A DICTIONARY OF SCIENTIFIC UNITS

INCLUDING DIMENSIONLESS NUMBERS AND SCALES

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LONDON : CHAPMAN & HALL : 1963

First published 1963

CHAPMAN & HALL, LTD.
37 ESSEX STREET
LONDON W.C.2

Catalogue No. 743/4

PRINTED IN GREAT BRITAIN BY THE PITMAN PRESS, BATH

PREFACE

The intense specialization that occurs in science today has meant that scientists working in one field are often not familiar with the nomenclature used by their colleagues in other fields. This is particularly so in Physics. This dictionary is designed to help overcome this difficulty by giving information about the units, dimensionless numbers and scales which have been used, or are still being used, throughout the world. Some four hundred entries are provided and these are supplemented by about five hundred references. The definition of each entry is given together with relevant historical facts. Where appropriate, some indication of the magnitude of each unit is included. Any scientific unit, which to the authors' knowledge has appeared in print, even if not universally adopted, has been listed. While it is too much to hope that there are no omissions, it is believed that there cannot be many and that this dictionary provides the most complete information of its kind available. The units are listed alphabetically and the references are numbered in sequence for each letter. In appendices are given a table of fundamental physical constants, details of standardization Committees and Conferences, a table of British and American weights and measures and conversion tables. The symbols and abbreviations used throughout the text are those recommended by the Institute of Physics and the Physical Society and by the British Standards Institution.

It is a pleasure to acknowledge the help given by numerous friends and colleagues and in particular that given by Dr. J. R. Clarkson of the Royal South Hants Hospital; Mr. C. H. Helmer of the Mechanical Engineering Department, Southampton University; Dr. Peter Lane of the Iraq Petroleum Company; Miss D. M. Marshallsay of the Department of Economics, Southampton University; Mr. R. E. Peroli of the Belfast Public Textile Testing House; Dr. L. G. A. Sims, Professor of Electrical Engineering, Southampton University; Mr. R. W. Watridge, the Southampton Borough analyst; Major H. W. H. West of the British Ceramic Research Association and by the Librarians and Staffs of the University and the Public Libraries at Southampton. Finally we wish to thank Mrs. H. G. Jerrard and Miss A. J. Tutte for typing the manuscript.

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INTRODUCTION

ALL non-electrical physical quantities may be defined in terms of mass, length and time which are the three fundamental mechanical units. Electrical and magnetic quantities generally require four units of which three are mass, length and time and the fourth can be some electrical or magnetic quantity such as current, permeability or permittivity. It is sometimes convenient to introduce temperature as an independent unit ranking equally with length, time and mass but if it is recognized that heat is of the same nature as energy, temperature may be defined in terms of the three fundamental mechanical units. It would appear, then, that all physical quantities can be expressed in terms of four units. The measurement of mass, length and time dates back to the dawn of history, whereas electrical and magnetic phenomena were not considered quantitatively until the middle of the nineteenth century.

In principle, measurement is finding an expression for a quantity in terms of a ratio of the quantity concerned to a defined amount of the same quantity. The defined amount can be chosen in an arbitrary manner—e.g. the yard—or it can have its origin in some natural phenomena, such as the metre, which can be defined in terms of the wavelength of a selected line of the Krypton emission spectra. The former type of units are called arbitrary, the latter natural. At present the fundamental unit of length is a natural unit whereas those of mass and time are arbitrary. Natural units are, in theory at least, capable of being reproduced anywhere at any time, whereas arbitrary units require the presence of a prototype. Once an arbitrary unit is defined it does not alter and neither would a natural unit once its real value is known, but in practice natural units have to be changed in size every time a discrepancy is found in the natural measurement from which the unit is derived. An example of this is given by the kilogramme which was originally intended to be a natural unit representing the mass of a cubic decimetre of water. More accurate measurement at a later date showed the volume of water used was 1·00028 cubic decimetre, so the kilogramme is a little too heavy. This could have been remedied by altering the mass of the kilogramme, but it was decided to keep the mass unchanged and to make the kilogramme an arbitrary unit which is called the International Prototype Kilogramme.

In general, units should be of such a size that the quantity being measured can be expressed in convenient figures. Thus the expenditure of a modern state may be given in units of millions of pounds but the cash in a child's money box is better counted in pennies. It sometimes happens that the choice of a unit is not suitable to cover all applications in which case the original unit is multiplied by a suitable power of ten to give a derived unit. For example the unit of length is the metre but it is often better to give the distance between two towns in kilometres (10^3 m) and the size of bacteria in microns (10^{-6} m). A measurement should always be expressed as a number followed by the name of the unit concerned so that the magnitude and description of the physical quantity concerned is conveyed to all who require to know it. A number without a unit is meaningless unless it be a recognized dimensionless number or a ratio. A unit should always be called by its recognized name.

