18)

W. B. Schultz *President, Macro Corporation* (SEC. 16)

C. B. Sharp *Assistant Vice President-Engineering and Network Services, American Telephone and Telegraph Company* (SEC. 26)

Kelly A. Shaw *Allis-Chalmers Corporation* (SEC. 10)

John Shepard *Consulting Engineer* (SEC. 21)

Sava I. Sherr *Managing Director, American National Standards Institute* (SEC. 29)

J. D. B. Smith *Insulation and Chemical Technology Department, Westinghouse Research Laboratories* (SEC. 4)

George W. Soete *Centrifugal Pump Department, De Laval Turbine, Inc.* (SEC. 21)

E. H. Spreckelmeier *American Laundry Industries* (SEC. 21)

G. R. Sprengling *Insulation and Chemical Technology Department, Westinghouse Research Laboratories* (SEC. 4)

H. Stackegård *High Voltage Direct Current Department, ASEA* (SEC. 15)

E. Uhlmann *Consulting Engineer, High Voltage Direct Current Department, ASEA* (SEC. 15)

Anthony L. VonHolle *Armco Steel Corporation* (SEC. 4)

Roland W. Ure, Jr. *Professor of Electrical Engineering and Professor of Materials Science, University of Utah* (SEC. 11)

Grover F. Wachter *Manager, Sales Engineering, Hydro-Turbine Division, Allis-Chalmers Corporation* (SEC. 9)

E. C. Wentz *Consulting Engineer, formerly Westinghouse Electric Corporation (retired)* (SEC. 10)

Jay A. Williams *Senior Engineer, Underground Cable Systems, Power Technologies, Inc.* (SEC. 14)

J. R. Willy *Chief Engineer, Capacitor Products, McGraw Edison Company* (SEC. 10)

Fred T. Wolford *Assistant Professor, Agricultural Machinery Department, Delaware Valley College of Science and Agriculture* (SEC. 21)

J. S. Young *McDonnell Douglas Astronautic., Inc.* (SEC. 23)

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Quantities, Units, Symbols, Constants, and Conversion Factors

DONALD G. FINK *Executive Director (Retired), Institute of Electrical and Electronics Engineers; Editor, Standard Handbook for Electrical Engineers and the Electronics Engineers' Handbook; Fellow, IEEE and IEE (London)*

CONTENTS

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1. The SI Units. The units of the quantities most commonly used in electrical engineering (volts, amperes, watts, ohms, etc.) are those of the metric system. They are embodied in the International System of Units (Système International d'Unités, abbrevi-

ated "SI"). The SI units are used throughout this handbook, in accordance with the established practice of electrical engineering publications throughout the world. Other units, notably the cgs (centimeter-gram-second) units, may be used in citations in the earlier literature. The cgs electrical units are listed in Table 1-9 with conversion factors to the SI units.

The SI electrical units are based on the mksa (meter-kilogram-second-ampere) system. They have been adopted by the standardization bodies of the world, including the International Electrotechnical Commission (IEC), the American National Standards Institute (ANSI), and the Standards Board of the Institute of Electrical and Electronics Engineers (IEEE).

2. CGPM Base Quantities. Seven quantities have been adopted by the General Conference on Weights and Measures (CGPM) as *base quantities,* that is, quantities that are not derived from other quantities. The base quantities are length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity. Table 1-1 lists these quantities, the name of the SI unit for each, and the standard letter symbol by which each is expressed in the International System (SI).

TABLE 1-1.   SI Base Units

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature*	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

*Celsius temperature is in general expressed in degrees Celsius (symbol °C). See Par. 6.
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The units of the base quantities have been defined by the CGPM as follows:

meter.   The length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $^2p_{10}$ and $^5d_5$ of the krypton 86 atom (CGPM, 1960).

kilogram.   The unit of mass; it is equal to the mass of the international prototype of the kilogram (CGPM, 1901).

> EDITOR'S NOTE: The prototype is a platinum-iridium cylinder maintained at the International Bureau of Weights and Measures, near Paris. The kilogram is approximately equal to the mass of 1000 cubic centimeters of water at its temperature of maximum density.

second.   The duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom (CGPM, 1967).

ampere.   The constant current that, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length (CGPM, 1948).

kelvin.   The unit of thermodynamic temperature is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (CGPM, 1967).

> EDITOR'S NOTE: The zero of the Celsius scale (the freezing point of water) is defined as 0.01 K below the triple point, that is, 273.15 K. See Table 1-26.

mole.   That amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12 (CGPM, 1971).

