Tables of Physical and Chemical Constants

and some Mathematical Functions

Originally compiled by
G. W. C. KAYE,
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NOTE ON LABORATORY SAFETY

To ensure safe working conditions in laboratories of all kinds is a matter of great importance. In many cases they are covered by regulations for industrial premises, such as the Health and Safety at Work Act in Britain or the Occupational Safety and Health Act in the USA. Some of the tables in this book can be of value in determining levels of exposure to various types of hazard and it seemed to the Editorial Board that it might be helpful to some readers to add a note on safety information in this edition.

For obvious reasons we cannot give a comprehensive list of safety requirements, nor can we accept any responsibility for the use made of the information, but it seems worthwhile to mention a few references of general interest known to us.

Standards for Safety in Laboratories (AS 2243) is published by the Standards Association of Australia (Sydney, NSW). Another general publication of interest is *Safety Aspects of Laboratory Instrumentation* (Conference held in London on 25 May 1982) published by Scientific Symposia Ltd, London, 1982.

Electrical hazards are very important. The UK national code of safety for electrical installations of all kinds (not only in laboratories) is set out in the 15th edition of the *IEE Wiring Regulations*, published by the Institution of Electrical Engineers, London, 1981; a Commentary and Guide to the Regulations are also available. Two publications particularly concerned with electrical-testing laboratories are: 'Safety for electrical measurement laboratories', by A. Brandolini, G. Gola and E. Tironi, in *TE Int (Italy)*, **3**, 1979, pp. 28–31; and 'Safety considerations in light electrical testing', by R. W. Nettleton, in *SERT J (GB)*, **6**, 1972, pp. 101–3.

Hazards arising from the use of lasers are discussed in section 1.7.6 of this book. British Standard BS4703:1983 classifies laser hazard levels.

From a wide range of material on chemical hazards, we may mention the following:

Hazards in the Chemical Laboratory, L. Bretherick (ed.) (3rd edn), Royal Society of Chemistry, London, 1981.

Safety in the Chemical Laboratory, N. V. Steere, American Chemical Society, Easton, 1974

CRC Handbook of Laboratory Safety, The Chemical Rubber Co., Cleveland, Ohio.

EH40: Occupational exposure limits, 1984, is published by the UK Health and Safety Executive (HMSO, 1984). The Executive also issues a *Toxic Substances Bulletin* which gives interim statements between the annual revisions of EH40.

A useful survey of health risks in the use of mercury (which is more dangerous than some laboratory users seem to think) is given by D. J. More and A. E. Timbs, *Chem Brit*, **20**, 1984, p. 622.

Guidance on the safe use of ionising radiations and radioactive materials is given in the publications of the International Commission on Radiological Protection (ICRP). Some of their publications of particular relevance are:

Publication 26: *Recommendations of the International Commission on Radiological Protection* (1977) together with the Statement from the 1978 Stockholm meeting of the ICRP (*Annals of the ICRP*, **2**, 1 (1978)).

Publication 30: *Limits for Intake of Radionuclides by Workers* (1979).

Publication 35: *General Principles of Monitoring for Radiation Workers* (1982).

Publication 36: *Protection against Ionising Radiation in the Teaching of Science* (1983).

The various recommendations of the ICRP have been embodied in the Directive of the European Communities of the 15 July 1980, laying down the basic safety standards for the health protection of the general public and workers against the dangers of ionising radiation. This directive is binding on the countries of the European Community and will be embodied in the UK legislation due to be introduced in 1985–6. The legislation will be accompanied by a substantial body of guidance as to its application in different areas, include those of research and teaching.

We cannot impress too strongly on those setting up and operating laboratories the need to be aware of the regulations and codes of practice relevant to their work and to make sure that they are followed.

A.E.B.

11.5.85

TABLE OF CONTENTS

GENERAL PHYSICS

CHEMISTRY

ATOMIC AND NUCLEAR PHYSICS

MATHEMATICAL FUNCTIONS

NOTE ON THE USE OF PAGE HEADINGS

The user of this book will find that the Index is the key to what it contains. Headings in heavy type on each page are intended to assist him in finding his way in the tables, within the sections listed briefly above, and without continual reference to the Index. When parts of more than one table are to be found on a single page, the heading refers in general to the first table which *starts* on that page.