SYSTEMS OF UNITS

ANY system of units defined in terms of the fundamental units of mass, length and time form an absolute system of units. The principle of absolute units was first proposed by K. F. Gauss (1777–1855) in 1832.[1] In 1851,[2] he and Weber drew up a set of units based on the millimetre, the milligramme and the second. This is known as the Gaussian system. Twenty two years later[3] the British Association adopted the metric system but used the centimetre, the gramme and the second as the fundamental units; these are often called the C.G.S. units. Other metric systems use the metre, the kilogramme and the second (M.K.S. units) and the tonne, metre, second (t.m.s. units). Engineers throughout the English speaking world generally use the foot, pound, second units. The history of the fundamental units is given briefly by Sir Richard Glazebrook in the 1931 Guthrie Lecture[4] and in some detail by R. W. Smith in the National Bureau of Standards Circular 593 entitled the Federal Basis for Weights and Measures.[5]

Electrical and magnetic quantities generally require a fourth term for their complete definition. In the C.G.S. electromagnetic system, the units of which are also called e.m.u. or abunits, the fourth term is permeability and its value is taken as unity if the medium be a vacuum. In the C.G.S. electrostatic system, in which the units are called e.s.u. or statunits, the fourth term is permittivity and this is considered to be unity in a vacuum. In the M.K.S. system the fourth term is the permeability of free space and this has a value of $4\pi \times 10^{-7}$ henry metre^{-1} or 10^{-7} henry metre^{-1} according to whether a rationalized or unrationalized system is used.

Atomic system of units

This system of units was suggested by Hartree in 1927[6] to reduce the numerical work in problems involving the atom.

The unit of charge e is the charge on the electron ($1{\cdot}6 \times 10^{-19}$ coulomb), the unit of mass m is the rest mass of an electron (9×10^{-31} kg) and the unit of length a is the radius of the first Bohr orbit in the hydrogen atom ($0{\cdot}53 \times 10^{-8}$ cm). The unit of time is the reciprocal of the angular frequency $1/4\pi Rc$ ($2{\cdot}4 \times 10^{-17}$ seconds), where R is Rydberg's constant and c the speed of light. The unit of action is $h/2\pi$, where h is Planck's constant. The unit of energy is $e^2/a^2 = 2\,Rhc$, which is the potential energy of unit charge situated at unit distance from a similar charge and which is also equal to twice the ionization energy of the hydrogen atom. Shull and Hall[7] suggest that since e^2/a^2 can be written as $4\pi^2me^4/h^2$, the quantity me^4/h^2 should be used as a unit of energy which they call the Hartree.

C.G.S., e.m.u., e.s.u., system of electrical units.

The force F between two magnetic poles of strength m_1 and m_2 placed a distance d apart in a medium of permeability μ is given by $F = m_1 m_2/\mu d^2$. If F, μ and d be each unity and if $m_1 = m_2 = m$, then m_1 and m_2 are poles of unit strength. Units based on this definition of m are known as electromagnetic units (e.m.u.). The quantities defined by these units are generally of an inconvenient size for practical work so units, known as practical units, are used. The latter may be obtained by multiplying the e.m. unit by a suitable conversion factor. In 1903[8] the prefix ab was suggested to denote the unit concerned is a C.G.S. electromagnetic unit, thus 1 abvolt = 10^{-8} practical volts, 1 abampere = 10 practical amperes. The suggestion met with little response at first but in recent years some authors have started using this notation.[9]

The force F between two charges q_1 and q_2, a distance d apart in a medium of permittivity ε, is given by $F = q_1q_2/\varepsilon d^2$. If F, ε and d be unity and if $q_1 = q_2 = q$, then q_1 and q_2 are unit charges. Electrostatic units (e.s.u.) are based on this value of q. Like the e.m. units electrostatic units are not of convenient size for practical work and are generally replaced by practical units for everyday electrical measurements. In recent years the prefix stat has sometimes been used to denote electrostatic units, thus 1 stat volt = 300 practical volts, 1 stat ampere = (1/3) × 10^{-9} ampere. This prefix is an abbreviation for abstat which was proposed for electrostatic units at the same time as ab was suggested for electromagnetic units.

Ab units and stat units are connected by the relationship $\mu\varepsilon = 1/c^2$, where c is the velocity of light in centimetres second^{-1}. Thus the ratio (ab unit/stat unit) for the primary units is equal to the velocity of light, or its reciprocal, viz. abampere/statampere = c and abvolt/statvolt = $1/c$. The ratio ab/stat for secondary units is obtained by considering each of the primary units concerned thus

$$\frac{\text{ab farad}}{\text{stat farad}} = \frac{\text{ab coulomb}}{\text{ab volt}} \times \frac{\text{stat volt}}{\text{stat coulomb}} = c^2$$

The inconvenience of having three systems of electrical units, ab units, stat units and practical units has been overcome by the introduction of the metre, kilogramme, second, ampere units (M.K.S.). In this system, the practical units have the same value as the theoretical ones, which themselves require no modification for use in either electromagnetic or electrostatic problems.

Gravitational system of units

In these units the three fundamental quantities are the unit of weight, the unit of length and the unit of time.[10] In the British system these are the pound weight, the foot and the second. In the metric system the units are either the gramme weight, the centimetre and the second or the kilogramme weight, the metre and the second. In both systems the unit of weight is the weight of the fundamental unit of mass when weighed in a standard gravitational field for which the value of g, the acceleration due to gravity, is known. The International Commission of Weights and Measures agreed in 1901 that for gravitational units g shall have a value of 32·1740 ft sec^{-2} or 980·665 cm sec^{-2}.

