DEPARTMENT OF COMMERCE

CIRCULAR
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, Director

No. 60

ELECTRIC UNITS AND STANDARDS

[2d Edition]

Issued March 12, 1920

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ELECTRIC UNITS AND STANDARDS

CONTENTS

I. THE SYSTEMS OF UNITS

1. UNITS AND STANDARDS IN GENERAL

Every measurement must be expressed in terms of two factors or components. One of these is a certain definite amount of the physical quantity measured, called the unit. The other is a mere number, being the number of times the unit is taken. When there is no possibility of misunderstanding, the unit is sometimes implied and not stated explicitly.

A unit of any physical quantity is defined in general as a definite amount of that physical quantity, specified in some particular way. A standard is the experimental realization or representation of a unit. Units are of two types, independent and derived. An independent unit of a physical quantity is the amount of that physical quantity in an arbitrarily chosen standard. A derived unit is the amount of the quantity existent when units of related physical quantities are combined in specified ways. Thus, an independent unit is defined in terms of a standard; whereas a derived unit is realized through the units of those quantities from which the unit is derived. For example, the units of length and time are independent, but the unit of velocity is a derived unit, being the velocity when unit distance is passed over in unit time.

While derived units are not defined in terms of standards, nevertheless any unit may be represented by standards. In fact, many of the units in practical use are each represented by a multitude of standards. Certain of the standards representing the unit of a given physical quantity are copies of certain other standards, so that they may be graded into "primary," "secondary," and "working" standards. The "primary" standard is the particular standard which is taken to represent the unit; it is maintained in general either at the International Bureau of Weights and Measures, at Sèvres, France, or at one or more of the national standardizing laboratories. In the case of an independent unit the primary standard is that standard in terms of which the unit is defined; in the case of a derived unit it is simply a standard closely representing the unit and accepted for practical purposes, its value having been fixed by certain measuring processes. "Secondary" or "reference" standards are copies (not necessarily duplicates) of a primary standard, used in the work of a standardizing laboratory, testing institution, etc. They are or should be occasionally tested and evaluated in terms of the primary standard. The third class, "working" standards, are standardized in terms of the secondary standards and are used in every-day measurements. In short, any unit may be represented by a certain definite standard, which is known as the primary [1] standard of that unit; it fixes the values of secondary standards, which in turn are used for the standardization of working standards.

Systems of units of physical quantities are based upon a few selected fundamental independent units, the units of all other physical quantities being derived from these by the simplest available relations. As the fundamental units of a system are defined in terms of certain standards those standards are of greater importance than any others. A standard of a derived unit can be checked at any time by a measuring process. But the primary standard of an independent unit is itself an ultimate sort of thing. The criteria of such a fundamental standard may be stated to be (1) permanence, (2) accuracy in use, (3) availability, (4) convenience. Permanence is taken to mean that quality of a standard in virtue of which the unit defined by it preserves the same value as time goes on. A standard may have permanence in virtue either of constancy or reproducibility. For example, the international prototype meter bar has the quality of permanence by reason of the constancy of its length. If the length of a certain light wave were taken as the unit of length, permanence would be assured by the possibility of reproducing this wave with length unchanged at any time. After the essential requirement of permanence comes

[1] The committee on nomenclature and standards of the Illuminating Engineering Society adopted, in 1912, a definition of primary luminous standard at variance with the above. This difference in interpretation is now under discussion between the committee and this Bureau.

the necessity of comparing quantities accurately with the standard; the standard must be defined with great exactness and so constructed that accurate comparisons with it are possible. The minor requirements of availability and convenience include those of concreteness and simplicity of measurement.

A system of units of mechanical quantities requires only three independent units. Electricity and heat each require the addition of one. The quantities taken as fundamental are chosen in large part on the basis of how well the standards, in terms of which the independent units must be defined, fulfill the criteria given above for fundamental standards. Other requirements of the fundamental quantities are that the definition of the various derived units shall be easy and their dimensions simple. Length, mass, and time are the fundamental quantities in the usual systems of dynamical units. Units belonging to these systems are called absolute units, as are likewise those electric or other units in systems which employ length, mass, and time as three of the fundamental quantities. There are a number of isolated units not belonging to the absolute systems to serve a particular convenience, as, e. g., the gallon as a unit of volume and the atmosphere as a unit of pressure. These isolated units are derived units in the sense of being defined in terms of units of other quantities, but they are not absolute units.

The precise meaning attached to the word "absolute" has been somewhat variable. It was originally used [2] as opposed to the word "relative." It implied the use of units which depend upon units of other quantities taken as the fundamental quantities of a complete and self-consistent system. The object of an absolute system was to avoid complex coefficients in passing from one kind of measurement to another. The term has, however, been so used as to exclude gravitational units; that is, the fundamental units of an absolute system must be [3] independent of variations in time and place. The actual use of the term "absolute" has been in connection with those systems which employ length, mass, and time as fundamental quantities. Thus, the "international" system of electric units is not spoken of as

[2] Report of British Association Committee on Electrical Standards; 1863.

[3] Webster, "The Theory of Electricity and Magnetism," p. 100; 1897.

an absolute system, two of its fundamental quantities being electrical and only two mechanical. To designate a unit simply as an absolute unit is ambiguous, for that does not tell to what system the unit belongs. It is preferable to indicate the system specifically by such expressions as cgs, "practical" electromagnetic, etc.

The use of "absolute" as opposed to "relative" is familiar also in connection with measurements. Absolute measurements are those in which a physical quantity is measured in terms of those fundamental quantities of the system which enter into the dimensional formula of the physical quantity. (See explanation of dimensional formulas below.)

Having selected the physical quantities to serve as the basis of a system, the question of which units of these quantities are to be used is quite a separate question. The units of length, mass, and time generally used in scientific work are the centimeter, the gram, and the second. Systems employing the meter, kilogram, and second, or other units of length, mass, and time are just as truly absolute systems as is the cgs system. There have been many proposals to replace the cgs by other absolute systems because of certain advantages they possess. It has been the aim of those who proposed these systems to have a system of universal application, i. e., to use a single system of units for all the quantities of physics. Of course in practice we use whatever decimal multiples of the units are of convenient magnitude, generally regardless of which units are taken as the basis of the system. The following table gives some of the units of length, mass, and time which have been proposed in various absolute systems. The only one of these which has even faintly approached the desired universality of acceptance is the cgs system.

TABLE 1

Proposed Absolute Systems of Units

	Weber and Gauss	CGS (Kelvin)	W. Moon, 1891	MKS (Prim. Stds.) (Giorgi)	France, 1914	B. A. Com., 1863	Practical (B. A. Com., 1873)	W. Stroud, 1891
Length	10^{-1} cm	cm	10 cm	10^2 cm	10^2 cm	10^3 cm	10^9 cm	10^9 cm
Mass	10^{-3} g	g	10^3 g	10^3 g	10^6 g	g	10^{-11} g	10^{-9} g
Time	sec.	sec	10^{-1} sec.	sec.	sec.	sec.	sec.	sec.

The relations among units are conveniently exhibited by means of dimensional equations. These equations show how the derived units change if any change is made in the independent units of the system. Suppose the units of length, mass, and time be designated by $[L]$, $[M]$, and $[T]$, respectively. The unit of force is, in the usual systems,

$$[F]=\left[\frac{ML}{T^2}\right],$$

and thus the unit of force is shown to vary proportionally as the units of mass and length and inversely as the square of the unit of time. A further use of dimensional equations is in checking the validity of physical equations. Physical equations must be homogeneous; i. e., if the dimensional expression be written for every quantity appearing in an equation, all the terms of the equation must become identically equal. For instance, the distance moved by a uniformly accelerated body is: $s=v_0t+\frac{1}{2}at^2$. The corresponding dimensional terms are:

$$[L], \left[\frac{L}{T}T\right], \left[\frac{L}{T^2}T^2\right]$$

The equality of these terms indicates that the physical equation is correct in form.

2. THE ELECTROSTATIC AND ELECTROMAGNETIC SYSTEMS

It was shown by W. Weber in 1846 that electric units could be expressed in an absolute system. Defining the unit of quantity of electricity as the quantity which exerts unit mechanical force upon an equal quantity of electricity, the two being at points unit distance apart in a vacuum,[4] units of all the other electrical quantities can then be derived by aid of the equations which constitute the mathematical theory of electricity. This gives the electrostatic system. Starting with a similar definition for the unit of quantity of magnetism, the electromagnetic system is obtained.

[4] Air is specified instead of a vacuum by some writers. Since air is of variable composition and density, it is not as appropriate a medium for the purposes of a fundamental definition as is empty space. The observed force in the two media differs so slightly, however, that the difference is appreciable only in measurements of extreme precision.

The mechanical force F between two quantities of electricity Q and Q' at points a distance r apart in a vacuum is

$$F=\frac{Q\,Q'}{r^2}, \tag{1}$$

Q being in electrostatic units.

Hence $[Q^2]=[FL^2]$, and since $[F]=\left[\frac{ML}{T^2}\right]$,

$$[Q]=\left[L^{3/2}M^{1/2}T^{-1}\right] \tag{2}$$

Similarly, the electromagnetic unit of magnetic pole strength m is defined by the equation

$$F=\frac{mm'}{r^2}, \tag{3}$$

from which it follows that

$$[m]=\left[L^{3/2}M^{1/2}T^{-1}\right]. \tag{4}$$

Thus m has the same dimensional formula in the electromagnetic system that Q has in the electrostatic system. This identity of dimensions of different physical quantities may lead to confusion, as was pointed out by A. W. Rücker in 1889. This is avoided if symbols for dielectric constant and magnetic permeability appear in the dimensional expressions for the electrostatic and electromagnetic systems, respectively. The way in which these two properties of the medium affect the equations is as follows. The force between two quantities of electricity in any medium is

$$F=\frac{Q\,Q'}{Kr^2}, \tag{5}$$

where K is a quantity, called the dielectric constant,[5] varying with the medium; this equation holds for any system of units. From this equation it follows that $[Q^2]=[FKL^2]$, and since $[F]=\left[\frac{ML}{T^2}\right]$,

$$[Q]=[L^{3/2}M^{1/2}T^{-1}K^{1/2}] \tag{6}$$

[5] The term "specific inductive capacity" is often used interchangeably with dielectric constant. It is probably more useful to regard these two terms as differing in the same way that density and specific gravity differ. Dielectric constant and density are physical properties. The specific inductive capacity and specific gravity are ratios or mere numerics. Specific inductive capacity of a medium is the ratio of the dielectric constant of the medium to the dielectric constant of vacuum. It is numerically equal to the dielectric constant only in the ordinary electrostatic system.

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This dimensional expression is more general than is required for the conversion of units in the ordinary electrostatic system, in which K_o (dielectric constant of empty space) equals unity; (6) would be used in converting units in various theoretically possible "electrostatic" systems in which K_o is not unity, while (2) is used in converting the ordinary electrostatic units. Dimensional expressions containing K are, however, desirable even for the ordinary electrostatic system, because of their greater power in checking the validity of physical equations. For instance, the incorrectness of an equation containing a length and an electrostatic capacity added together, or containing an electric field intensity and an electric charge per unit area added together, would be shown by dimensional expressions in which the K was retained, but would not be if K were suppressed. Again, the former and not the latter dimensional expressions would show the incorrectness of an equation in which electrostatic capacity was calculated from a length times the square of the dielectric constant.

The electrostatic dimensional expressions are given in Table 2 below in terms of L, M, T, and K, and the electromagnetic dimensional expressions are given in terms of L, M, T, and μ. The reasons given for the retention of K in the electrostatic dimensional formulas hold also for the retention of μ in the electromagnetic formulas. Dimensional formulas in either system may be obtained in terms of L, M, and T only, as given by some writers, by merely omitting K or μ wherever it occurs.

The quantities tabulated are the principal ones in electromagnetic theory. All others (e. g., reluctivity, permeance, magnetic moment, strength of magnetic shell), are very simply deducible from these. A few quantities which have been used by certain writers are now almost obsolete. For example, Maxwell used the quantities $(\mathcal{E}\ d\ S)$ and $\iint(\mathcal{E}\ d\ S)$, which he called the "induction." The name "induction" has also been applied, in Webster's "Theory of electricity and magnetism," to $K\mathcal{E}$. These are no longer used much, the closely related D being used for most purposes, and the name "induction" is now generally reserved for the magnetic induction.

The electromagnetic system is the historical basis of the international electric units, which form an independent system and are the units now used. The international units are described on page 16 below and in reference No. 9d, Appendix 3.

TABLE 2

Electrostatic and Electromagnetic Dimensions

Quantity	Symbol	Dimensional formulas	
		Electrostatic	Electromagnetic
Quantity of electricity [a]	Q	$\left[\frac{L^{3/2}M^{1/2}K^{1/2}}{T}\right]$	$\left[\frac{L^{1/2}M^{1/2}}{\mu^{1/2}}\right]$
Dielectric constant [b]	K	$[K]$	$\left[\frac{T^2}{L^2\mu}\right]$
Electric field intensity	$\mathcal{E}$	$\left[\frac{M^{1/2}}{L^{1/2}\,T\,K^{1/2}}\right]$	$\left[\frac{L^{1/2}M^{1/2}\mu^{1/2}}{T^2}\right]$
Electric potential Electromotive force	V E	$\left[\frac{L^{1/2}M^{1/2}}{T\,K^{1/2}}\right]$	$\left[\frac{L^{3/2}M^{1/2}\mu^{1/2}}{T^2}\right]$
Electric displacement [c]	D	$\left[\frac{M^{1/2}K^{1/2}}{L^{1/2}T}\right]$	$\left[\frac{M^{1/2}}{L^{3/2}\mu^{1/2}}\right]$
Electrostatic capacity	C	$[LK]$	$\left[\frac{T^2}{L\mu}\right]$
Current	I	$\left[\frac{L^{3/2}M^{1/2}K^{1/2}}{T^2}\right]$	$\left[\frac{L^{1/2}M^{1/2}}{T\mu^{1/2}}\right]$
Resistance	R	$\left[\frac{T}{LK}\right]$	$\left[\frac{L\mu}{T}\right]$
Self-inductance Mutual inductance	$\mathcal{L}$ $\mathfrak{M}$	$\left[\frac{T^2}{LK}\right]$	$[L\mu]$
Magnetizing force [d]	H	$\left[\frac{L^{1/2}M^{1/2}K^{1/2}}{T^2}\right]$	$\left[\frac{M^{1/2}}{L^{1/2}T\mu^{1/2}}\right]$
Magnetic potential Magnetomotive force	Ω $\mathfrak{F}$	$\left[\frac{L^{3/2}M^{1/2}K^{1/2}}{T^2}\right]$	$\left[\frac{L^{1/2}M^{1/2}}{T\mu^{1/2}}\right]$
Magnetic pole strength [e]	m	$\left[\frac{L^{1/2}M^{1/2}}{K^{1/2}}\right]$	$\left[\frac{L^{3/2}M^{1/2}\mu^{1/2}}{T}\right]$
Magnetic permeability	μ	$\left[\frac{T^2}{L^2K}\right]$	$[\mu]$
Magnetic induction [f]	B	$\left[\frac{M^{1/2}}{L^{3/2}K^{1/2}}\right]$	$\left[\frac{M^{1/2}\mu^{1/2}}{L^{1/2}T}\right]$
Magnetic flux	ϕ	$\left[\frac{L^{1/2}M^{1/2}}{K^{1/2}}\right]$	$\left[\frac{L^{3/2}M^{1/2}\mu^{1/2}}{T}\right]$
Reluctance	$\mathfrak{R}$	$\left[\frac{LK}{T^2}\right]$	$\left[\frac{1}{L\mu}\right]$
Intensity of magnetization	J	$\left[\frac{M^{1/2}}{L^{3/2}K^{1/2}}\right]$	$\left[\frac{M^{1/2}\mu^{1/2}}{L^{1/2}T}\right]$
Magnetic susceptibility	κ	$\left[\frac{T^2}{L^2K}\right]$	$[\mu]$

[a] Also called "electric charge."