1.1 Units

1.1.1 The international system of units (SI)

History

In the second half of the nineteenth century the centimetre, gram and second were in fairly general use as base units for scientific work even in such countries as the UK and the USA where the foot and the pound were employed for commerce and engineering. As a result, the units required by the rapidly emerging science of electricity were based on the centimetre, gram and second, with which they formed a coherent system known as the CGS electromagnetic system. A system of units is said to be coherent when derived units are formed from the base units without the insertion of factors of proportionality other than unity. There was also the CGS electrostatic system, but the only quantities frequently expressed in electrostatic units were electric charge, electric potential, and capacitance.

The young but fast-growing electrical industry soon found that many CGS electromagnetic units were of an extremely inconvenient size for its needs. Accordingly, in 1881, international agreement was reached to fix the practical unit of potential, to be called the volt, at 10^8 CGS units (which is approximately equal to the e.m.f. of a primary cell), and the unit of resistance, the ohm, at 10^9 CGS units (which is approximately the resistance of a column of mercury 1 m long and 1 mm^2 in cross-section). The unit of electric current, the ampere, was made a tenth of the CGS unit. A coherent system of practical electric units was thus secured which, however, was not coherent with the mechanical units based on the centimetre and gram. The practical electric units suited the needs of telegraphy, which was then the main electrical industry, and they also happen to be convenient for heavy electrical engineering and for electronics.

The magnetic units, however, were left at their CGS values, presumably because the CGS unit of magnetic flux density, subsequently called 'gauss', is of the order of the flux density of the Earth's field, and, as it was suitable for geomagnetism, there seemed no point in changing it for a unit 10^4 times larger. Coherence was thereby lost to electromagnetism as it had already been lost to the system embracing the mechanical units and the practical electric units.

Whereas the electric units, by the agreement of 1881, were chosen to be of suitable magnitude for everyday use, and whereas the centimetre and the second have acceptable sizes, the gram is too small for the practical needs of man, which are better served by a unit nearer the size of the pound or the kilogram. Moreover, the CGS unit of force, the dyne, and the unit of energy, the erg, are much too small. On the other hand, the unit of energy provided by the practical electric units, the volt-ampere-second, called the joule—which equals 10^7 ergs—is of a satisfactory size.

These considerations—the advantages of coherence and the fortuitous circumstance that a mechanical system based on the metre and the kilogram has precisely the same unit of energy as is provided by the practical electric units—led G. Giorgi in 1902 to propose a system based on the **metre**, the **kilogram**, the **second**, and one of the practical electric units. He pointed out that if magnetic field strength were expressed as amperes per metre instead of 4π times amperes per metre, which is the definition corresponding to that of the CGS unit, the number π would disappear from most electric and magnetic formulae involving rectilinear geometry, but would appear, as is to be expected, in those involving cylinders or spheres.

The International Electrotechnical Commission eventually chose the **ampere** as the fourth base unit of the MKSA or 'Giorgi' system, and in 1948 the 9th General Conference of Weights and Measures† recommended it for science and technology, as well as for commerce and industry. This system admirably covers mechanics and electromagnetism, but it does not provide for other branches of science such as heat. In 1960, in the hope of securing world-wide uniformity in the units employed

† The General Conference of Weights and Measures (CGPM) is the authority set up by the Metre Convention of 1875 to promote and improve the metric system, and to secure international uniformity in metric units and standards of measurement. It consists of delegations from the member nations (of which there were 46, including the UK, in 1982), which meet every few years, the 15th, 16th and 17th Conferences having been held in 1975, 1979, and 1983 the International Bureau of Weights and Measures (BIPM), Sèvres (near Paris), is the central office and laboratory of the organization, and is managed, under the authority of the General Conference, by the International Committee of Weights and Measures (CIPM) consisting of 18

in natural science, the 11th CGPM added to the units metre, kilogram, second and ampere, the **kelvin** for thermodynamic temperature, the **candela** for luminous intensity, and the radian and steradian for plane and solid angle. The first two joined the original four in being called 'base' units, and the last two were called 'supplementary' units. Any unit formed from two or more base units is called 'derived'. The radian and steradian are regarded as derived units. The MKSA system thus broadened is called the International System of Units, often abbreviated to SI, and is the most satisfactory system of units we have had so far, in that it caters for the commercial and industrial activities of man as well as for the needs of science. In 1971, the 14th CGPM added the **mole,** the unit of amount of substance used in chemistry, to the list of base units, thus making them seven in all.