> NOTE: When the mole is used, the elementary entities must be specified. They may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles. This definition specifies the nature of the quantity whose unit is the mole.

candela.   The luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square meter of a blackbody at the temperature of freezing platinum under a pressure of 101 325 newtons per square meter (CGPM, 1967).

EDITOR'S NOTE: Until Jan. 1, 1948, the generally accepted unit of luminous intensity was the *international candle*. The difference between the candela and the international candle is so small that only measurements of high precision are affected. The use of the term candle is deprecated.

3. **Supplementary SI Units.**   Two additional SI units, numerics which may be considered as either base units or derived units (see Par. 4), are the radian and the steradian, for the quantities plane angle and solid angle, respectively. Table 1-2 lists these quantities, their units and symbols. The supplementary units are defined as:

radian.   The plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius (CGPM, 1960).

steradian.   The solid angle which, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides equal to the radius of the sphere (CGPM, 1960).

TABLE 1-2.   SI Supplementary Units

Quantity	Unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

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4. **Derived SI Units.**   Most of the quantities and units used in electrical engineering fall in the category of *SI derived units*, that is, units which can be completely defined in terms of the base and supplementary quantities described above. Table 1-3 lists the principal electrical quantities in the SI system, and shows their equivalents in terms of the base and supplementary units. The definitions of these quantities, as they appear in the *IEEE Standard Dictionary of Electrical and Electronics Terms*[19]* are:

*Superior numbers refer to the Bibliography, Par. 17.

TABLE 1-3.   SI Derived Units Used in Electrical Engineering

Quantity	SI unit			
	Name	Symbol	Expression in terms of other units	Expression in terms of SI base units
Frequency	hertz	Hz		s^{-1}
Force	newton	N		$m \cdot kg \cdot s^{-2}$
Pressure, stress	pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
Energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
Power, radiant flux	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
Quantity of electricity, electric charge	coulomb	C	$A \cdot s$	$s \cdot A$
Potential difference, electric potential electromotive force	volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
Capacitance	farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
Electric resistance	ohm	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
Conductance	siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
Magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
Magnetic flux density	tesla	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
Inductance	henry	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Luminous flux	lumen	lm		$cd \cdot sr^*$
Illuminance	lux	lx		$m^{-2} \cdot cd \cdot sr^*$
Activity (of radionuclides)	becquerel	Bq		s^{-1}
Absorbed dose	gray	Gy		$m^2 \cdot s^{-2}$

*In this expression the steradian (sr) is treated as a base unit. See Table 1-2.
Adapted from IEEE Standards 268-1973 and 268-1976.

hertz.   The unit of frequency, 1 cycle per second.

newton.   The force that will impart an acceleration of 1 meter per second per second to a mass of 1 kilogram.

pascal.   The pressure exerted by a force of 1 newton uniformly distributed on a surface of 1 square meter.

joule.   The work done by a force of 1 newton acting through a distance of 1 meter.

watt.   The power required to do work at the rate of 1 joule per second.

coulomb.   The quantity of electric charge that passes any cross section of a conductor in 1 second when the current is maintained constant at 1 ampere.

volt.   The potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is 1 watt.

farad.   The capacitance of a capacitor in which a charge of 1 coulomb produces 1 volt potential difference between its terminals.

TABLE 1-4.   Examples of SI Derived Units of General Application in Engineering

Quantity	SI unit	
	Name	Symbol
Angular velocity	radian per second	rad/s
Angular acceleration	radian per second squared	rad/s^2
Radiant intensity	watt per steradian	W/sr
Radiance	watt per square meter steradian	$W \cdot m^{-2} \cdot sr^{-1}$
Area	square meter	m^2
Volume	cubic meter	m^3
Speed, velocity	meter per second	m/s
Acceleration	meter per second squared	m/s^2
Wavenumber	1 per meter	m^{-1}
Density, mass density	kilogram per cubic meter	kg/m^3
Concentration (of amount of substance)	mole per cubic meter	mol/m^3
Activity (radioactive)	1 per second	s^{-1}
Specific volume	cubic meter per kilogram	m^3/kg
Luminance	candela per square meter	cd/m^2

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ohm.   The resistance of a conductor such that a constant current of 1 ampere in it produces a voltage of 1 volt between its ends.

siemens (mho).   The conductance of a conductor such that a constant voltage of 1 volt between its ends produces a current of 1 ampere in it.

weber.   The magnetic flux whose decrease to zero when linked with a single turn induces in the turn a voltage whose time integral is 1 volt-second.

tesla.   The magnetic induction equal to 1 weber per square meter.

henry.   The inductance for which the induced voltage in volts is numerically equal to the rate of change of current in amperes per second.

lumen.   The flux through a unit solid angle (steradian) from a uniform point source of 1 candela; the flux on a unit surface all points of which are at a unit distance from a uniform point source of 1 candela.

lux.   The illumination on a surface of 1 square meter on which there is uniformly distributed a flux of 1 lumen; the illumination produced at a surface all points of which are 1 meter from a uniform point source of 1 candela.