[b] This quantity has also been called "electric inductive capacity," "electric inductivity," and "permittivity."

[c] This has also been known by the names "polarization," "electrostatic induction," and "electrostatic flux density."

[d] Also called "magnetic force" and "magnetic field intensity." The latter is liable to confusion with "intensity of magnetization."

[e] Also known by the name "quantity of magnetism."

[f] Also called "flux density."

(*a*) **The Numerically Different Systems of Units.**—When the physical quantities which form the basis of a system are stated, it does not follow that the system is thereby determined. In fact, upon any set of four fundamental quantities, a great many different systems of units may be built up, the units differing in magnitude from one another. The electrostatic and electromagnetic systems are really, therefore, systems of electric quantities rather than units. To state that a unit is electrostatic or electromagnetic gives no information as to its size. The different systems of units of any one type may differ in two ways: (1) The units chosen for the fundamental quantities may be different; (2) the defining equations by which the system is built up may contain different constants.

The electrostatic units most frequently used are those based on the centimeter, gram, second, and dielectric constant of vacuum. Other electrostatic units, differing from these in the first way, have appeared in electrical literature—for instance, units taking the foot, grain, and second in place of the centimeter, gram, and second. Units differing from these in the second way are the Heaviside units, which are used in some theoretical treatises. They introduce the factor 4π at different places in the equations from the ordinary.

There are, similarly, several systems of electromagnetic units in use. Thus, we have the cgs electromagnetic, the "practical" electromagnetic, and the Heaviside electromagnetic units. The "practical" system is discussed below. The Heaviside system differs from the others as mentioned above.

The names applied to the various "practical" and other units will be stated below. Names have not been given to the cgs units of electric quantities in either the electrostatic or electromagnetic systems; names have, however, been provided for cgs units of magnetic quantities. It was suggested in 1904 by Kennelly that the cgs electromagnetic unit of an electric quantity be designated by prefixing "ab" to the name of the "practical" unit, e. g., "abohm"; and that the cgs electrostatic unit be designated by the prefix "abstat," e. g., "abstatohm." The suggestion has found favor with some writers, but it is more usual to write simply "cgs unit." Another suggestion has been made by A. E. Caswell in Science (**42**, p. 695; 1915). He proposed to use the prefix "es" for cgs electrostatic units and "em" for cgs electromagnetic units.

(*b*) **Gaussian Systems, and Ratios of the Units.**—The complexity of the interrelations of the units is increased by the fact that not one of the systems is used as a whole, consistently for all electromagnetic quantities. The "systems" at present used are therefore combinations of certain of the systems of units.

Some writers [6] on the theory of electricity prefer to use what is called a Gaussian system, which means a combination of electrostatic units for purely electric quantities and electromagnetic units for magnetic quantities. There are two such Gaussian systems in vogue—one a combination of the cgs electrostatic and the cgs electromagnetic systems, and the other a combination of the two corresponding Heaviside systems.

When a Gaussian system is used, caution is necessary when an equation contains both electric and magnetic quantities. A factor expressing the ratio between the electrostatic and electromagnetic units of one of the quantities has to be introduced. This factor is the first or second power of c, the number of electrostatic units of electric charge in one electromagnetic unit of the same. There is sometimes a question as to whether electric current is to be expressed in electrostatic or electromagnetic units, since it has both electric and magnetic attributes. It is usually expressed in the electrostatic units in a Gaussian system.

It may be observed, from the dimensions of K given in Table 2, that $\left[\frac{1}{K\mu}\right]=\left[\frac{L^2}{T^2}\right]$. Furthermore, the same relation may be obtained by equating the electrostatic and electromagnetic dimensional expressions for any quantity as given in Table 2. In other words, $\frac{1}{\sqrt{K\mu}}$ has the dimensions of a velocity. It is found by experiment that $\frac{1}{\sqrt{K\mu}}$ is numerically equal to the velocity of light, provided the values of K and μ are both expressed in the same system of units. Maxwell proved theoretically that $\frac{1}{\sqrt{K\mu}}$ is the velocity of any electromagnetic wave. That is, $\frac{1}{\sqrt{K\mu}}=v$, where v is wave velocity. When electromagnetic waves were finally produced experimentally and their velocities measured, this theoretical prediction of Maxwell's was verified. Thus it was demonstrated that light is an electromagnetic phenomenon.

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[6] For example, A. G. Webster, "Theory of electricity and magnetism," 1897; J. H. Jeans, "Electricity and magnetism," 1911; H. A. Lorentz, "The theory of electrons," 1909; and O. W. Richardson, "The electron theory of matter," 1914.

When a Gaussian system is used, this equation becomes $\frac{c}{\sqrt{K\mu}}=v$. For the ether, $K=1$ in electrostatic units and $\mu=1$ in electromagnetic units. Hence $c=v$, for the ether. In words, the velocity of an electromagnetic wave in the ether is equal to the ratio of the cgs electromagnetic to the cgs electrostatic unit of electric charge.

The constant c is of primary importance in electrical theory. It has been measured in three ways—(1) by determining the ratio of the units directly, (2) by measuring the velocity of experimentally-produced electric waves in the ether, (3) by measuring the velocity of light in the ether. Such determinations agree, within the errors of experiment. The probable value [7] of c is within 1 part in 10 000 of 2.9982×10^{10} centimeters per second. The round number 3.0×10^{10} is usually used for this constant.

From Table 2 one may easily obtain the ratio of the electromagnetic to the electrostatic unit of any quantity (the same units of length, mass, and time being used in both systems). The ratio is in every case that power of c having an exponent equal to twice the exponent of K in the electrostatic dimensional formula of the quantity. (This holds for Q, by the definition of c, and must then hold for all the quantities, because K is the only one of the four factors in the dimensional expression which is numerically different in the two systems). For instance, the electrostatic dimensional formula of magnetic flux is $\left[\frac{L^{1/2}M^{1/2}}{K^{1/2}}\right]$; the exponent of K in the denominator is 1/2 and the ratio sought is therefore $\frac{1}{c}$. The ratios can similarly be found from the electromagnetic dimensional formulas by taking the exponent of c equal to minus two times the exponent of μ.

TABLE 3

Conversion Factors

Electric and magnetic quantities	Number electrostatic units in 1 electromagnetic unit
$Q, D, I, H, \mathfrak{J}$	c
$\mathcal{E}, E, m, B, \phi, J$	$\frac{1}{c}$
$C, K, \mathfrak{R}$	c^2
$R, \mathcal{L}, \mu, \kappa$	$\frac{1}{c^2}$

[7] Rosa and Dorsey (Bull. B. S., 3, pp. 433–622; 1907) found the ratio of the units = $(2.9971 \pm 0.0003) \times 10^{10}$ in terms of the international ohm. Reducing to absolute units by the factor given in Sec. III 1c below, this gives $c = (2.9979 \pm 0.0003) \times 10^{10}$. The velocity of light, as found by Michelson (1885) and according to Weinberg's mean (1904), is 2.9985 ± 0.0003. The mean of these two values of c is 2.9982.

(*c*) **"Practical" Electromagnetic Units.**—This is never used as a complete system. The ohm, ampere, etc., were chosen as convenient multiples of the cgs electromagnetic units. These "practical" units are consistent with the four fundamental units: 10^9 cm, 10^{-11} gram, second, μ of the ether. It does not follow that the units of all the electric quantities in the "practical" system are of convenient size. As may be seen from the table below, the units of K, $\mathcal{E}$, D, H, B, J, m are all of inconvenient size; and they are, in fact, never used. The reason is that they each involve the awkward unit of length, 10^9 cm, combined with certain of the convenient-sized units of the system. These quantities have much more convenient units in the international system (see next section), because there the centimeter is retained as the unit of length.

TABLE 4

The "Practical" Electromagnetic Units

Quantity	Name of unit	Number cgs electromagnetic units in 1 "practical" electromagnetic unit	Quantity	Name of unit	Number cgs electromagnetic units in 1 "practical" electromagnetic unit
R	ohm	10^9	$\mathfrak{F}$		10^{-1}
I	ampere	10^{-1}	H		10^{-10}
E	volt	10^8	ϕ		10^8
Q	coulomb	10^{-1}	B		10^{-10}
C	farad	10^{-9}	μ		1
K		10^{-18}	$\mathfrak{R}$		10^{-9}
$\mathcal{E}$		10^{-1}	J		10^{-10}
D		10^{-19}	κ		1
$\mathcal{L}$	henry	10^9	m		10^8

This system has sometimes been considered as a complete system for all electromagnetic quantities. Since some of its units, however, are of very inconvenient size, it is not used as a system. The fundamental unit of length being of inconvenient magnitude, the system is never used in calculations involving length. In some electrical calculations cgs units are used, and the results reduced to "practical" units after the computation is completed. Calculations are frequently made in a set of units not belonging to any one system. This is done because it is easier to insert a numerical factor in an equation than to work with units of inconvenient magnitude. The "practical" units are used for certain electric quantities, the "cgs" units are used for magnetic quantities, and dielectric constant is always given in electrostatic units. This mixture of units makes it necessary to accompany dielectric constant with the factor $\frac{1}{c^2}$ ($=0.11124\times 10^{-20}$) wherever it occurs, and to put a power of 10 in every equation containing both electric and magnetic quantities. The microfarad is generally used instead of the farad as the unit of capacity, consequently the factor 10^{-6} accompanies C.

The "practical" system has therefore become merely a set of convenient multiples of the cgs units for particular quantities, the ohm, ampere, etc. There has grown up about these a set of units that are in general use (described in next section), and the historical connection with the "practical" electromagnetic system has been largely lost.

3. THE INTERNATIONAL ELECTRIC UNITS

It has been found desirable to represent certain of the electric units by definite standards and define units in terms of them. Electrical comparisons with these standards can be made more readily and accurately than absolute measurements in terms of the fundamental units can be made. Two electric units, the international ohm and the international ampere, were defined in terms of specified standards by international congresses. The standards were so defined as to make the units as nearly as possible equal to the "practical" electromagnetic units of resistance and current. The latter units are sometimes called "absolute" units. The "international" units are the ones always used in practice although the word "international" is frequently omitted.

The international ohm, the international ampere, and the second, have been used as the basis of definition of the international coulomb, volt, farad, henry, watt, and joule. (See Sec. II below for 1893 and 1908 definitions.) It is possible, by the addition of the centimeter as the unit of length, to develop a complete and independent system of electric and magnetic units on the basis of the international definitions, which is in fact the system actually used. (See reference No. 9d, Appendix 3.) While the international units are, for most purposes, practically equal to the electromagnetic units, the small differences have been measured and are given below.

The choice of the ohm and ampere as fundamental was purely arbitrary. These are the two quantities directly measured in absolute electrical measurements. The ohm and volt have been urged as more suitable for definition in terms of arbitrary standards, because the primary standard of electromotive force (standard cell) has greater simplicity and utility than the primary standard of current (silver voltameter). The standard cell is in fact used, together with resistance standards, for the actual maintenance of the units, rather than the silver voltameter and resistance standards. Again, the volt and ampere have some claim for consideration for fundamental definition, both being units of quantities more fundamental in electrical theory than resistance. On the whole, it is likely that the international ohm and ampere will remain the two fundamental electric units for some time to come.

The international units of the principal electric quantities are defined and discussed in later sections of this circular. The international units and the corresponding absolute units differ only very slightly in magnitude. The differences represent the accuracy with which it was possible to fix the values of the international ohm and ampere at the time they were defined (London Conference of 1908). It is unlikely that the definitions of the international units will be changed in the near future to make the agreement any closer. The differences are small, and the occasional investigator who needs to do so can convert from one system to the other. It would be very inconvenient if the values of the international units were continually being changed to conform to the latest absolute measurements.

The case is similar to that of the standard value of the acceleration of gravity. It was fixed in 1901 as 980.665 cm per second per second, and corresponded to a latitude of 45° and sea level as closely as was known at that time. Subsequent researches give a different value for that locality, but the standard value remains as adopted, it being recognized that it does not correspond exactly to 45° and sea level.

It is accordingly worth while to know the numerical magnitudes of the differences between the international units and the corresponding absolute or electromagnetic units. Very accurate absolute measurements of current and resistance have been made, and the results are given in later sections of this circular. From these results the following relations are deduced:

1 international ohm=1.00052 absolute ohm.
1 international ampere=0.99991 absolute ampere.
1 international volt=1.00043 absolute volt.
1 international watt=1.00034 absolute watt.
1 international joule=1.00034 absolute joule.
1 international coulomb=0.99991 absolute coulomb.
1 international farad=0.99948 absolute farad.
1 international henry=1.00052 absolute henry.
1 international gilbert=0.99991 absolute gilbert.
1 international maxwell=1.00043 absolute maxwell.

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II. EVOLUTION OF PRESENT SYSTEM OF CONCRETE STANDARDS

1. EARLY ELECTRIC STANDARDS

The need of a definite and universal system of electric units and standards made itself felt as soon as industrial applications of electricity were made. At first the principal measurements were those of resistance (line resistance, insulation resistance, measurements for the location of faults, etc.). Until the middle of the nineteenth century these were expressed in terms of ill-defined standards, such as the resistance of a given length of an iron or copper wire of given mass or cross section. This naturally led to a great multiplicity of units, none of which ever gained general acceptance.