Definitions of some SI units

The seven base quantities, each with its unit and unit symbol, are listed below.

SI base quantities and units

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

The SI base units are defined as follows:

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

The second is 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 caesium-133 atom.

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

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

The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.

The SI supplementary units are defined thus:

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

The steradian is the solid angle which, having its vertex in the centre of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

members, each from a different nation. The International Committee meets yearly and is responsible for recommending proposals for approval by the General Conference. Eight specialist advisory committees assist the International Committee in planning co-operative programmes of research, and in the preparation of recommendations on units of measurement, on length (definition of the metre), mass, time (definition of the second), temperature, electricity, photometry and radiometry, and ionizing radiations.

Derived units. The table below lists some of the more common SI derived quantities, each with its unit and unit symbol. The composite symbols in the last column are to some extent indicative of the definition of the quantity.

Quantity	*Unit*	*Symbol*	
Supplementary			
Plane angle	radian	rad	
Solid angle	steradian	sr	
Derived			
Area	square metre		m^2
Volume	cubic metre		m^3
Frequency	hertz	Hz	s^{-1}
Density	kilogram per cubic metre		$kg\ m^{-3}$
Concentration	mole per cubic metre		$mol\ m^{-3}$
Velocity	metre per second		$m\ s^{-1}$
Angular velocity	radian per second		$rad\ s^{-1}$
Acceleration	metre per second squared		$m\ s^{-2}$
Angular acceleration	radian per second squared		$rad\ s^{-2}$
Force	newton	N	$m\ kg\ s^{-2}$
Pressure, stress	pascal	Pa	$N\ m^{-2}$
Viscosity (dynamic)	pascal second		Pa s
Viscosity (kinematic)	metre squared per second		$m^2\ s^{-1}$
Energy, work, quantity of heat	joule	J	N m
Power, radiant flux	watt	W	$J\ s^{-1}$
Quantity of electricity	coulomb	C	A s
Potential difference, electromotive force	volt	V	$W\ A^{-1}$
Electric field strength	volt per metre		$V\ m^{-1}$
Electric resistance	ohm	Ω	$V\ A^{-1}$
Electric conductance	siemens	S	Ω^{-1}
Capacitance	farad	F	$C\ V^{-1}$
Magnetic flux	weber	Wb	V s
Magnetic flux density	tesla	T	$Wb\ m^{-2}$
Inductance	henry	H	Ω s
Magnetic field strength	ampere per metre		$A\ m^{-1}$
Magnetomotive force	ampere	A	
Wave number*	1 per metre		m^{-1}
Activity (of a radionuclide)	becquerel	Bq	s^{-1}
Absorbed dose	gray	Gy	$J\ kg^{-1}$
Dose equivalent	sievert	Sv	$J\ kg^{-1}$
Luminous flux	lumen	lm	cd sr
Luminance	candela per square metre		$cd\ m^{-2}$
Illuminance	lux	lx	$lm\ m^{-2}$
Heat flux density, irradiance	watt per square metre		$W\ m^{-2}$
Heat capacity, entropy	joule per kelvin		$J\ K^{-1}$
Specific heat capacity, specific entropy	joule per kilogram kelvin		$J\ kg^{-1}\ K^{-1}$
Thermal conductivity	watt per metre kelvin		$W\ m^{-1}\ K^{-1}$
Molar energy	joule per mole		$J\ mol^{-1}$
Molar entropy, molar heat capacity	joule per mole kelvin		$J\ mol^{-1}\ K^{-1}$

* Wave numbers in the infra-red are still often expressed in cm^{-1}.

Multiples. Prefixes may be used, instead of powers of 10, to express certain decimal multiples of the units. Their names and symbols are listed below.

Factor	*Name*	*Symbol*	*Factor*	*Name*	*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	deca	da	10^{-18}	atto	a

An exponent attached to a symbol containing a prefix indicates that the multiple of the unit is raised to the power expressed by the exponent.

Example: $1\ cm^3 = 10^{-6}\ m^3$; $1\ cm^{-1} = 10^2\ m^{-1}$.

Compound prefixes should not be used, e.g. p not μμ. Names of multiples of the unit of mass are formed by attaching prefixes to the word 'gram'.