Table 1-4 lists other quantities and the SI derived unit names and symbols useful in engineering applications. Table 1-5 lists additional quantities and the SI derived units and symbols used in mechanics, heat, and electricity.

5. **SI Decimal Prefixes.**   All SI units may have affixed to them standard prefixes which multiply the indicated quantity by a power of 10. Table 1-6 lists the standard prefixes and their symbols. A substantial part of the extensive range (10^{36}) covered by these prefixes is in common use in electrical engineering (e.g., gigawatt, gigahertz, nanosecond, and picofarad). The practice of compounding a prefix (e.g., micromicrofarad) is deprecated (the correct term is picofarad).

6. **Usage of SI Units, Symbols, and Prefixes.**   Care must be exercised in using the SI symbols and prefixes to follow exactly the capital-letter and lowercase-letter usage prescribed in Tables 1-1 through 1-8, inclusive. Otherwise serious confusion may occur. For example, pA is the SI symbol for 10^{-12} of the SI unit for electric current (picoampere) while Pa is the SI symbol for pressure (the pascal).

The spelled-out names of the SI units (e.g., volt, ampere, watt) are not capitalized. The SI letter symbols are capitalized only when the name of the unit stands for, or is directly derived from, the name of a person. Examples are V for volt, after the Italian physicist Alessandro Volta (1745–1827); A for ampere, after the French physicist André Ampère

TABLE 1-5.   Examples of SI Derived Units Used in Mechanics, Heat, and Electricity

Quantity	SI unit		
	Name	Symbol	Expression in terms of SI base units
Dynamic viscosity	pascal second	Pa·s	$m^{-1}\cdot kg\cdot s^{-1}$
Moment of force	newton meter	N·m	$m^2\cdot kg\cdot s^{-2}$
Surface tension	newton per meter	N/m	$kg\cdot s^{-2}$
Heat flux density, irradiance	watt per square meter	W/m²	$kg\cdot s^{-3}$
Heat capacity, entropy	joule per kelvin	J/K	$m^2\cdot kg\cdot s^{-2}\cdot K^{-1}$
Specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg·K)	$m^2\cdot s^{-2}\cdot K^{-1}$
Specific energy	joule per kilogram	J/kg	$m^2\cdot s^{-2}$
Thermal conductivity	watt per meter kelvin	W/(m·K)	$m\cdot kg\cdot s^{-3}\cdot K^{-1}$
Energy density	joule per cubic meter	J/m³	$m^{-1}\cdot kg\cdot s^{-2}$
Electric field strength	volt per meter	V/m	$m\cdot kg\cdot s^{-3}\cdot A^{-1}$
Electric charge density	coulomb per cubic meter	C/m³	$m^{-3}\cdot s\cdot A$
Electric flux density	coulomb per square meter	C/m²	$m^{-2}\cdot s\cdot A$
Permittivity	farad per meter	F/m	$m^{-3}\cdot kg^{-1}\cdot s^4\cdot A^2$
Current density	ampere per square meter	A/m²	
Magnetic field strength	ampere per meter	A/m	
Permeability	henry per meter	H/m	$m\cdot kg\cdot s^{-2}\cdot A^{-2}$
Molar energy	joule per mole	J/mol	$m^2\cdot kg\cdot s^{-2}\cdot mol^{-1}$
Molar entropy, molar heat capacity	joule per mole kelvin	J/(mol·K)	$m^2\cdot kg\cdot s^{-2}\cdot K^{-1}mol^{-1}$

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(1775–1836); and W for watt, after the Scottish engineer James Watt (1736–1819). The letter symbols serve the function of abbreviations, but they are used without periods.

It will be noted from Tables 1-1, 1-3, and 1-5 that, with the exception of the ampere, all the SI electrical quantities and units are derived from the SI base and supplementary units, or from other SI derived units. Thus, many of the short names of SI units may be expressed in compound form embracing the SI units from which they are derived. Examples are the volt per ampere for the ohm, the joule per second for the watt, the

TABLE 1-6.   SI Prefixes Expressing Decimal Factors

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10^{1}	deka	da	10^{-18}	atto	a

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