In 1848 Jacobi pointed out that it would be more satisfactory to adopt as a universal standard the resistance of some particular piece of wire, copies having the same resistance being easily constructed. Jacobi carried this suggestion into practice by sending copies of his standard, since known as the "Jacobi Etalon," to the leading physicists of that period. In 1860 Werner von Siemens proposed as the unit of resistance, the resistance, at 0° C, of a column of mercury of a uniform cross section of 1 mm^2 and 1 m in length. The unit thus defined is called the "Siemens unit" and is abbreviated S. E. (Siemens-Einheit).

In 1861 a committee composed of eminent English physicists was appointed by the British Association for the Advancement of Science to consider the question of standards of electrical resistance. The leading foreign physicists were invited to offer suggestions, and various special investigations of the problems with which the committee was confronted were undertaken by its members. It was decided that the unit of resistance should be defined in terms of the Gauss-Weber absolute system of electromagnetic units, which had already received well-merited recognition. The unit chosen was 10^7 units in an absolute electromagnetic system in which the meter was the unit of length, or 10^{10} units in such a system in which the millimeter was the unit of length. The fundamental units used by Gauss and Weber were the millimeter, milligram, and second. In England efforts were being made to establish an absolute system for the definition of all physical units, for which the fundamental units of Weber were held to be of inconvenient magnitude. As fundamental units the centimeter, gram, and second were finally adopted (the cgs system). The unit of resistance defined in 1861 was 10^9 cgs electromagnetic units.

It was impossible to express resistance in terms of this unit until absolute measurements of one or more standards of resistance were made, to realize experimentally the theoretical definition. These absolute measurements were and still are very difficult. The highest precision is necessarily sought, entailing an extensive research. Special apparatus must be designed and constructed, and the instrumental constants determined by the aid of elaborate mathematical calculations. The errors of the very best absolute measurements are much larger than the errors of comparing one resistance with another. Consequently, the unit fixed by an absolute measurement must be maintained by means of material standards of resistance, such as resistance coils. In order to preserve the unit fixed by this early research of the British association, a special form of resistance standard known as the B. A. type was designed. After an investigation of the constancy of a great number of alloys, one containing two parts by weight of silver to one part by weight of platinum was selected as best meeting all requirements. In 1863 and 1864 the values of certain coils were determined in absolute units by one of the methods proposed by Weber, and from these measurements the "B. A. unit" was derived. A number of copies were issued gratis by the British association, and arrangements were made for supplying others at a moderate price. The B. A. unit soon gained general acceptance in the English speaking countries, while the Siemens unit retained its supremacy for some years on the Continent.

No action was taken at that time by the British association committee to define other electric units, further than to recommend the use of the absolute cgs system. For a long time the emf of the Daniell cell was used as the unit of electromotive force. In 1872 Latimer Clark brought to the attention of the committee the superiority of the cell which now bears his name, recommending it as a suitable standard of electromotive force, but no definite action was taken by the committee.

In 1878 it was shown by Prof. H. A. Rowland that the B. A. unit was in error by more than 1 per cent, and soon afterward the existence of a discrepancy of this magnitude was verified by a number of other investigators.

The emf of the Daniell cell being very close to 10^8 cgs electromagnetic units, it gradually became customary to use the latter as the unit of emf, the name "volt" being given to it. The "volt" = 10^8 cgs units was recommended by the British association in 1881.

In 1881 a call was issued by the French Government for an international electrical congress at Paris, for the purpose of adopting definitions of the electrical units which might serve as a basis for legislative enactments. In the meantime a number of mercury standards had been constructed and had been found to be in satisfactory agreement; moreover, the results of most of the absolute determinations had been referred either directly or indirectly to the Siemens unit. The Paris congress recommended that the practical electric units be defined in terms of the units of the cgs system of electromagnetic units; and that the unit of resistance be represented by a column of mercury 1 mm^2 in cross section, at the temperature of 0° C, of a length to be determined by an international commission appointed for this purpose, as appears in the following resolutions:

RESOLUTIONS OF THE INTERNATIONAL CONGRESS OF ELECTRICIANS, PARIS, 1881

(1) That the cgs system of electromagnetic units be adopted as the fundamental units.

(2) That the practical units, the ohm and the volt, preserve their previous definitions, 10^9 and 10^8 cgs units respectively.

(3) That the unit of resistance, the ohm, be represented by a column of mercury 1 mm^2 in cross-section at the temperature of 0° C.

(4) That an international commission be charged with the determination, by new experiments, of the length of the mercury column 1 mm^2 in cross-section at a temperature of 0° C.

(5) That the current produced by a volt in the ohm be called an ampere.

(6) That the quantity of electricity produced by a current of 1 ampere in one second be called a coulomb.

(7) That the unit of capacity be called a farad, which is defined by the condition that a coulomb in a farad raises the potential 1 volt.

The international commission appointed in accordance with paragraph (4) of the resolutions of the Paris congress of 1881 met at Paris in 1882, but definite action was deferred until two years later, when the following definitions were unanimously recommended by the International Conference of 1884:

The legal ohm is the resistance of a column of mercury 1 mm^2 in cross-section, and 106 cm in length, at the temperature of melting ice.

The ampere is equal to one-tenth of a cgs unit of the electromagnetic system.

The volt is the electromotive force which will maintain a current of 1 ampere in a conductor of which the resistance is a legal ohm.

The value adopted for the length of the mercury column was taken as 106 cm, notwithstanding that most of the best results were very close to 106.3 cm, it being thought advisable to adopt provisionally a value known to be true to the last figure given. On account of this uncertainty no steps were actually taken to legalize these definitions by the various Governments represented. The so-called "legal ohm" has, however, been used to some extent. Since its value is 0.3 per cent smaller than the international ohm, the name of this unit is very misleading.

In 1889 a second International Congress of Electricians was held at Paris, which adopted the following definitions:

The joule, the practical unit of energy, is equal to 10^7 cgs units. It is equal to the energy disengaged as heat in one second by a current of 1 ampere flowing through a resistance of 1 ohm.

The practical unit of power is the watt. The watt is equal to 10^7 cgs units, and is the power of one joule per second.

The practical unit of self-induction is the quadrant, which is equal to 10^9 cms.

The period of an alternating current is the duration of a complete oscillation.

The frequency is the number of periods per second.

The mean intensity is defined as the mean value of the current during a complete period, without reference to its sign.

The effective intensity is the square root of its mean-squared value.

The effective electromotive force is the square root of its mean-squared value.

The apparent resistance is the factor by which the effective current must be multiplied to obtain the effective electromotive force.

The positive pole of a storage cell is that which is connected to the positive pole of a dynamo in charging, and which is the positive pole during its discharge.

The increased accuracy obtainable by the use of apparatus of improved construction, and by refinements in the methods employed, led to much closer agreement among the various redeterminations of the absolute electric units. Their relations to the Siemens unit, the Clark cell, and the electrochemical equivalent of silver, in terms of which many measurements were made, became known with considerable accuracy. The rapid development of the electrical industries also called for a redefinition of the units, and the legalization of such definitions.

In December, 1890, a committee was appointed by the English Board of Trade to consider "what action should be taken by the board with a view to the preparation of new denominations of standards for the measurements of electricity for use in trade." The members of this committee consisted of two representatives each of the Board of Trade, the General Post Office, the Royal Society, the British association, and the Institution of Electrical Engineers. A set of resolutions was drafted, embodying proposals for standards of resistance, current, and electromotive force. These were discussed at the British association meeting in Edinburgh in 1892. Representatives of Germany, France, and the

United States participated in the conference. It was resolved to adopt for the length of the mercury column 106.3 cms, and to specify that the mass of the column of uniform cross-section shall be 14.4521 grams instead of specifying that the cross-sectional area shall be 1 mm^2. It was also agreed that 0.001118 should be adopted as the number of grams of silver deposited by 1 ampere in 1 second, and that 1.434 volts should be adopted as the electromotive force of the Clark cell at 15° C. Final action was deferred to await the decision of the Chicago International Electrical Congress, arrangements for which had then been made.

2. BASIS OF PRESENT LAWS

The laws defining electric standards in most countries are based upon the decisions of the International Electrical Congress held at Chicago in 1893. This congress, to which the various Governments were invited to send delegates, met at the time of the Chicago Exposition. The Governments represented were: United States, Great Britain, France, Italy, Germany, Mexico, Austria, Switzerland, Sweden, and Canada. The Chamber of Delegates was composed of the official delegates of the various Governments represented. It adopted the following resolutions after six days of deliberation:

RESOLUTIONS OF THE INTERNATIONAL ELECTRICAL CONGRESS, CHICAGO, 1893

Resolved, That the several governments represented by the delegates of this International Congress of Electricians be, and they are hereby, recommended to formally adopt as legal units of electrical measure the following:

Ohm.—As a unit of resistance, the *international ohm*, which is based upon the ohm equal to 10^9 units of resistance of the cgs system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice 14.4521 grams in mass, of a constant cross-sectional area and of the length of 106.3 cms.

Ampere.—As a unit of current, the *international ampere*, which is one-tenth of the unit of current of the cgs system of electromagnetic units, and which is represented sufficiently well for practical use by the unvarying current which, when passed through a solution of nitrate of silver in water, and in accordance with accompanying specifications, deposits silver at the rate of 0.001118 of a gram per second.

Volt.—As a unit of electromotive force, the *international volt*, which is the electromotive force that, steadily applied to a conductor whose resistance is 1 international ohm, will produce a current of 1 international ampere, and which is represented sufficiently well for practical use by $\frac{1000}{1434}$ of the electromotive force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of 15° C, and prepared in the manner described in the accompanying specifications.

Coulomb.—As a unit of quantity, the *international coulomb*, which is the quantity of electricity transferred by a current of 1 international ampere in one second.

Farad.—As a unit of quantity, the *international farad*, which is the capacity of a condenser charged to a potential of 1 international volt by 1 international coulomb of electricity.

Joule.—As a unit of work, the *joule*, which is equal to 10^7 units of work in the cgs system, and which is represented sufficiently well for practical use by the energy expended in one second by an international ampere in an international ohm.

Watt.—As a unit of power, the *watt*, which is equal to 10^7 units of power in the cgs system, and which is represented sufficiently well for practical use by work done at the rate of 1 joule per second.

Henry.—As the unit of induction, the *henry*, which is the induction in a circuit when the electromotive force induced in this circuit is 1 international volt, while the inducing current varies at the rate of 1 ampere per second.

SPECIFICATIONS

In the following specifications the term silver voltameter means the arrangement of apparatus by means of which an electric current is passed through a solution of nitrate of silver in water. The silver voltameter measures the total electrical quantity which was passed during the time of the experiment, and by noting this time the time average of the current, or if the current has been kept constant, the current itself can be deduced.

In employing the silver voltameter to measure currents of about 1 ampere, the following arrangements should be adopted:

The kathode on which the silver is to be deposited should take the form of a platinum bowl not less than 10 cms in diameter and from 4 to 5 cms in depth.

The anode should be a plate of pure silver some 30 cm^2 in area and 2 or 3 mms in thickness.

This is supported horizontally in the liquid near the top of the solution by a platinum wire passed through holes in the plate at opposite corners. To prevent the disintegrated silver which is formed on the anode from falling on to the kathode, the anode should be wrapped round with pure filter paper, secured at the back with sealing wax.

The liquid should consist of a neutral solution of pure silver nitrate, containing about 15 parts by weight of the nitrate to 85 parts of water.

The resistance of the voltameter changes somewhat as the current passes. To prevent these changes having too great an effect on the current, some resistance besides that of the voltameter should be inserted in the circuit. The total metallic resistance of the circuit should not be less than 10 ohms.

A committee was appointed to prepare specifications for the Clark cell. No report was ever made by this committee.

A motion was carried that for magnetic units the cgs electromagnetic system be recommended, and that for the present no names be given to these units.

Notwithstanding that the resolutions of the Chicago congress were adopted with practical unanimity, and might have been considered as in a sense binding on all the Governments, only six Governments, United States, Great Britain, Canada, Germany, Austria, and France, legislated on this subject, and few of these acted strictly in accordance with the resolution of the Chicago congress. The laws enacted are given in Appendix 2 of this circular (except that more recent laws are given for Great Britain, which replace those enacted in 1894). Strictly speaking, no two countries defined the electrical units in the same way. The reasons for this may in part be traced to the insufficiency of the Chicago definitions.

(1) It is evident that only two of the three units, the ohm, ampere, and volt, should be defined in terms of concrete standards, the third being derived by Ohm's law from those two.

(2) The international units were not clearly recognized as separate and distinct from the absolute units on which they are based.

(3) The specifications for the silver voltameter were shown to be entirely inadequate shortly after their adoption.

(4) Redeterminations of the electromotive force of the Clark cell at 15° C indicated that this value was nearer 1.433 than 1.434 absolute volts.

While the definitions by the Chicago congress were thus imperfect, nevertheless some of the laws clearly violate the principles laid down at the congress. For instance, in some countries the same unit is defined effectively in three or four different ways in the same law.

3. PROGRESS SINCE 1893

The legal definitions of electric units were enacted, some before and some after, the inconsistencies in the Chicago resolutions were recognized. The need of more concordant definitions became more and more apparent. Besides the definitions of the fundamental electric quantities, there was a growing need for definitions of magnetic units and for the settling of other secondary questions. The next official congress, held at Paris in 1900, acted only upon magnetic units. (See section on "Magnetic units," below.)

The task still remained to define the fundamental electric quantities more consistently than was done by the resolutions of the Chicago congress and by the laws based on them. Official international recognition of the discrepancies between the laws was taken by the St. Louis congress in 1904, which adopted resolutions to the effect that the questions could best be dealt with by an international commission on units, standards, and nomenclature, that such a commission might in the first instance be appointed by those countries in which legislation on electric units had been adopted, and that provision should be made for securing the adhesion of other countries prepared to adopt the conclusions of the commission. The commission has never been appointed, although another resolution to the same effect was adopted by the London conference in 1908. (However, another resolution of the St.

Louis congress, regarding the standardization of machinery, has borne fruit. This was a resolution "that steps should be taken to secure the cooperation of the technical societies of the world, by the appointment of a representative commission to consider the question of the standardization of the nomenclature and ratings of electrical apparatus and machinery," This resulted in the creation of the International Electrotechnical Commission, which has become a powerful and active body.)

After the St. Louis congress, the next step in the international standardization of electric units was a conference at Berlin in October, 1905, upon the invitation of the Physikalisch-Technische Reichsanstalt. Representatives were present from Austria, Belgium, England, France, Germany, and the United States. The decisions reached by the Berlin conference [8] were as follows:

(1) That only two electrical units shall be chosen as fundamental units.

(2) The international ohm, defined by the resistance of a column of mercury, and the international ampere, defined by the deposition of silver, are to be taken as the undamental electrical units.