1.1.2 Realization of SI units

The metre

In 1975 the 16th CGPM, having examined results of recent measurements of the frequencies and wavelengths of several laser lines, recommended the use of the value 299 792 458 m s^{-1} for the speed of light in vacuum. In 1983, further measurements having shown no cause for changing this value, the 17th CGPM confirmed it, and re-defined the metre in terms of it and of the second defined on p. 2. The new definition, also given on p. 2, supersedes the definition based on the wavelength of a spectral line of krypton.

In order to facilitate realization of the metre by laboratory workers according to the new definition, CIPM has recommended the procedures to follow. The methods fall into two classes: (1) a time of flight measurement, using the relation $l = c.t$; (2) an interferometric measurement, using a wavelength derived from a frequency by the relation $\lambda = c/f$. The first method is suitable for long distances, the second for the laboratory and small-scale engineering. To avoid the need for frequency measurements by individual workers using the second method, CIPM has listed the wavelengths: (a) of five stabilized laser radiations, with operating conditions and uncertainties; (b) of the former krypton-86 standard; and (c) of the other discharge tube standards recommended in 1963.

In most cases what is required is not realization of the unit itself, but rather measurement of a particular distance, e.g. the length of a rod or the separation of two optical flats. Interferometers, usually of the Fabry–Perot or of the Michelson type, are employed to determine the number of waves covering the distance. The krypton-86 line gives satisfactory fringes at path differences less than half a metre, but stabilized lasers, for instance those listed by CIPM, which have much narrower lines, have increased the workable distance to over 100 m.

The kilogram

Realization of the kilogram consists in making weights equal in mass to the mass of the prototype of the kilogram. The prototype is kept by BIPM, and the various nations adhering to the Metre Convention have copies which from time to time they send to Sèvres for comparison with the prototype or with the Bureau's copies of the prototype.

Methods of adjusting weights are well known, as also are balances for comparing them. Similarly, the production of masses which are multiples of the unit, and their calibration by means of balances, are standard practice. With reliable weights—for example, of platinum–iridium or of stainless steel—and good balances, and with a great deal of care, masses of the order of 1 kg can be compared to 1 in 10^9.

The second

The second of time was formerly defined as 1/86 400 of the mean solar day. Its present definition in terms of the radiation corresponding to the hyperfine transition of the caesium-133 atom was adopted at the 13th General Conference of Weights and Measures in 1966, the duration of 9 192 631 770 periods of this radiation being chosen in order to secure as close agreement as possible with astronomical definitions.

The transition of the caesium atom is observed in an atomic beam equipment designed to eliminate the major causes tending to broaden or shift the line. The atoms pass through a system of magnets in which they are deflected, and through an electrical resonator supplied with an alternating field at a frequency derived by synthesis from a quartz oscillator. When the applied frequency equals that of the spectral line, transitions between the states are induced and deflection of the atoms is reversed. A resonant line is thus observed and, if the frequency deviates from that of the spectral line, an error signal is produced and applied to the quartz oscillator to pull its frequency to the correct value. The quartz oscillator acts as the working standard, as it did when time was based on astronomical measurements.

Although the unit has been defined in terms of the caesium line, similar lines of other atoms can be measured with great accuracy, and can then be used as standards. The frequency of the hydrogen line, for example, is 1 420 405 751.77 Hz.

It is not necessary for other than highly specialized organizations to own caesium beam or similar standards with which to realize the second, for many countries broadcast frequency and time signals by which any laboratory having a suitable radio receiver can calibrate its wavemeters and electronic counters (see p. 152). These transmissions are, in general, accurate to 1 in 10^{11}, and corrections to 1 in 10^{12} are published later.

The ampere

The definition of the ampere is simple and satisfies legal requirements, but the configuration it specifies precludes it from being applied as it stands to the measurement of electric current. However, as it is consistent with electromagnetic theory, other more practical configurations can be employed. The force per unit current between current-carrying coils of circular or helical shape can be calculated from the dimensions of the coils by fairly simple, exact formulae, and the current becomes known if the force is also measured with, for instance, a balance. These current balances, or dynamometers, are only used at rare intervals of, say, a few years. As their accuracy of a few p.p.m. is far superior to the precision of pointer or even reflecting ammeters, they are fed with a current stabilized by equalizing the volt drop RI across a standard resistor to the e.m.f. E of a Weston cell. The current I in the balance is then E/R, where *a priori* neither E nor R is known in absolute value. As explained below, however, R can be measured independently in terms of the metre and the second, and the two measurements thus yield E and R. In the intervals between measurements with current balances, the ampere is maintained, to a precision of about 1 p.p.m., by means of standard resistors and Weston cells.