Heaviside-Lorentz system of units

These are C.G.S. units in which the force between two magnetic poles m_1 and m_2, a distance d apart in a medium of permeability μ is given as $m_1m_2/4\pi\mu d^2$. An analogous equation $q_1q_2/4\pi\varepsilon d^2$ gives the force between two charges q_1 and q_2 in a medium of permittivity ε. The Heaviside-Lorentz units were the earliest rationalized units, they were proposed by Heaviside[11] in 1883 and used by him in a classical paper on electrical theory published nine years later.[12]

International system of units

This is the name recommended in 1960 by the International Conference on Weights and Measures for the system of units based on the metre, kilogramme, second, ampere, degree kelvin and the candela.

Ludovici system of units

A system of units proposed in 1956[13] in which the fundamental quantities are the free space values of the gravitational constant, permeability, permittivity and charge. These values give a unit of length equal to $4{\cdot}88 \times 10^{-36}$ m and a unit of time equivalent to $1{\cdot}63 \times 10^{-44}$ second.

M.K.S. system of electrical units

The C.G.S. electromagnetic and electrostatic units are somewhat inconvenient when calculating certain electrical properties such as inductance and capacitance as certain factors involving powers of ten or the figures 3 and 9 have to be introduced to derive practical units from those obtained from theoretical considerations. As early as 1873 Clerk Maxwell[14] showed the practical electromagnetic units could be substituted directly in the fundamental theoretical equations if the unit of length were taken as the earth's quadrant (10^9 cm), the unit of mass as 10^{-11} gramme, the permeability of a vacuum μ_0 as unity and the unit of time as the second. Twenty years later G. Giorgi[15] pointed out that if the unit of length be taken as the metre, the unit of mass as the kilogramme, μ_0 as $4\pi \times 10^{-7}$ and the unit of time remain unchanged as the second, then the practical units could be used directly in both the electromagnetic and the electrostatic systems. Furthermore, the introduction of 4π into the value of μ_0 meant that most of the electrical units would be rationalized, i.e. the factor 2π would occur if the system were cylindrically symmetrical and 4π if spherically symmetrical. A disadvantage of the Giorgi system is that the difference between *magnetic induction* (B) and field strength (H) can no longer be ignored as it is in the C.G.S. system in cases where the permeability is unity, such as when the medium is air. Similarly the difference between the electric field (E) and the electric displacement (D) cannot be neglected as it is when the permittivity is unity.

The Giorgi or M.K.S. system attracted little attention until about 1935[16] but after this interest in them increased and in 1948[17] the 9th International Conference on Weights and Measures adopted the M.K.S. definition as their definition of the ampere and recommended the fourth unit in the rationalized M.K.S. system be $4\pi \times 10^{-7}$ henry metre^{-1}, a term which is known as the permeability of free space. The ampere is now defined as the steady current which, when maintained in two parallel conductors of infinite length and of negligible cross section one metre apart in a vacuum, produces between the conductors a force equal to 2×10^{-7} M.K.S. units of force per metre length.

O.A.S.M. units

A system of units proposed in 1945[18] in which the ohm, ampere, second and metre are the fundamental quantities.

Stroud system of units

These were devised by Professor W. Stroud of Leeds about 1880[19] to give engineers a set of absolute units based on the pound, the foot and the second and in which the distinction between mass and weight was emphasized. Stroud used capital letters for forces and small letters for masses, thus one Pound could accelerate one pound by 32 feet per second per second.

[A]

Abampere (abcoulomb, abfarad, abohm, abvolt)

The prefix ab- denotes the C.G.S. electromagnetic system of units, e.g. abampere is the unit of current in the C.G.S. system. (*See* **C.G.S. units**, page 12.)

Acoustic ohm

The acoustic ohm is the unit of acoustic impedance.[1] The acoustic impedance of a surface is defined as the ratio of the effective sound pressure averaged over the surface (i.e. pressure/area) to the effective volume velocity through it. This ratio is a complex number. Volume velocity is defined as the rate of flow of the medium perpendicular to the surface. A surface has an acoustic impedance of one ohm when unit effective pressure produces unit velocity across it. The C.G.S. acoustic ohm has dimensions of dyne second cm^{-5}, whereas the dimensions of the M.K.S. unit, called the M.K.S. acoustic ohm,[2] are newton second $metre^{-5}$. The baffle of a loudspeaker has generally an acoustic impedance of the order of several hundred M.K.S. acoustic ohms. The idea of applying Kirchhoff's electrical circuit procedures to solve acoustical problems was suggested by Webster[3] as early as 1919 but the acoustic ohm was first used by Stewart[4] in 1926.

Acre

A unit of area equal to 4840 square yards. The acre was first defined in England in the reign of Edward I (1272–1307) and is reputed to be the area which a yoke of oxen could plough in a day.