(3) The international volt is the electromotive force which produces an electric current of 1 international ampere in a conductor whose resistance is 1 international ohm.

Recommendations were also made that more detailed specifications be adopted for the mercury ohm, and that the Weston cadmium cell with solid hydrated cadmium sulphate and a 12 to 13 per cent cadmium amalgam be adopted as the standard cell.

The recommendation made at the conference by the American delegate and by the Bureau of Standards that the volt be selected as the second fundamental unit was rejected, as was also the recommendation of the Bureau advocating a systematic program of absolute measurements before the next International Electrical Congress.

One of the notable recommendations of the Berlin conference was the replacement of the Clark cell by the Weston cadmium cell. The standard cell has been much more important in the establishment and maintenance of the international units than would appear from the formal definitions. In practice the international volt has been fixed by reference to standard cells; and furthermore, standard cells in combination with resistance standards have been used to maintain the international unit of current. Current is more accurately and conveniently measurable by that method than by either an absolute method or by the silver voltameter. The Weston cell superseded the Clark cell in actual

[8] Verh. Int. Konf. Elektr. Masseinheiten, p. 42.

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practice because of numerous advantages, such as its much smaller temperature coefficient, less hysteresis, and absence of cracking and gas in the anode limb. The resolution of the Chicago congress defining the practical equivalent of the international volt in terms of the Clark cell was subject to change for another reason, viz, it was soon found by absolute measurements that the value assigned to the electromotive force of the Clark cell was too large by about a millivolt. The task of assigning a numerical value to the electromotive force of the Weston cell was therefore one of those awaiting the next international congress, which was held in 1908.

The 1908 International Conference on Electrical Units and Standards was held at London. Delegates were present from 21 countries. The conference drew up its resolutions in such form as to distinguish clearly between the ohm, ampere, etc., and the international ohm, international ampere, etc. The definitions follow.

These fundamental units are:

1. The *ohm*, the unit of electric resistance, which has the value of 1 000 000 000 (10^9) in terms of the centimeter and the second;

2. The *ampere*, the unit of electric current, which has the value of one-tenth (0.1) in terms of the centimeter, gram, and second;

3. The *volt*, the unit of electromotive force, which has the value of 100 000 000 (10^8) in terms of the centimeter, gram, and second;

4. The *watt*, the unit of power, which has the value of 10 000 000 (10^7) in terms of the centimeter, the gram, and the second.

As a system of units representing the above and sufficiently near for the purposes of electrical measurements, and as a basis for legislation, the conference recommended the adoption of the international ohm, the international ampere, the international volt, and the international watt, defined as follows:

1. The *international ohm* is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass, of a constant cross-sectional area and of a length of 106.300 centimeters.

2. The *international ampere* is the unvarying electric current which, when passed through a solution of nitrate of silver in water, in accordance with the Specification II attached to these Resolutions, deposits silver at the rate of 0.00111800 of a gram per second.

3. The *international volt* is the electrical pressure which, when steadily applied to a conductor the resistance of which is one international ohm, will produce a current of one international ampere.

4. The *international watt* is the energy expended per second by an unvarying electric current of one international ampere under an electric pressure of one international volt.

The procedures for realizing the international ohm from the resistance of the specified column of mercury and for realizing the international ampere from the silver voltameter were given in accompanying specifications; the specifications for the silver voltameter, however, were very inadequate. The reason for this was that the experience of those who had done most work with the silver voltameter was so diverse that agreement could not be reached as to the best procedure. It was not strictly logical to specify the precise amount of silver deposited by an ampere before the specifications were agreed upon, as it was possible that when the voltameter became better understood and the best procedure determined the number chosen might entail a considerable difference between the ampere and the international ampere as so defined. But a majority of the delegates felt that the change would be slight at the most and preferred to specify the round number (0.00111800 g per second) that had previously been used rather than some odd figure that might be more exact. Subsequent work has shown that the number was fortunately chosen and is much nearer the absolute value than the data before the conference indicated.

Having chosen the old figures to express the value of the international ohm and the international ampere, it remained to adopt a value for the electromotive force of the Weston normal cell in terms of the international volt, so that it should be consistent with the values of the two units chosen as fundamental. Data at hand did not enable the conference to fix this value with certainty to 1 part in 10 000, and hence it adopted as provisional only the number 1.0184 international volts as the value of the electromotive force at 20° C of the Weston normal cell. The specifications adopted for the cell were quite inadequate, as in the case of the voltameter. The specifications followed in the several national laboratories differ in some particulars.

In order that a more accurate value might be determined for the Weston normal cell and that the specifications of the silver voltameter might be completed as speedily as possible, the conference appointed an international committee on electrical units and standards which was authorized to take up this work and also to complete the work of the conference in any other particulars that seemed necessary. This committee is to serve until the establishment of a permanent international commission by the various nations. The permanent commission has not yet been established. The committee was authorized to encourage cooperative investigations among the several national standardizing institutions and to secure frequent comparisons of the electrical standards of different countries in order to insure international uniformity in electrical measurements. This committee represents 11 countries, there being two members each from America, England, France, and Germany, and one member each from Austria, Italy, Russia, Switzerland, Holland, Belgium, and Japan. There are also five associate members.

It was impossible to select a new value of the Weston normal cell in terms of the ohm and the ampere until the latter should be more precisely defined than had been done by the London conference. It was therefore proposed that a joint investigation, to clear up as far as possible outstanding problems on the silver voltameter and the standard cell, be arranged with representatives of several of the national standardizing laboratories as participants.

It was arranged that the proposed investigation should be carried out at the Bureau of Standards by representatives of that institution together with one delegate from the Physikalisch-Technische Reichsanstalt, Berlin, one from the National Physical Laboratory, near London, and one from the Laboratoire Central d'Électricité, Paris. This work was done in 1910. Voltameters from all four institutions were put in series under a variety of experimental conditions. Standard Weston cells and resistance standards of the four laboratories were also intercompared.

The main result of this international cooperative investigation was to show that the electromotive force of the Weston normal cell derived from the international ohm and the international ampere according to the resolutions of the London conference was, within 1 part in 10 000, 1.0183 international volts at 20° C. (Considered as the basis of electromotive force measurements, this number may be written 1.01830, just as in the numerical values of the ohm and ampere, adopted at London, the numbers were written 106.300 and 0.00111800, the two zeros in each case being added to avoid any ambiguity; that is, to show that the numbers are assumed exact and not simply approximate. In the value of the electromotive force of the Weston cell it was first ascertained by experiment that the number consistent with the formal definition was (within 1 part in 10 000) 1.0183 international volts. It was then agreed to use this round value as the exact value of the Weston normal cell at 20° C. Hence, since this is to be the exact value for some time and since the emf's of cells are commonly expressed to six significant figures, it seems better to use six figures in the formal definition, consistently with the numbers given in the definitions of the ohm and ampere.)

This new value for the Weston normal cell was officially recognized on January 1, 1911, and has been the value generally used since then. The new value was assigned to the mean of the four groups of cells brought from the four laboratories.

Similarly, the value of the international ohm was taken to be the mean of the values realized at the Physikalisch-Technische Reichsanstalt and the National Physical Laboratory, as represented by wire standards which had been compared with the mercury standards. At that time only those two institutions had made recent comparisons between wire standards and mercury standards.

Thus, an important result of this cooperative investigation was that it established a common basis of electrical measurements for the different countries. A complete account of the investigation is given in the "Report to the International Committee on Electrical Units and Standards," of January 1, 1912, and its "Supplement" of the same date, published by this Bureau.

The several units are discussed in detail in the following sections of this circular.

III. UNITS AND STANDARDS OF THE PRINCIPAL ELECTRIC QUANTITIES

1. RESISTANCE

Electrical resistance is that property of a conductor in virtue of which electric energy is converted into heat within the conductor. Resistance was the first electrical magnitude for which a definite standard was established. Standards of resistance are of fundamental importance in electrical measurements.

(*a*) **International Ohm.**—DEFINITION.—"The *international ohm* is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass, of a constant cross-sectional area and of a length of 106.300 centimeters."

This is the definition adopted by the London conference in 1908, and is accepted everywhere. The laws of the various countries are in agreement with this definition, although in some cases other more or less equivalent definitions are given in the same law. The laws upon electrical units in the United States are given in the act approved July 12, 1894, reprinted in Appendix 2. The international ohm is there said to be "represented by" the resistance of a column of mercury as defined above. The London definition states that it "is" the said resistance. The two expressions in this case mean the same thing.

Mercury Standards.—Mercury standards conforming to the definition of the international ohm have been constructed in England, France, Germany, Japan, Russia, and the United States. The mean resistances defined thereby in the national laboratories of these countries agree to about 2 parts in 100 000. To attain this accuracy, elaborate experiment and painstaking precautions were necessary. The mercury is contained in glass tubes having a bore of about 1 mm^2. The tubes are never quite uniform in cross section, so the slight variation of cross section has to be determined, and a resulting caliber factor applied to the resistance. The accurate measurement of the mass of mercury filling the tube is attended with difficulty, partly because of a surface film on the walls of the tube. The greatest refinements are necessary in determining the length of the tube. In the electrical comparison of the resistance with wire standards, the largest source of error is in the filling of the tube. A correction is necessary because of the resistance at the ends of the tube, where the current flows from the tube into end bulbs; this correction is, however, a constant for tubes of approximately the standard length. These sources of error have necessitated a certain uniformity in the procedure of setting up mercury standards. This was recognized at the London conference, which gave the following:

SPECIFICATION RELATING TO MERCURY STANDARDS OF RESISTANCE

The glass tubes used for mercury standards of resistance must be made of a glass such that the dimensions may remain as constant as possible. The tubes must be well annealed and straight. The bore must be as nearly as possible uniform and circular, and the area of cross-section of the bore must be approximately one square millimeter. The mercury must have a resistance of approximately one ohm.

Each of the tubes must be accurately calibrated. The correction to be applied to allow for the area of the cross-section of the bore not being exactly the same at all parts of the tube must not exceed 5 parts in 10 000.

The mercury filling the tube must be considered as bounded by plane surfaces placed in contact with the ends of the tube.

The length of the axis of the tube, the mass of mercury the tube contains, and the electrical resistance of the mercury are to be determined at a temperature as near to 0° C as possible. The measurements are to be corrected to 0° C.

For the purpose of the electrical measurements, end vessels carrying connections for the current and potential terminals are to be fitted on to the tube. These end vessels are to be spherical in shape (of a diameter of approximately four centimeters) and should have cylindrical pieces attached to make connections with the tubes. The outside edge of each end of the tube is to be coincident with the inner surface of the corresponding end vessel. The leads which make contact with the mercury are to be of thin platinum wire fused into glass. The point of entry of the current lead and the end of the tube are to be at opposite ends of a diameter of the bulb; the potential lead is to be midway between these two points. All the leads must be so thin that no error in the resistance is introduced through conduction of heat to the mercury. The filling of the tube with mercury for the purpose of the resistance measurements must be carried out under the same conditions as the filling for the determination of the mass.

The resistance which has to be added to the resistance of the tube to allow for the effect of the end vessels is to be calculated by the formula

$$A=\frac{0.80}{1063\pi}\left(\frac{1}{r_1}+\frac{1}{r_2}\right)\text{ ohm,}$$

where $r1$ and $r2$ are the radii in millimeters of the end sections of the bore of the tube.

The mean of the calculated resistances of at least five tubes shall be taken to determine the value of the unit of resistance.

For the purpose of the comparison of resistances with a mercury tube the measurements shall be made with at least three separate fillings of the tube.

Secondary Standards.—While the international ohm is represented in the national laboratories primarily by the mercury standards, these are seldom used in measurements. The secondary standards, the values of which have been derived from the mercury standards and which are in turn used to give values to working standards of resistance, are certain coils of manganin wire kept in the national laboratories. Their resistances are adjusted to correspond to the unit or to its decimal multiples or submultiples. The values assigned to these coils are checked from time to time by comparison with the similar coils of the other countries. The values at present in use are based on the comparison made at the Bureau of Standards in 1910, the values assigned being made to depend on a mean of the mercury ohm measurements previously made. The unit thus determined may be called the "1910 ohm." Additional measurements upon various mercury standards since 1910 have checked the values then used within 2 parts in 100 000. Thus, the basis of resistance measurement is maintained not by the mercury standards of a single laboratory, but by all the mercury standards of the various national laboratories; and is furthermore the same in all countries, except for very slight outstanding discrepancies due to the errors of measurement and variations of the standards with time.

(*b*) **Resistance Standards in Practice.**—In ordinary measurements, working standards of resistance are usually coils of manganin [9] wire. The resistances are usually decimal multiples or

[9] The composition of manganin is approximately 84 per cent copper+12 per cent manganese+4 per cent nickel.

submultiples of 1 ohm, ranging from 0.0001 ohm to 100 000 ohms. Resistance standards exceeding these limits are in use for special purposes, but not primarily as standards for resistance measurement. The standards of smaller resistance are made of manganin strips supported from terminal lugs, while standards of 0.1 ohm or more are made of silk-covered manganin wire. A brass tube is covered with silk cloth and then shellacked; the wire is wound upon this frame and then shellacked and baked. The whole is mounted in a case, with suitable terminals for electrical connection. The coils are used in oil, which carries away the heat developed by the current in the coil and facilitates the regulation and measurement of the temperature.

The best type of standard is inclosed in a sealed case, so that it is not subjected to the influence of atmospheric humidity. Moisture causes the shellac to swell, which introduces changes in the tension upon the wires. The varying humidity of the atmosphere thus causes changes in the resistance, the resistance of open coils often being several parts in 10 000 higher in the summer than in the winter. Sealed standards of 1 ohm and 0.1 ohm have been found to remain constant to about 1 part in 100 000.

The term "resistance standard" is preferable to "standard resistance." The word "resistance" means the physical quantity, while the "standard" is the concrete representation of a certain amount of resistance. To designate a coil or other device used in such a way that the electric resistance is its important property, the name "resistor" is coming into use. This term is given in rule 81 of the 1915 Standardization Rules of the American Institute of Electrical Engineers.

(*c*) **Absolute Ohm.**—When the ohm is referred to in ordinary practice, the international ohm is always meant; and similarly with the other electric units. The absolute ohm, or "ohm" defined by the London conference of 1908 as 10^9 cgs electromagnetic units, is of interest only to the student or an occasional experimenter. The relation of the international ohm to the electromagnetic units has been measured in a number of different ways. These have included revolving coil, revolving disk, and alternating current methods. Probably the most accurate determination was that made in 1913 by F. E. Smith,[10] of the National Physical Laboratory of England, using a modification of the Lorenz revolving disk method. His conclusion is that

$$1 \text{ international ohm} = 1.00052 \pm 0.00004 \text{ absolute ohms.}$$

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[10] See ref. No. 21, Appendix 3.