The monitoring, though not the realization, of the ampere—i.e. of the resistors and cells which serve to maintain it—may also be effected by an application of nuclear magnetic resonance. The current, nominally equal to E/R as for the current balance, is carried by a coil of shape such that the magnetic field near its centre is uniform, and the frequency of precession of protons in that field is observed. If the dimensions of the coil do not change from year to year, or if the change is measured and allowed for, the frequency of precession provides a check on the stability of E/R. Measurement of a frequency is less laborious than accurate 'weighing' of a current.

The volt and the ohm

The volt, or watt/ampere, could, according to its definition, be realized from the ampere by a measurement of dissipation of energy in the form of heat. However, as energy is not easily measured to an accuracy of 1 p.p.m., it has been the practice to realize the volt, or the ohm, by an independent measurement involving electromagnetism. Whichever is realized, the other is obtained from it and the ampere by Ohm's law.

In the past the ohm has in general been chosen for the independent measurement. If we remember that the quantities ωL, ωM, $1/\omega C$—where ω, L, M and C stand for angular frequency, self-inductance, mutual inductance and capacitance—all have the dimensions of R, we see that a method of determining R is to compare it with one of those quantities. Self- and mutual inductors and capacitors have all been used. They are designed so that their values may be calculated from their linear dimensions. Accuracies of 1 in 10^7 and even better have been claimed for the calculable capacitor method of realizing the ohm. As the metre and the second are defined in terms of atomic constants, the ohm also depends on those constants.

The calculable capacitor, being fairly easy to use once it has been adjusted, is also suitable for monitoring standard resistors. The Weston cells which serve to maintain the volt can be monitored independently by an application of the Josephson effect in superconductivity. The p.d. between two superconductors separated by a narrow gap assumes values which are multiples of $hf/2e$, where f is the frequency of electromagnetic waves irradiating the superconductors, h is Planck's constant and e the electronic charge. For the mere purpose of monitoring the Weston cell from year to year, it is not even necessary to know the value of the constant $h/2e$.

Standard resistors for preserving the ohm are in general of nominal value 1 Ω. The e.m.f. of Weston cells depends slightly on temperature and on the acidity of the electrolyte. The figures below are representative of the variation with temperature.

E.M.F. of saturated (0.05 N) Weston cell

Temperature/°C	*Electromotive force*/V	*Temperature*/°C	*Electromotive force*/V
0	1.018 97	25	1.018 40
5	1.018 98	30	1.018 14
10	1.018 92	35	1.017 84
15	1.018 80	40	1.017 51
20	1.018 62		

International electric units. From the beginning of the century until 1948, the electric and magnetic units were not derived directly from the base units of length, mass and time, but from internationally agreed values for the electrochemical equivalent of silver and for the specific resistance of mercury. These units were called 'international units'. As one would not, for accurate work, use tables of constants published before 1948, the need for conversion factors hardly ever arises. The figures given by the International Bureau of Weights and Measures are

1 'mean international ohm' = 1.000 49 Ω
1 'mean international volt' = 1.000 34 V

The kelvin

The unit of thermodynamic temperature, the kelvin, is defined by assigning the value 273.16 K to the temperature of the triple point of water. The determination of other temperatures in terms of this unit requires measurements, by means of a gas thermometer for example, which can be evaluated in accordance with the thermodynamic definition of temperature. Absolute measurements of this kind are difficult, and their accuracy is usually less than the reproducibility attainable by non-absolute methods based on the fixed points of various substances, and interpolation or extrapolation by instruments such as resistance thermometers, thermocouples, and optical pyrometers. This situation has led to the adoption, by international agreement, of a practical temperature scale, IPTS-68, based on the use of these more reproducible methods, and adjusted to conform to the best available knowledge of the thermodynamic temperatures of fixed points (see section 1.5, p. 44).

The mole

Although the mole is defined in terms of number of entities, it is usually realized by weighing rather than by counting. A mole of atoms of an element X, for example, is obtained by weighing an amount, in grams, of X, equal to its relative atomic mass (atomic weight); similarly a mole of molecules of a substance Y is obtained by weighing an amount, in grams, of Y, equal to its relative molecular mass (molecular weight).