The result may also be expressed by saying that while 1 international ohm is represented by a mercury column 106.300 cm long as defined above, 1 absolute ohm is represented by a similar mercury column 106.245 cm long.

Absolute measurement of resistance involves the precise measurement of a length and a time (usually an angular velocity), in a medium of unit permeability. It should be borne in mind that the dimensional formula of resistance in the electromagnetic system is

$$[R]=\left[\frac{L\mu}{T}\right]$$

so that an absolute measurement gives R, not in $\frac{\text{cm}}{\text{sec}}$, as it is sometimes stated, but in $\frac{\text{cm}\times\mu}{\text{sec}}$. That is, the absolute unit depends upon the permeability of space as well as upon the centimeter and the second. The definitions of the "ohm," "ampere," and "volt," by the 1908 London conference tacitly assume permeability equal to unity.

2. CURRENT

(*a*) **International Ampere.**—Since the ohm, the ampere, and the volt are connected by Ohm's law (which law experiment has shown to be accurately realized in practice, and is assumed exact in the definitions), it is obvious that only two of these units should have independent definitions, the third being derived from the other two. There has been much discussion as to which two should be taken as fundamental. On account of the directness of its absolute measurement and the accuracy of the mercury standard, the ohm has long been accepted as one of the two. There has been considerable difference of opinion as to whether the ampere or the volt should be the second fundamental unit. At the time of the London conference (1908), the uncertainty of the standard cell was undoubtedly less than that of the silver voltameter, although there was no agreement on this point at that time. Furthermore, the standard cell was in very extensive use because of its convenience and portability, while the silver voltameter was used very little, as it is a very inconvenient instrument. Nevertheless, the ampere was selected as the second fundamental unit, partly because the absolute measurement of the ampere is more direct than that of the volt; partly because of the historical standing of the silver voltameter as a concrete standard; and partly because it was

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believed by many to be a simpler and more suitable instrument for the purpose of fixing the second fundamental unit than was the standard cell.

While many believed at the time of the London conference that this last reason was unsound, the extensive investigations that have been made of the silver voltameter since then have rendered that instrument far more reliable and reproducible than before. The same order of accuracy may be attained with it as with the standard cell, and it is now a worthy companion of the mercury standard of resistance in serving as one of the fundamental standards of the international system of units. However, an international agreement upon the specifications for the voltameter has not yet been attained.

Although the international ampere is the second fundamental unit and is defined in terms of a definite standard or process of measurement, it does not follow that a standard of current is actually used in electrical standardizing. In the case of resistance, we have the *primary* mercury standard fixing the international ohm, and then *secondary* resistance standards consisting of wire coils used in the work of the standardizing laboratory. There are no similar secondary current standards taking the place in practice of the primary current standard, the silver voltameter. Because of the transitory character of electric current, recourse must be had to secondary standards of electromotive force in conjunction with resistance standards. The values assigned to the standards of electromotive force in the national standardizing laboratories at the present time are based upon the international ohm and upon the mean of the international voltameter experiments of 1910, as explained below. The international ampere is thus taken to be represented by what may be called the "1910 mean voltameter."

Definition.—"The *international ampere* is the unvarying electric current which, when passed through a solution of nitrate of silver in water, in accordance with the Specification II attached to these resolutions, deposits silver at the rate of 0.00111800 of a gram per second." (The specifications referred to were quite inadequate. In this matter the definition is indeterminate.)

This is substantially in agreement with the United States law of 1894, reprinted in Appendix 2. The law defining the unit of current fails to make proper distinction between the absolute and the international ampere, but does state that the international ampere "is the practical equivalent of" the unvarying current, etc., as defined above.

The Silver Voltameter.—The silver voltameter is a concrete means of measuring in terms of the unit of current as defined above, and is the primary standard representing the international ampere. The voltameter was devised by Faraday, who announced it in 1834 under the name of the "volta-electrometer," i. e., an instrument for measuring voltaic electricity. The name was subsequently shortened to "voltameter." The name "coulometer" has also been in use recently. The silver voltameter, as used for the realization of the international ampere, consists of a platinum cathode in the form of a cup holding the silver nitrate solution, a silver anode partly or wholly immersed in the solution, and some means to prevent anode slime and particles of silver mechanically detached from the anode from reaching the cathode. Strictly, as a standard representing the international ampere, the "silver voltameter" includes also the chronometer used to measure time. The degree of purity and the mode of preparation of the various parts of the voltameter affect the mass of the deposit. There are numerous sources of error, and the suitability of the silver voltameter as a primary standard of current has been under investigation since 1893. Differences of as much as 0.1 per cent or more may be obtained by different procedures, the larger differences being mainly due to impurities produced in the electrolyte (by filter paper, for instance). Hence, in order that the definition of current be precise, it must be accompanied by *specifications* for using the voltameter.

The very meager specifications given by the 1908 London conference were recognized to be inadequate, and the conference appointed an international committee on electrical units and standards to complete these specifications. It was also recognized by the conference that the silver voltameter is not used in practical work and that the place of secondary current standards is taken by standard cells in conjunction with resistance standards. The international committee therefore had the additional duty of fixing a value for the electromotive force of the Weston normal cell, derived from experiments on the silver voltameter. This duty was successfully discharged by the committee in the cooperative international investigation mentioned above in Section II, 3. By the joint comparison of standard cells and silver voltameters particular values were assigned to the standard cells from each national standardizing laboratory. The different countries were thus enabled to have a common basis of measurement, which has since been maintained by the aid of standard cells and resistance standards, but which derived its value from the international voltameter investigation of 1910.

While the work of the various delegates in this investigation was sufficiently concordant to fix the value of the Weston normal cell to 1 part in 10 000, it was not found possible to draw up final specifications for the silver voltameter in 1910, as there were still some outstanding questions which required further research.[11] Provisional specifications were submitted by the Bureau of Standards and are given in the "Report to the International Committee on Electrical Units and Standards" (Jan. 1, 1912), page 199. More complete specifications have been proposed in correspondence between the national laboratories and members of the international committee in the time which has intervened since 1910, but no agreement upon final specifications has yet been reached.

(*b*) **Resistance Standards Used in Current Measurements.**—Precise measurements of current are made with the aid of a potentiometer, using a standard cell and a resistance standard. The latter does not differ essentially from the standards used in resistance measurement, except that they must be so designed as to carry the maximum current for which they are intended to be used without undue change of resistance. For the measurement of small and moderate currents the resistances are usually designed for a maximum voltage of the order of 1 volt, so that (e. g.) currents up to 1 ampere are measured on a 1-ohm standard, etc. For currents of several hundred amperes and more the maximum voltage is 0.1 volt, and currents up to 10 000 amperes are measured on a 0.00001-ohm standard.

The resistance material of the standard must be so disposed that the standard is not unduly heated when the maximum current is carried. This means that the resistance metal must have a sufficient area in contact with the air, oil, or other cooling fluid. It is requisite to have resistance material of a small temperature coefficient of resistance, so that a given temperature rise may not produce too great a change in the resistance. The resistance material must also have small thermal electromotive force against copper. Manganin satisfies these conditions and is

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[11] For the investigations of the Bureau of Standards into voltameter problems, see reference No. 63, Appendix 3.

usually used. The terminals of the standard must have sufficient contact area so that there shall be no undue heating because of contact resistance. The design must be such that the current distribution in the resistance material does not depend upon the mode of connection to the circuit. Care is necessary to see that oil used as a cooling fluid has no constituents which corrode the metal.

Resistance standards for current measurements are often called "shunts" when used in conjunction with millivoltmeters for current measurement. (They are actually used as a shunt upon the instrument.) For the standards used with a potentiometer in precise measurements the expression "resistance standard" is preferable.

(*c*) **Absolute Ampere.**—The absolute ampere, or "ampere" defined as one-tenth cgs electromagnetic unit, differs by a negligible amount from the international ampere. Its relation to the international ampere has been determined by a number of methods. An absolute measurement of current involves fundamentally the precise measurement of a force in a medium of unit permeability. This is seen from the dimensional formula of current in the electromagnetic system:

$$[I]=\left[\frac{L^{1/2}M^{1/2}}{T\mu^{1/2}}\right]$$

Since the dimensions of force are given by

$$[F]=\left[\frac{LM}{T^2}\right]$$

it follows that

$$[I]=\left[\frac{F^{1/2}}{\mu^{1/2}}\right]$$

In most absolute current measurements of high precision an electrodynamometer has been used, of the form known as a current balance. Probably the most accurate determinations with current balances were made by the National Physical Laboratory [12] of England and by this Bureau.[13] In both of these investigations, comparisons of the silver voltameter and the current balance were made. The international ampere as determined by the Bureau of Standards voltameters, 1910 to 1912, was found to be 5 parts in 100 000 smaller than the absolute ampere as determined by the Bureau of Standards current balance (the value

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[12] See reference No. 31, Appendix 3.

[13] See reference No. 32, Appendix 3.

given for the Weston cell in terms of the voltameters and the international ohm was 1.01827 at 20° C, and in terms of the current balance and the international ohm was 1.01822). That is, the electrochemical equivalent of silver, in terms of the Bureau of Standards current balance and voltameters, was found to be about 0.00111805 per absolute coulomb. (See Bull., Bureau of Standards, **10**, p. 477, 1913.)

The voltameters just referred to defined a unit of current 3 parts in 100 000 larger than the international ampere as realized by the "1910 mean voltameter," upon which the recognized value [14] of the Weston normal cell is based. Consequently, in terms of the "1910 mean voltameter" and the Bureau of Standards current balance, 1 international ampere = 0.99992 absolute ampere. The ampere defined by the National Physical Laboratory current balance is 4 parts in 100 000 larger than that defined by the Bureau of Standards current balance; i. e., the N. P. L. result is 1 international ampere = 0.99988 absolute ampere. The only other recent determination of high accuracy is that of Haga and Boerema [15] at the University of Groningen, Holland, using a tangent galvanometer. Their result, expressed in the same terms as the two preceding, is 0.99994.

The best available value is probably the mean of these three results, as follows. Taking the international ampere as realized by the "1910 mean voltameter" and the absolute ampere as realized by the mean results of the English, Dutch, and American researches,

1 international ampere = 0.99991 absolute ampere.

This result may also be expressed in terms of the electrochemical equivalent of silver, which, based on the "1910 mean voltameter," thus equals 0.00111810 g per absolute coulomb. By the definition of the international ampere, the value is 0.00111800 g per international coulomb. The way in which these relations affect the value of the Weston normal cell is given below in Section III, 3*c*.

3. ELECTROMOTIVE FORCE

(*a*) **International Volt.**—The international volt is derived by Ohm's law from the international ohm and ampere. Its value is maintained by the aid of the Weston normal cell. The national

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[14] As stated in Bull., Bureau of Standards, **10**, p. 479, 1913, and **13**, p. 162; 1915, the later work on the voltameter has indicated that a slightly different value results for the Weston cell from voltameters set up according to the best procedure now available. As there stated, however, the 1910 value should always be used in practice.

[15] See reference No. 33, Appendix 3.

standardizing laboratories have groups of such cells, to which values in terms of the international ohm and ampere have been assigned by international experiments, and thus a basis of reference is maintained for the standardization of the standard cells used in practical measurements.

DEFINITION.—"The *international volt* is the electrical pressure which, when steadily applied to a conductor the resistance of which is one international ohm, will produce a current of one international ampere." (The term "electrical pressure" was used in accordance with practice in England. In America the preferred term is "electromotive force.")

The United States law of 1894 (see Appendix 2) gives this same definition, appending to it a "practically equivalent" value in terms of the Clark cell. The Clark cell is now seldom used, having been superseded by the Weston normal cell.

WESTON NORMAL CELL.—The Weston normal cell is the standard used to maintain the international volt and, in conjunction with resistance standards, to maintain the international ampere. The cell is a simple voltaic combination very similar to the old Clark cell, which it replaces; the main difference is that it employs cadmium instead of zinc. The anode, or negative electrode, is cadmium amalgam, consisting of 10 per cent by weight of cadmium and 90 per cent mercury. The cathode, or positive electrode, is pure mercury, which is covered with a paste consisting of mercurous sulphate, cadmium-sulphate crystals, and solution. The electrolyte is cadmium-sulphate solution in contact with an excess of cadmium-sulphate crystals. The containing vessel is of glass, usually in the H form. Connection is made to the electrodes by means of platinum wires sealed into the glass. The cells are sealed, preferably hermetically, and when in use are submerged in a bath of oil kept at constant temperature. The resistance of a cell is usually about 600 to 1000 ohms. The Weston cell used in connection with potentiometers is not the Weston normal cell, but differs from it only slightly, the cadmium-sulphate solution not being saturated. It is described in the next section below.

One of the great advantages of the Weston normal cell is its small change of electromotive force with change of temperature. At any temperature, t (centigrade), between 0° and 40° C, $E_t = E_{20} - 0.0000406\ (t-20) - 0.00000095\ (t-20)^2 + 0.00000001\ (t-20)^3$. This temperature formula was adopted by the London conference of 1908. In order that this formula may apply, the cell must be of a strictly uniform temperature throughout. One leg of the cell has a large positive temperature coefficient and the other leg a large negative temperature coefficient. If the temperature of one leg changes faster than the other, the formula does not hold.

When the best of care is taken as to purity of materials and mode of procedure, Weston normal cells are reproducible within 1 part in 100 000. The source of the greatest variations has probably been the mercurous sulphate. Cells using the best samples of this material have an electromotive force the constancy of which over a period of one year is about 1 part in 100 000. Only very meager specifications for the cell have as yet been agreed upon internationally, however, and the procedures in various laboratories differ in some respects. For the preliminary specifications which have been issued and the reports of investigations of standard cells, see references 71 to 78 in the Bibliography, Appendix 3.

The basis of measurements of electromotive force is the same in all countries, as a result of the joint international experiments of 1910. As already stated, a large number of observations were made at that time with the silver voltameter, and a considerable number of Weston normal cells from the national laboratories of England, France, Germany, and the United States were compared. From the results of these voltameter experiments and from resistance measurements, the value

1.0183 international volts at 20° C

was assigned to the Weston normal cell. A mean of the groups of cells from the four laboratories was taken as most accurately representing the Weston normal cell. Each laboratory thus has a means of preserving the unit. Any discrepancies between the bases of the different countries at the present time would be due only to possible variations in the reference cells of the national laboratories. Such discrepancies are probably less than 2 parts in 100 000.

The value, 1.0183, has been in use since January 1, 1911. Before that time there was no agreement among the countries as to the value for the electromotive force of the Weston normal cell; the values given in Appendix 1 under "Electromotive force" were in use. The value used in the United States before 1911 was 1.019126 at 20° C (or 1.0189 at 25° C). This value was assigned to a certain group of cells maintained as the standard of electromotive force at the Bureau of Standards. This value was based on the Clark cell = 1.434 at 15° C. The high value is partly due to the use of commercial mercurous sulphate in the cells. The new value 1.0183 is assigned to a mean of the standards of four countries, as stated above. The old and the new values, 1.019126 and 1.0183, thus apply to different groups of cells. The group of cells to which the value 1.019126 was assigned before 1910 differed by 26 microvolts from the mean of the international group, such that the international group to which the value 1.0183 is now assigned had the value 1.019126 + 0.000026, or 1.019152, in terms of the old United States basis. The difference between 1.019152 and 1.0183 is 0.000852.

The electromotive force of any Weston cell as now given is therefore 0.000852 volt smaller than on the old United States basis, i. e., the present international volt is 84 parts in 100 000 larger than the old international volt of the United States.

Upon the new international basis the Clark cell set up according to the old United States legal specifications has an emf of 1.4328_0 international volts at 15° C. The Clark cell set up (with specially purified mercurous sulphate) according to improved specifications used at the Bureau of Standards has an emf of 1.4325_0 international volts at 15° C, or 1.4263_7 at 20° C.

(*b*) **Portable Weston Cells.**—The standard cell used in practice is the Weston portable cell; that is, the unsaturated cadmium cell. It resembles the Weston normal cell in all essentials except that in the normal cell the cadmium-sulphate solution is saturated at ordinary temperatures and in the portable cell it is unsaturated. Plugs of asbestos or other material are placed within the cell to hold the materials in place, and the cell is mounted in a convenient case so as to be portable. The resistance is usually of the order of 200 to 300 ohms. As usually made, the cadmium-sulphate solution is saturated at a temperature of about 4° C; at higher temperatures the crystals are dissolved. The temperature coefficient is practically zero. The change of emf is less than 0.00001 volt per degree centigrade, which is wholly negligible in most electrical measurements. What was said in regard to temperature changes of the Weston normal cell applies also to the portable cell, viz, the two legs of the cell have large and opposite temperature coefficients. Hence care must be taken that the temperature of the cell is kept uniform throughout. On this account it should be protected from draughts or from large changes of temperature. The electromotive force of any particular cell must be determined by comparison with standards, as they range from 1.0181 to 1.0191 international volts. The electromotive force decreases very slightly with time, usually less than 0.0001 volt per year.

(*c*) **Absolute and Semiabsolute Volt.**—The direct determination of the volt in absolute measure presents great difficulties, and such determinations have not been made with great accuracy. The absolute value of the volt is therefore derived from the absolute measurements of resistance and current. From the absolute value of the ohm as determined by Smith at the National Physical Laboratory of England, and the mean value of the ampere as obtained in England, Holland, and America, already given, it follows that

$$1 \text{ international volt} = 1.00043 \text{ absolute volts.}$$

This result is readily expressed in terms of the Weston normal cell as follows: The electromotive force of the Weston normal cell at 20° C is 1.0183_0 international volts and 1.0187_4 absolute volts. (It is an interesting coincidence that 1.0187 is the mean of the three formerly used values in international volts 1.0191, 1.0186, and 1.0184.)

It has been found convenient to express the results of absolute current measurements in semiabsolute volts, a semiabsolute volt being defined at that potential difference which exists between the terminals of a resistance of one *international* ohm when the latter carries a current of 1 *absolute* ampere. Thus, according to the results of the Bureau of Standards current balance the emf of the Weston normal cell at 20° C = 1.01822 semiabsolute volts, and from the National Physical Laboratory current balance the value was 1.01818. Haga and Boerema, in Holland, obtained 1.01824. Taking the mean, the emf of the Weston normal cell at 20° C = 1.01821 semiabsolute volts. This value differs from the emf in absolute *volts* by the same proportional amount as the international *ohm* differs from the absolute *ohm*.

4. QUANTITY OF ELECTRICITY

(*a*) **Units.**—The unit generally used for quantity of electricity[16] is the international coulomb. It was defined by the 1893 Chicago congress as "the quantity of electricity transferred by a current of one international ampere in one second."

[16] While quantity of electricity is more closely related to current than the other units, it was not thought desirable to interject this discussion between the closely related treatments of resistance, current, and emf.

The equivalents of the coulomb (the word "international" being usually omitted) in terms of electrostatic and other units are the same as for the corresponding units of current. (See Appendix 1.) The amperehour, a unit used in connection with voltaic cells, is equal to 3600 coulombs.

A unit in use in electrochemistry is the faraday, which is the quantity of electricity required to liberate 1 gram equivalent in electrolysis. Its value is 96500 coulombs.[17] The amount of electricity required to liberate 1 gram of any chemical element or ion is given by dividing the faraday by the equivalent weight of the element or ion. (The equivalent weight is the quotient of the atomic weight of the element or of the molecular weight of the ion, by the valency.) Also, the electrochemical equivalent (i. e., the number of grams liberated in electrolysis per coulomb) is given for any element or ion by dividing the equivalent weight by the faraday.

Another quantity of electricity of fundamental importance is the negative charge of 1 electron. This charge has been found to be the same regardless of the source or condition of the electron, whether it is found in the cathode rays or in the β rays from radium or elsewhere. The same charge is carried by an ion in a conducting gas, and by a monovalent ion in electrolysis. No smaller quantity of electricity has been observed, and all charges are integral multiples of this quantity (so that the name of the "atom of electricity" has been applied to it). This quantity is usually denoted by e, and its value [18] is

$$\begin{aligned} &4.77 \times 10^{-10} \text{ cgs electrostatic unit} \\ &= 1.59 \times 10^{-20} \text{ cgs electromagnetic unit} \\ &= 1.59 \times 10^{-19} \text{ coulomb} \end{aligned}$$

(*b*) **Standards.**—There are no standards of electric quantity except in so far as the silver voltameter may be considered such a standard. The mass of metal deposited in a voltameter is, under ideal conditions, proportional to the quantity of electricity which has flowed. It is rather as an instrument of measurement that the voltameter has found application. It has been used commercially to measure the total quantity of electricity furnished by a power company to a consumer; on the assumption of a constant voltage this enabled the energy to be calculated.

The electron could be considered a standard of electric quantity, inasmuch as its charge is a constant. This constant is not meas-

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[17] See reference No. 101, Appendix 3. [18] See reference No. 104, Appendix 3.

urable accurately enough nor conveniently enough, however, to permit its use in precise measurements.

Measurements of electric quantity to high precision are made by joint measurements of current and time. The current is kept constant and is measured at any convenient time during the run.

5. CAPACITY

The unit generally used for capacity is the international microfarad. It is one-millionth of the international farad, which was defined by the Chicago congress of 1893 as "the capacity of a condenser charged to a potential of one international volt by one international coulomb of electricity."

The relations of the various units of capacity are given in Appendix 1. The cgs electrostatic unit is sometimes called the "centimeter." This has been found convenient because the capacity of a system is directly proportional to a length, and capacity has the dimensions of length in the electrostatic system with dimensions of dielectric constant suppressed. It is a case of using a word in two entirely different meanings, length and capacity being different physical quantities. The micromicrofarad (=0.8989 cgs electrostatic units) is in general the most convenient unit for small capacities.

Capacities are commonly measured by comparison with standards. The values of the standards are determined by measurement in terms of resistance and time. The international ohm being the unit in use, consequently capacities as ordinarily determined are in international units. The ratio of the international to the absolute microfarad is the reciprocal of the ratio of the international to the absolute ohm. A standard of capacity is some form of condenser, which consists of two sets of metal plates separated by a dielectric. The condenser should be surrounded by a metal shield connected to one set of plates, in order that the capacity may be independent of the presence of surrounding objects. An ideal condenser would have a constant capacity under all circumstances, with zero resistance in its leads and plates, infinite resistance between the plates, and no absorption in the dielectric. Actual condensers do not strictly fulfill these conditions, but vary with temperature, atmospheric pressure, and the voltage, frequency, and time of charge and discharge. A well-constructed air condenser having heavy metal plates and suitable insulating supports is practically free from these effects and is used as a standard of capacity.

For reasons of construction the plates of an air condenser must be separated 1 mm or more. Hence, such a condenser can not be of very great capacity. The more the capacity is increased by putting the plates closer together the greater sacrifice is made to mechanical stability and the less constant is the capacity. Condensers of greater capacity are made with solid dielectrics. The best of these have a dielectric consisting of mica sheets and conducting plates of tinfoil. When maintained at a constant temperature, the best mica condensers are constant and are excellent standards. The dielectric absorption is small, but is not quite zero, so that the variation of the capacity of these standards with different methods of measurement must be carefully determined.

6. INDUCTANCE

The principal unit of inductance is the international henry. It was defined by the 1893 Chicago congress as the inductance "in a circuit when the electromotive force induced in this circuit is 1 international volt, while the inducing current varies at the rate of 1 ampere per second." The unit is the same for self-inductance and for mutual inductance. In the case of self-inductance the inducing current is in the circuit itself, while in the case of mutual inductance the inducing current is in some outside circuit.

The equivalents of the henry in other units are given in Appendix 1. For small inductances the millihenry and microhenry are usually used. The cgs electromagnetic unit (=0.001 microhenry) is also used and is sometimes called the "centimeter." Inductance has the dimensions of length in the electromagnetic system with dimensions of permeability suppressed. The use of "centimeter" is justified in the same way as the use of this name is justified for the cgs electrostatic unit of capacity and the same objections apply. The use of the same name for units of several different physical quantities, particularly when more than one occur in the same equation, is unsatisfactory. For instance, inductance and capacity both occur in formulas commonly used in radiotelegraphy and it tends to cause confusion when both are measured in "centimeters."

The henry has been known also by the names "quadrant" and "secohm." Both names are based on dimensional considerations. The length of a quadrant or quarter of the earth's circumference is approximately 10^9 centimeters and a henry is

10^9 "centimeters" of inductance. The name "secohm" is a combination of second and ohm, inductance having the same dimensions as time multiplied by resistance, and this unit fitting into the same system as the ohm and the second.

The values of inductance standards are determined by measurements in terms of resistance and time or in terms of resistance and capacity by alternating-current bridge methods. As resistance and capacity are ordinarily standardized in international units, the values of inductances obtained from measurements are likewise in international units. When, however, inductances are calculated from dimensions, the values are obtained in absolute electromagnetic units. The ratio of the international to the absolute henry is the same as the ratio of the international to the absolute ohm.

The measurement of inductance in terms of capacity and resistance by an alternating-current bridge method is about as simple and convenient as the comparison of two inductances. Consequently, a standardizing laboratory does not necessarily maintain standards of inductance for the purposes of inductance measurement. Standards of inductance are, however, of value in magnetic, alternating-current, and absolute electric measurements. Inductance is a property of a circuit and so a standard of inductance is simply a part of a circuit so arranged that when it is used to complete some circuit it adds a definite amount of inductance. In other words, it must either have such a form or must have so great an inductance that the mutual inductance of the rest of the circuit upon it may be negligible. It usually consists of a coil of wire wound upon an insulating frame, the turns being all in the same direction, so as to make the self-inductance a maximum. A standard the inductance of which may be calculated from the dimensions consists of a single-layer coil upon a frame of very simple geometrical form. Standards of very small inductance which are to be calculable from dimensions consist not of coils but of some simple arrangement, such as a pair of parallel wires or a single turn of wire. Such standards must be used with great care in order that the mutual inductance upon them of the leads and other parts of the circuit may be negligible. Any standard of inductance should always be separated from the measuring bridge or other apparatus by long leads. An inductance standard must be so wound that the distributed capacity between its turns is negligible; otherwise the measured inductance varies with frequency and is not the true inductance.

7. POWER AND ENERGY

(*a*) **Units.**—Power and energy are not primarily electric quantities. Nevertheless, they must be considered in a treatment of electric units and standards because of their relations with the various electric quantities, and because they are measured to a higher precision by electrical methods than in any other way. Power and energy being mechanical quantities as well as electrical, being, in fact, common to all branches of physical phenomena, their units, such as the watt and joule, are mechanical units. Thus, the joule = 10^7 ergs = the work done by the action, through a distance of 1 m, of a force capable of giving to a mass of 1kg in one second a velocity of 1 m per second. The watt = a power of 1 joule per second. In full agreement with these definitions, the 1908 London conference adopted the following unit: "The *watt*, the unit of power, which has the value of 10 000 000 (10^7) in terms of the centimeter, the gram, and the second."

The watt and the electric units were chosen as such multiples of the cgs units that the unit of power bears a very simple relation to the units of ordinary electric quantities. Thus the product of current in amperes by electromotive force in volts = the power in watts (for continuous or instantaneous values). It is this circumstance which has sometimes given rise to the mistaken idea that the watt and the kilowatt are primarily electric units. The closest realization of the watt in practice is the "international watt," defined by the 1908 electrical conference as "the energy expended per second by an unvarying electric current of one international ampere under an electric pressure of one international volt." The difference between the international watt and the absolute watt is very small. (See Appendix 1.)

(*b*) **Standards and Measurements.**—There are no standards of power or energy, except certain substances whose heats of combustion are used as standard in calorimetry. Measurements are always made, in electrical practice, in terms of some of the purely electrical quantities which are represented by standards. In precise measurements of direct-current power, standard cells and resistance standards are used, in connection with a potentiometer. Two of the three quantities are measured, electromotive force, current, resistance. An additional measurement of the time during which the current flows gives the energy expended during that time.

8. RESISTIVITY

Resistivity [19] may be defined [20] in general as that property of a substance in virtue of which electric energy is converted into heat within the substance. The resistance of a conductor is proportional to the resistivity of the substance of which it is composed. A numerical value of resistivity is given by stating the resistance of a unit specimen. This unit specimen may be defined in terms of any convenient units, combined in those relations which experiment has shown to be correct. The most familiar relation is

$$R=\rho\frac{l}{s}$$

where R = resistance, l = length, s = cross section, and ρ is a property of the substance called the volume resistivity, or simply the resistivity. The unit specimen is specified by stating the length and cross section.

An equally valid relation is

$$R=\delta\frac{l^2}{m}$$

where m = mass, and δ is a property of the substance called the mass resistivity. The unit specimen is specified by stating the length and mass. Mass resistivity is in extensive use where wires in large quantity are handled. The mass and length are measured instead of cross section and length, because of greater convenience and accuracy. This makes the use of mass resistivity more suitable than volume resistivity in such cases. If the density, d, is known, either resistivity can be calculated from the other through the relation

$$\delta=\rho d$$

Except in the technique of wire production and wire calculations, the term "resistivity" used alone usually means volume resistivity.