In the case of perfect gases, 1 mole of molecules occupies the same volume, independently of the particular gas, at any given temperature and pressure. This relation provides a method for measuring equal amounts of substance of perfect gases. The method of volume comparison can be extended to non-perfect gases, because the corrections to apply are well known.

Ratios of amounts of substance liberated in electrolytic reactions can be determined by measuring the corresponding quantities of electricity. For example, 1 mole of Ag and 1 mole of Cu(1/2) are deposited on a cathode by the same quantity, approximately 96 485 C, of electricity.

The candela

The definition of the candela on p. 2 was promulgated by the 16th CGPM, in 1979, to replace that based on black-body radiation. The secondary standards of luminous intensity are tungsten-filament lamps powered by a specified direct current. They are calibrated by comparison with the monochromatic radiation prescribed in the definition, account being taken of their 'relative spectral luminous efficiencies', $V(\lambda)$ (see section 1.7.3., p. 86), recommended by CIPM. This experimentally determined function is a relation between the sensitivity of the average eye and the wavelength of the light falling on it. There are two such functions, $V(\lambda)$ for photopic vision, $V'(\lambda)$ for scotopic vision. By their means photometric quantities are defined in purely physical terms as quantities proportional to the sum or integral of a spectral power distribution, weighted according to a specified function of wavelength.

1.1.3 Relations between SI and other units

CGS units

Many books and papers on electromagnetism were written before the general adoption of SI. The following table gives the relations between the units, and the conversion factor by which the number expressing the value of the quantity in CGS units must be multiplied to express its value in SI units.

Electric and magnetic units

Quantity and symbol	*SI unit*			*Conversion factors*	
	Name and symbol		*Defining equation*	*CGSm*	*CGSe*
1. Electric current, I	ampere	A	$F_z = 10^{-7} I^2 (dN/dz)$‡	10	$10/c$†
2. Current density, J		$A\ m^{-2}$		10^5	$10^5/c$
3. Electromotive force, potential difference, V	volt	V	P§ $= IV$	10^{-8}	$10^{-8}c$

Electric and magnetic units

Quantity and symbol	SI unit			Conversion factors	
	Name and symbol		Defining equation	CGSm	CGSe†
4. Electric field strength, E		$\mathrm{V\,m^{-1}}$	$E = V/l$	10^{-6}	$10^{-6}c$
5. Resistance, R	ohm	Ω	$R = V/I$	10^{-9}	$10^{-9}c^2$
6. Conductance, G	siemens	S	$G = 1/R$	10^{9}	$10^{9}/c^2$
7. Volume resistivity, ρ		$\Omega\,\mathrm{m}$		10^{-2}	$10^{-11}c^2$
8. Conductivity, γ		$\mathrm{S\,m^{-1}}$	$\gamma = 1/\rho = J/E$	10^{2}	$10^{11}/c^2$
9. Electric charge, Q	coulomb	C	$Q = It$	10	$10/c$
10. Capacitance, C	farad	F	$C = Q/V$	10^{9}	$10^{9}/c^2$
11. Electric flux density, D		$\mathrm{C\,m^{-2}}$	$D = Q/l^2$ ‖	10^{5}	$10^{5}/c$
12. Permittivity, ϵ		$\mathrm{F\,m^{-1}}$	$\epsilon = D/E$		$10^{11}/4\pi c^2$
13. Magnetic field strength, H		$\mathrm{A\,m^{-1}}$	$\oint H\,\mathrm{d}l = nI$	$10^{3}/4\pi$	
14. Magnetic flux, ϕ	weber	Wb	$E = \mathrm{d}\phi/\mathrm{d}t$	10^{-8}	
15. Magnetic flux density, B	tesla	T	$B = \phi/l^2$ ‖	10^{-4}	
16. Inductance, L, M	henry	H	$M = \phi/I$	10^{-9}	
17. Permeability, μ		$\mathrm{H\,m^{-1}}$	$\mu = B/H$	$4\pi \times 10^{-7}$	

† c = velocity of light in free space in $\mathrm{cm\,s^{-1}} = 2.997\,924\,58 \times 10^{10}$.

‡ N denotes Neumann's integral for two linear circuits each carrying the current I; F_z in the force between the two circuits in any direction z, the circuits being in a vacuum; r is the distance between the vector elements $\mathrm{d}s_1$, $\mathrm{d}s_2$.

$$N = \oint_1 \oint_2 \frac{\mathrm{d}s_1 \cdot \mathrm{d}s_2}{r}$$

§ P denotes power.