It has been said that a numerical value of resistivity is given by stating the resistance of a unit specimen. The numerical value can be considered as the number of certain units of resistivity, just as the numerical value of any other physical quantity is the number of units of that quantity. For example, suppose the resistivity of a certain kind of iron is given as 0.1 ohm per meter of

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[19] The discussion of resistivity belongs, in a sense, with the section on resistance, above, but it was not thought desirable to interject this material between the closely related treatments of resistance, current, and emf.

[20] See reference No. 94, Appendix 3.

a uniform wire 1 mm^2 in cross section. The unit is in this case the resistivity of a specimen whose resistance is 1 ohm, length 1 m, and cross section 1 mm^2. In terms of this unit, the resistivity of the given kind of iron is 0.1.

A great many units of resistivity are in common use. The most usual unit of volume resistivity is the resistivity of a specimen whose resistance is 1 microhm, length 1 cm, and cross section 1 cm^2. It is called the "microhm-centimeter."[21] Those units of volume resistivity in which the length and cross section are taken in terms of the same length unit have their names made up in this same way. The hyphen suggests a product, and the name thus suggests the dimensional relation, as may be seen from

$$[\rho]=\left[\frac{RL^2}{L}\right]=[RL]$$

The most common unit of mass resistivity is the resistivity of a specimen whose resistance is 1 ohm, length 1 m, and mass 1 g. This unit has been called by various names, more or less appropriate; the name used by this Bureau is the "ohm (meter, gram)." This name states the units which go to make up the resistivity unit, and this manner of writing the name is applicable to many other units of both kinds of resistivity. In the tables of conversion factors in Appendix 1 various units of resistivity are exhibited. The names carry their definitions with them; where two lengths are given in the parenthesis, the greater is the length of the unit specimen and the smaller is the diameter. An advantage of these abbreviated forms for the names of resistivity units is that the same method of writing lends itself readily to the units of conductivity. For example, the conductivity unit written as 1/ohm (meter, mm^2) readily suggests its own definition.

Another unit, of a somewhat different kind, is the resistivity represented by the "international annealed copper standard." This resistivity is an approximate average of the high-conductivity copper of commerce. Full details regarding it are given in this Bureau's Circular No. 31. In practice, it is used as the basis of the expression of "per cent conductivity."

The term "specific resistance" has been extensively used in the past for volume resistivity. It is not a suitable term and is

[21] Also called "microhm per centimeter cube." The term "microhm per cubic centimeter" is objectionable, because it suggests that resistance is a function of volume.

going out of use. Similar terms, such as "specific gravity" and "specific heat," refer primarily not to the property of a substance but to the *ratio* of the property of a substance to the same property of a standard substance. The term "resistivity" is better than "specific resistance," just as "conductivity" is better than "specific conductance" would be.

IV. MAGNETIC UNITS

1. HISTORICAL

The centimeter-gram-second system of units was adopted by the British Association for the Advancement of Science in 1873. By this action, the cgs electromagnetic units were implicitly adopted for magnetic quantities. No names were assigned to the units at that time. The "line" was in use as the name of the unit of magnetic flux. The units of other quantities were simply called "cgs units."

In a report prepared in 1888, John Perry suggested that the unit of magnetic flux be 10^8 cgs units, in order that a change of unit flux per second through a circuit might generate 1 volt. Another of his proposals was that the unit of magnetomotive force be the "ampere-turn"; this would remove the factor 4π in the relation between magnetomotive force and current. This was also one of the advantages of the system proposed by Heaviside somewhat earlier. Heaviside's system, however, required numerical changes in practically all the electric and magnetic units. It has some theoretical advantages, but its revolutionary character has prevented its general adoption.

At the second International Congress of Electricians, at Paris, 1889, the question of defining and naming practical magnetic units was discussed. The "weber" was proposed as the name for 10^8 cgs units of magnetic flux. The name "gauss" was proposed as the name for 10^8 cgs units of magnetic induction. As this unit is larger than the inductions dealt with in practice, the "microgauss" was suggested for ordinary use. No action was taken by the congress on these proposals. These propositions were brought up again at the Frankfort International Electrical Congress in 1891, and again no action was taken.

A committee appointed by the American Institute of Electrical Engineers in 1891 recommended the following practical units: 0.1 cgs unit of magnetomotive force, 10^8 cgs units of magnetic flux, 10^8 cgs units of magnetic induction, and 10^{-9} cgs unit of reluctance. Names were not suggested for these units. No action was taken by the Institute.

No official action was taken between 1873 and 1893, but the tendency seemed to be toward the selection of multiples of the cgs units such as to fit into the "practical" electric units, volt, ohm, etc. Discussion upon these propositions brought out the fact that these multiples were not as convenient as the cgs units in practical magnetic work. In consequence the action of the 1893 International Electrical Congress at Chicago was to recommend the cgs magnetic units. No names for the units were decided upon.

The American Institute of Electrical Engineers accepted the decision of the Chicago congress and has used the cgs units for magnetic quantities since then. Names were provisionally adopted for the units in 1894. A committee on units and standards recommended the name "gilbert" for the cgs unit of magnetomotive force; "weber" for the cgs unit of magnetic flux; "oersted" for the cgs unit of reluctance; and "gauss" for the cgs unit of magnetic induction. These recommendations were adopted provisionally, i. e., until some suitable authority replaced them. Since then an international congress has given a different name to the unit of flux and has used "gauss" for a different unit. Only two of the 1894 units therefore retained official standing in the United States—the "gilbert" and the "oersted."

The British Association committee on electrical standards did not follow strictly the Chicago recommendation as to magnetic units. In 1895 the committee recommended for tentative adoption the following two units: The "weber" $=10^8$ cgs units of flux and the "gauss" = cgs unit of magnetomotive force. These two have been superseded by the definitions adopted by the 1900 Paris congress.

At the Paris electrical congress of 1900 the following report was adopted after consideration by section 1 of the congress:

1. The section recommends giving the name "gauss" to the cgs unit of magnetic field intensity.

2. The section recommends giving the name "maxwell" to the cgs unit of magnetic flux.

In its 1911 standardization rules the American Institute of Electrical Engineers adopted the "maxwell" as the cgs unit of magnetic flux, the "gauss" as the cgs unit of magnetic induction, and the "gilbert per centimeter" as the cgs unit of magnetic field intensity. In its 1914 standardization rules the institute added "gauss" as an alternative name for the unit of magnetic field intensity, making the statement: "The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density on the assumption that permeability is a simple numeric." The name "gauss" is applied to both units also by the American Society for Testing Materials. It was so adopted by that society in 1911 in its "Standard tests for magnetic properties of iron and steel."

The history of magnetic units has thus been a series of conflicting recommendations. The outstanding result of official decisions has been the adoption of the cgs electromagnetic units. The names given the magnetic units have fluctuated and some confusion still exists in the nomenclature.

2. PRESENT STATUS OF THE MAGNETIC UNITS

The units of the cgs electromagnetic system are used more generally than any others for magnetic quantities. (In terrestrial magnetic work some Russian writers use the units of the original Gauss system, which took the millimeter, milligram, and second as fundamental. The unit of magnetic field intensity in these units is one-tenth the cgs unit.) It is common, both in European and American practice, to assume cgs units when magnetic data are given without naming any unit. American practice is fairly uniform in the names used for the cgs units. The cgs unit of magnetomotive force is called the "gilbert," and the cgs unit of reluctance the "oersted," following the 1894 provisional definitions of the American Institute of Electrical Engineers. The cgs unit of flux is called the "maxwell," as defined by the 1900 Paris congress. The name "line" has also been extensively used for this unit; it has not had the sanction of any formal adoption and it is generally giving way to "maxwell."

The name "gauss" is used both for the cgs unit of induction, as defined by the A. I. E. E. in 1894, and for the cgs unit of magnetic field intensity or magnetizing force, as defined by the 1900 Paris congress. This double usage, recently sanctioned by engineering societies, is based upon the mathematical convenience of defining induction and magnetizing force both as the force on a unit magnetic pole in a narrow cavity in the material, the cavity being in the one case perpendicular, and in the other case parallel, to the direction of magnetization. This definition, however, only applies in the ordinary electromagnetic units. There are a number of reasons for considering induction and magnetizing force to be two physically distinct quantities, just as electromotive force and current are physically different. "Gauss" is therefore not as distinctive a name as might be desired, it meaning either cgs unit of induction or cgs unit of magnetizing force. Thus, if the statement is made that the iron in a machine was worked at 100 gausses, one would not know, unless aided by context or convention, whether gausses of induction or magnetizing force were meant.

In the United States "gauss" has been used much more for the cgs unit of induction than for the cgs unit of magnetizing force. It was adopted in the former sense by the A. I. E. E. in 1894 and 1911. The longer name "maxwell per cm^2" is also sometimes used for this unit, when it is desired to distinguish clearly between induction and magnetizing force. The cgs unit of magnetizing force is usually called the "gilbert per cm."

A unit frequently used, which does not fit into the ordinary cgs system, is the "ampere-turn." It is a convenient unit, because it eliminates the factor 4π in certain calculations. Thus, the magnetomotive force in a magnetic circuit linked with N turns of wire carrying a current of I amperes is $\frac{4\pi}{10} NI$ gilberts or NI ampere-turns. From the ampere-turn is derived the "ampere-turn per cm" as a unit of magnetizing force.

The ampere-turn has usually been regarded as an isolated unit rather than a member of a formal system. It may be shown, however, that it and certain of the ordinary cgs magnetic units taken together form a complete system. (See references 9d and 132, Appendix 3.) Some of the equations appropriate to these units differ from the ordinary equations by the factor 4π, somewhat as in the Heaviside system.

Isolated units, using the inch as the unit of length, are also in use. Thus, magnetizing force is sometimes given in ampere-turns per inch and the maxwell per square inch is in use as a unit of induction. The relations of the various magnetic units are given in Appendix 1.

In works on magnetism and in actual practice the unit of magnetomotive force is fixed in terms of the current in a solenoid and the unit of flux in terms of the electromotive force produced by a change in flux. Since emf and current are measured in international units, the magnetic units actually used are likewise international units. The international gilbert, maxwell, etc., differ slightly in magnitude from the corresponding absolute gilbert, maxwell, etc.; the numerical differences are given at the end of section on the international units (p. 17). The existence of these differences is usually overlooked in treatments of magnetic units.

APPENDIXES

Appendix 1.—CONVERSION FACTORS

[See also pp. 14 and 17]

RESISTANCE

The relation given here between the international and absolute ohm is based on the result obtained by Smith at the National Physical Laboratory of England. (See p. 32.) The international ohm has now the same value in all countries. As used in France before 1911 it had the value below, according to Janet, Laporte, and Jouaust (Bull. Soc. Int. Electriciens, 1910). The value for the British Board of Trade unit is that stated in B. A. Report, 1903. The value given for the British Association unit is that used by the American Institute of Electrical Engineers (Trans. A. I. E. E., **10**, supplement, October, 1893), and is the value used in England. The relation of the absolute ohm to the cgs electrostatic unit involves the constant *c*, whose value was given above on page 14 as 2.9982×10^{10}.

The relations between the international ohm and old resistance units are not of wide applicability, since it is usually uncertain how closely resistances expressed in these old units were known in terms of the standard.

1 international ohm = 1.00052 absolute ohms
= 1.0001 international ohms (France, before 1911)
= 1.00016 Board of Trade units (England, 1903)
= 1.01358 B. A. units
= 1.00283 "legal ohms" of 1884
= 1.06300 Siemens units

1 absolute ohm = 0.99948 international ohm
= 1 "practical" electromagnetic unit
= 10^9 cgs electromagnetic units
= 1.1124×10^{-12} cgs electrostatic unit

CURRENT

The relation below between the international and absolute ampere is based upon absolute measurements in England, Holland, and the United States, as explained on page 38. The international ampere is maintained by the national laboratories by the aid of resistance standards and standard cells. This unit now has the same value in all countries, but in the past has varied somewhat; the old values below are calculated from the values of the standard cell at various times, as given under "Electromotive force" below. The old French value is based on the French value of the volt below and of the ohm above.

1 international ampere = 0.99991 absolute ampere
= 1.00084 international amperes (United States, before 1911)
= 1.00130 international amperes (England, before 1906)
= 1.00106 international amperes (England, 1906 to 1908)
= 1.00010 international amperes (England, 1909 to 1910)
= 1.00032 international amperes (Germany, before 1911)
= 1.0002 international amperes (France, before 1911)

1 absolute ampere = 1.00009 international amperes
= 1 "practical" electromagnetic unit
= 0.1 cgs electromagnetic unit
= 2.9982×10^9 cgs electrostatic units

ELECTROMOTIVE FORCE

The basis of the relation between the international and absolute volt is given on page 42. The relation between the old international volt as used in the United States and the present international volt, which has the same value in all countries, is explained on page 40. The old values given for the volt in England are based on the following values of the Weston normal cell at 20° C, respectively: 1.01962 (1906 statement as to tests of National Physical Laboratory), 1.01938 (value used in England, 1906 to 1908), and 1.0184 (provisional value recommended by the London conference of 1908 and used in England in 1909 and 1910). The calculations take no account of a possible difference between the particular cells to which the old values and the present value of 1.0183 were assigned. The value given for Germany and France is based on the value 1.01863; this is the value used in Germany prior to 1911, and it is presumed that it was used in France as well, on the basis of a statement by P. Janet (Bull. Soc. Int. Electriciens, 1908).

1 international volt = 1.00043 absolute volts.
= 1.00084 international volts (United States, before 1911)
= 1.00130 international volts (England, before 1906)
= 1.00106 international volts (England, 1906 to 1908)
= 1.00010 international volts (England, 1909 to 1910)
= 1.00032 international volts (Germany and France, before 1911)

1 absolute volt = 0.99957 international volt
= 1 "practical" electromagnetic unit
= 10^8 cgs electromagnetic units
= 0.003 3353 cgs electrostatic unit

QUANTITY OF ELECTRICITY

The units of quantity have the same relations as the corresponding units of current. The relations between the international coulomb and certain additional units are as follows:

$$1 \text{ international coulomb} = \frac{1}{3600} \text{ ampere-hour}$$

$$= \frac{1}{96500} \text{ faraday}$$

CAPACITY

1 absolute farad = 1.000 52 international farads
= 1 "practical" electromagnetic unit
= 10^{-9} cgs electromagnetic unit
= 8.9892×10^{11} cgs electrostatic units

INDUCTANCE

1 absolute henry = 0.99948 international henry
= 1 "practical" electromagnetic unit
= 10^9 cgs electromagnetic units
= 1.1124×10^{-12} cgs electrostatic unit

ENERGY AND POWER

The relation between the international and absolute joule or watt was calculated from the values for the ohm and ampere. The "standard foot-pound" below is defined as the energy used in raising a pound mass 1 foot against the force of gravity at a place where the acceleration of gravity is 980.665 cm per second per second (or

32.1740 feet per second per second). The "standard kilogram-meter" involves the same constant.