‖ l^2 denotes area.

The proportionality constants in the following equations are determined by use of the defining equations (1) to (17) in the table above.

For the mutual inductance M of two linear circuits, for which Neumann's integral is N, in a medium of permeability μ:

$$M = \frac{\mu}{4\pi} N \qquad \ldots(18)$$

For the force F_z due to currents I_1 and I_2 in the above two circuits:

$$F_z = I_1 I_2 \frac{\mathrm{d}M}{\mathrm{d}z} = \frac{\mu}{4\pi} I_1 I_2 \frac{\mathrm{d}N}{\mathrm{d}z} \qquad \ldots(19)$$

For the capacitance δC of an element of volume of length δl and cross-sectional area δA in a uniform dielectric medium of permittivity ϵ, the electric field having the direction of l:

$$\delta C = \epsilon \frac{\delta A}{\delta l} \qquad \ldots(20)$$

In the SI, Maxwell's equations for propagation in a medium are

$$\nabla \times H = \dot{D} + J, \qquad -\nabla \times E = \dot{B} \qquad \ldots(21)$$

where the dot means $\mathrm{d}/\mathrm{d}t$, J is current density, and the other quantities are as in the table. The velocity of propagation of an electromagnetic wave in the medium is given by

$$v^2 = 1/\mu\epsilon \qquad \ldots(22)$$

In free space, where J is zero, and where D and B are linked with E and H by the electric and magnetic constants ϵ_0 and μ_0, the equations may be written

$$c^2 \nabla \times B = \dot{E}, \qquad -\nabla \times E = \dot{B} \qquad \ldots(23)$$

The velocity of propagation c is given by

$$c^2 = 1/\mu_0\epsilon_0 \qquad \ldots(24)$$

The values of μ_0, ϵ_0 and of the characteristic impedance Z_0 of free space are

$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}} = 1.256\,637\ \mu\mathrm{H\,m^{-1}}$$
$$\epsilon_0 = 8.854\,19\ \mathrm{pF\,m^{-1}}$$
$$Z_0 = \sqrt{(\mu_0/\epsilon_0)} = 376.730\,\Omega$$

Coulomb's law of force f between electric charges Q, Q' a distance r apart, and its analogue for magnetic poles ϕ, ϕ', can be deduced from Maxwell's equations. The expressions are

$$f = \frac{QQ'}{4\pi\epsilon r^2} \qquad \ldots(25)$$

$$f = \frac{\phi\phi'}{4\pi\mu r^2} \qquad \ldots(26)$$

Other mechanical units

In the gravitational systems of units sometimes still used in engineering and aerodynamics, the units of length and time are base units, but the third base unit is a unit of force, namely the force due to a conventional value of gravity, called standard gravity, acting on a specified mass. The unit of mass is thus a derived unit, and since unit mass is given unit acceleration when acted on by unit force, the unit of mass is equal to the standard value of gravity multiplied by the specified mass.

In the metric gravitational system, standard gravity is 9.806 65 m s^{-2}, the unit of force is called kilogram-force, symbol kgf, the specified mass is the kilogram, and the unit of mass is therefore 9.806 65 kg. In Germany and some other European countries the same unit of force is called kilopond, symbol kp.

In the foot–pound–second gravitational system the base unit of force is the pound-force, symbol lbf, standard gravity is 32.174 ft s^{-2}, and the derived unit of mass, the slug, is now 32.174 lb. although originally it was 32.2 lb, based on 32.2 ft s^{-2} for gravity.

Conversion factors

The following table gives conversion factors for British and other units which are still used in some fields, but which, for the most part, are likely to disappear in course of time. Exact conversion factors are in bold type.

Unit name and symbol		*SI equivalent*		*Reciprocal*
Length				
ångström	Å	**0.1**	nm	**10**
fermi		**1**	fm	
micron	μ	**1**	μm	
yard	yd	**0.914 4**	m	1.093 61
foot	ft	**30.48**	cm	0.032 808 4
inch	in	**2.54**	cm	0.393 701
statute mile		**1.609 344**	km	0.621 371
nautical mile (international)		**1.852**	km	0.539 957
fathom (6 ft)		**1.828 8**	m	0.546 807
X unit		0.100 2	pm	
astronomical unit (AU)		0.149 6	Tm	
parsec	pc	30.857	Pm	