The units of power have the same relations as the corresponding units of energy given herewith.

1 absolute joule = 0.999 66 international joule
= 10^7 ergs
= 0.737 560 standard foot-pound
= 0.101 972 standard kilogram-meter
= $0.277\ 778 \times 10^{-6}$ kilowatt-hour

RESISTIVITY

The units of resistivity in use are in terms of the international ohm. They may be obtained in terms of other resistance units by applying the conversion factors under "Resistance," above.

1 ohm-cm = 0.393 700 ohm-inch
= 10 000.0 ohm (meter, mm^2)
= 12 732.4 ohm (meter, mm)
= 393 700 microhm-inch
= 1 000 000 microhm-cm
= 6 015 290 ohm (mil, foot)
1 ohm (meter, gram) = 5710.0 ohm (mile, pound)

MAGNETIC QUANTITIES

1 international gilbert = 0.999 91 absolute gilbert
1 international maxwell = 1.000 43 absolute maxwell.

The following relations hold either for international or absolute units. In practice the international units are used.

1 gilbert	= 0.7958 ampere-turn
1 gilbert per cm	= 0.7958 ampere-turn per cm
	= 2.021 ampere-turns per inch
1 maxwell	= 1 line
	= 10^{-8} volt-second
1 maxwell per cm^2	= 6.452 maxwells per square inch

Appendix 2.—LEGISLATION ON ELECTRIC UNITS

1. LAWS OF VARIOUS COUNTRIES

UNITED STATES OF AMERICA

Act approved July 12, 1894

The legal units of electrical measure in the United States shall be as follows:

Ohm

First. The unit of resistance shall be what is known as the international ohm, which is substantially equal to one thousand million units of resistance of the centimeter-gram-second system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice fourteen and four thousand five hundred and twenty-one ten-thousandths grams in mass, of a constant cross-sectional area, and of the length of one hundred and six and three-tenths centimeters.

Ampere

Second. The unit of current shall be what is known as the international ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electromagnetic units, and is the practical equivalent of the unvarying current, which, when passed through a solution of nirtate of silver in water in accordance with standard specifications, deposits silver at the rate of one thousand one hundred and eighteen millionths of a gram per second.

Volt

Third. The unit of electromotive force shall be what is known as the international volt, which is the electromotive force that, steadily applied to a conductor whose resistance is one international ohm, will produce a current of an international ampere, and is practically equivalent to one thousand fourteen hundred and thirty-fourths of the electromotive force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of fifteen degrees centigrade, and prepared in the manner described in the standard specifications.

Coulomb

Fourth. The unit of quantity shall be what is known as the international coulomb, which is the quantity of electricity transferred by a current of one international ampere in one second.

Farad

Fiftn. The unit of capacity shall be what is known as the international farad, which is the capacity of a condenser charged to a potential of one international volt by one international coulomb of electricity.

Joule

Sixth. The unit of work shall be the joule, which is equal to ten million units of work in the centimeter-gram-second system, and which is practically equivalent to the energy expended in one second by an international ampere in an international ohm.

Watt

Seventh. The unitof power shall be the watt, which is equal to ten million units of power in the centimeter-gram-second system, and which is practically equivalent to the work done at the rate of one joule per second.

Henry

Eighth. The unit of induction shall be the henry, which is the induction in a circuit when the electromotive force induced in this circuit is one international volt while the inducing current varies at the rate of one ampere per second.

Sec. 2. That it shall be the duty of the National Academy of Sciences to prescribe and publish, as soon as possible after the passage of this act, such specifications of detail as shall be necessary for the practical application of the definitions of the ampere and volt hereinbefore given, and such specifications shall be the standard specifications herein mentioned.

GREAT BRITAIN

ORDER IN COUNCIL, JANUARY 10, 1910

Whereas by the "Weights and Measures Act, 1889," it is, among other things, enacted that the Board of Trade shall from time to time cause such new denominations of standards for the measurement of electricity as appear to them to be required for use in trade to be made and duly verified.

And whereas by Order of Council dated the 23rd day of August, 1894, Her late Majesty Queen Victoria, by virtue of the power vested in Her by the said Act, by and with the advice of Her Privy Council, was pleased to approve the several denominations of standards set forth in the Schedule thereto as new denominations of standards for electrical measurement.

And whereas in the said Schedule the limits of accuracy attainable in the use of the said denominations of standards are stated as follows:

For the Ohm within one hundredth part of one per cent.

For the Ampere within one tenth part of one per cent.

For the Volt within one tenth part of one per cent.

And whereas, at an International Conference on Electrical Units and Standards held in London in the month of October, 1908, the International Electrical Units corresponding with the said denominations of standards were defined as follows:

The International Ohm is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice 14.4521 grams in mass of a constant cross sectional area and of a length of 106.300 centimeters.

The International Ampere is the unvarying electric current which when passed through a solution of nitrate of silver in water deposits silver at the rate of 0.00111800 of a gram per second.

The International Volt is the electrical pressure which when steadily applied to a conductor whose resistance is one International Ohm will produce a current of one International Ampere.

And whereas it has been made to appear to the Board of Trade to be desirable that the denominations of standards for the measurement of electricity should agree in value with the said International Electrical Units within the said limits of accuracy attainable.

And whereas the denominations of standards made and duly verified in 1894 and set forth in the Schedule to the said Order in Council have been again verified.

And whereas the Board of Trade are advised that the said denominations of standards agree in value with the said International electrical units within the said limits of accuracy attainable, except that in the case of the Ohm the temperature should be 16.4 C. in place of 15.4 C. as specified in the Schedule to the said Order in Council.

And whereas it has been made to appear to the Board of Trade that the said denominations of standards should be amended so that the aforesaid exception may be remedied.

Now, THEREFORE, His Majesty, by virtue of the power vested in him by the said Act, by and with the advice of His Privy Council, is pleased to revoke the said Order of Council dated the 23rd day of August, 1894, and is further pleased to approve the several denominations of standards set out in the Schedule hereto as denominations of standards for the measurement of electricity.

ALMERIC FITZROY.

"SCHEDULE ABOVE REFERRED TO

"I. STANDARD OF ELECTRICAL RESISTANCE

"A standard of electrical resistance denominated one Ohm agreeing in value within the limits of accuracy aforesaid with that of the International Ohm and being the resistance between the copper terminals of the instrument marked 'Board of Trade Ohm Standard Verified, 1894 and 1909,' to the passage of an unvarying electrical current when the coil of insulated wire forming part of the aforesaid instrument and connected to the aforesaid terminals is in all parts at a temperature of 16.4 C.

"II. STANDARD OF ELECTRICAL CURRENT

"A standard of electrical current denominated one Ampere agreeing in value within the limits of accuracy aforesaid with that of the International Ampere and being the current which is passing in and through the coils of wire forming part of the instrument marked 'Board of Trade Ampere Standard Verified, 1894 and 1909,' when on reversing the current in the fixed coils the change in the forces acting upon the suspended coil in its sighted position is exactly balanced by the force exerted by gravity in Westminster upon the iridioplatinum weight marked A and forming part of the said instrument.

"III. STANDARD OF ELECTRICAL PRESSURE

"A standard of electrical pressure denominated one volt agreeing in value within the limits of accuracy aforesaid with that of the International Volt and being one hundredth part of the pressure which when applied between the terminals forming part of the instrument marked 'Board of Trade Volt Standard Verified, 1894 and 1909,' causes that rotation of the suspended portion of the instrument which is exactly measured by the coincidence of the sighting wire with the image of the fiducial mark A before and after application of the pressure and with that of the fiducial mark B during the application of the pressure these images being produced by the suspended mirror and observed by means of the eyepiece.

"In the use of the above standards the limits of accuracy attainable are as follows

"For the Ohm, within one hundredth part of one per cent.

"For the Ampere, within one tenth part of one per cent.

"For the Volt, within one tenth part of one per cent.

"The coils and instruments referred to in this Schedule are deposited at the Board of Trade Standardizing Laboratory, 8, Richmond Terrace, Whitehall, London."

CANADA

ELECTRICAL UNITS ACT, Assented to July 23, 1894, 57–58, Vict., C. 38, S. 1.

1. This Act may be cited as The Electrical Units Act.
2. The units of electrical measure for Canada shall be the following:

Ohm

(a) As a unit of resistance, the ohm, which is based upon the ohm equal to 10^9 units of resistance of the centimeter-gram-second system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury, at the temperature of melting ice 14.4521 grams in mass, of a constant cross-sectional area and of the length of 106.3 centimeters.

Ampere

(b) As a unit of current, the ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electromagnetic units, and is represented sufficiently well for practical use by the unvarying current, which, when passed through a solution of nitrate of silver in water, and in accordance with the specification contained in schedule 1 to this Act, deposits silver at the rate of 0.001118 of a gram per second.

Volt

(c) As a unit of electromotive force, the volt, which is the electromotive force that, steadily applied to a conductor whose resistance is 1 ohm, will produce a current of 1 ampere, and which is represented sufficiently well for practical use by $\frac{1000}{1434}$ of the electromotive force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of 15° centigrade and prepared in accordance with the specification contained in schedule 2 to this Act.

Coulomb

(d) As a unit of quantity, the coulomb, which is the quantity of electricity transferred by a current of 1 ampere in one second.

Farad

(e) As a unit of capacity, the farad, which is the capacity of a condenser charged to a potential of 1 volt by 1 coulomb.

Joule

(f) As a unit of work, the joule, which is equal to 10^7 units of work in the centimeter-gram-second system, and is represented sufficiently well for practical use by the energy expended in one second by 1 ampere in 1 ohm.

Watt

(g) As a unit of power, the watt, which is equal to 10^7 units of power in the centimeter-gram-second system, and is represented sufficiently well for practical use by the work done at the rate of 1 joule per second.

Henry

(h) As the unit of induction, the henry, which is the induction in a circuit when the electromotive force induced in that circuit is 1 volt, while the inducing current varies at the rate of 1 ampere per second.

3. The units of electrical measure described in the next preceding section, or such standard apparatus as is necessary to produce them, shall be deposited in the Department of Inland Revenue and shall form part of the system of standards of measure and weight established by The Weights and Measures Act.

GERMANY

LAW OF JUNE 1, 1898, R. G. BL., P. 905

SECTION 1. The legal units for electrical measurements are the ohm, ampere, and volt.

Ohm

SEC. 2. The unit of electrical resistance is the ohm. It is represented by the resistance of a column of mercury, at the temperature of melting ice, of uniform cross section, practically equivalent to 1 square millimeter, of a length of 106.3 centimeters, and of a mass of 14.4521 grams.

Ampere

SEC. 3. The unit of electric current strength is the ampere. It is represented by the unvarying electric current which in passing through an aqueous solution of silver nitrate deposits in one second 0.001118 gram of silver.

Volt

SEC. 4. The unit of electromotive force is the volt. It is represented by the electromotive force which when applied to a conductor having a resistance of 1 ohm produces a current of 1 ampere.

SEC. 5. The Bundesrath is empowered—

(a) To fix the conditions under which the silver is to be deposited, in the definition of the ampere. (Sec. 3.)

(b) To fix designations for the units of electric quantity, energy, power, capacity, and inductance.

(c) To prescribe designations for the multiples and submultiples of the electrical units.

(d) To fix the manner in which the strength, electromotive force, energy, and power of alternating currents is to be calculated.

SEC. 6. According to this paragraph instruments used in the measurement of electrical power for commercial purposes must have their indications based on the legal units. The use of incorrect measuring instruments is prohibited. The Bundesrath is empowered to fix the limits of tolerance for such apparatus, after giving a hearing to the Physikalisch-Technische Reichsanstalt.

The Bundesrath is empowered to issue regulations concerning the official verification and periodic reverification of measuring apparatus.

SEC. 7. The Physikalisch–Technische Reichsanstalt is directed to construct primary mercurial resistance standards and assume responsibility for their control and safe custody at different places. It is also to reverify the resistance of standards of solid metals used in the intercomparisons by an annual recomparison with the mercurial standards.

SEC. 8. The Physikalisch-Technische Reichsanstalt is to provide for the issue of officially certified standard resistances and standard cells for the measurement of current and electromotive force.

SEC. 9. The official testing and certification of electrical measuring instruments shall be carried out by the Physikalisch-Technische Reichsanstalt. The Imperial Chancellor may intrust this authority elsewhere. All standards and measuring apparatus employed in official verifications must be certified to by the Physikalisch-Technische Reichsanstalt.

SEC. 10. The Physikalisch-Technische Reichsanstalt is to assume the responsibility that the official testing and verification of electrical measuring apparatus in the German Empire shall be made in a uniform manner. It is to assume the technical supervision of the inspection service, and to prescribe all technical specifications concerning the same. It is especially to determine what kind of measuring instruments shall be admitted to official verification, to adopt regulations concerning the material, construction, or designation of the apparatus, to regulate the methods employed in testing and verification, and to fix the fees and specify the seal to be employed.

SEC. 11. Measuring apparatus verified in accordance with this law may be used in trade in any part of the Empire.

SEC. 12. Whoever, engaged in the industrial supply of electrical energy, does not comply with section 6, or the regulations based thereon, will be subjected to a fine not exceeding 100 marks, or imprisonment not to exceed four weeks. In addition, the incorrect instruments, or the instruments not complying with the regulations, shall be subject to seizure.

SEC. 13. This law and the regulations adopted in accordance with sections 6 and 12 shall take effect January 1, 1902; the remainder on the date of its promulgation.

REGULATIONS FOR CARRYING OUT THE LAW, ISSUED BY THE BUNDESRATH. R. G. BL., 1901. NO. 16

In accordance with paragraph 5 of the law defining the electrical unites of measurement (R. G. Bl., p. 905), the following specifications are adopted:

1. *Conditions under which the silver is to be deposited* in the specification of the ampere.

2. *Designation of the electrical units* (sec. 5b).

(a) The quantity of electricity flowing through the cross section of a conductor in one second when the current in the same is equal to one ampere is called an ampere-second (coulomb), and the quantity flowing in one hour an amperehour.

(b) The power corresponding to an ampere in a conductor having a potential difference of 1 volt between its terminals is called a watt.

(c) The work done in one hour when the power is equal to 1 watt is called a watt-hour.

(d) The capacity of a condenser which is charged by an ampere-second to one volt is called a farad.

(e) The self-inductance of a conductor in which 1 volt is induced by a uniform change in the current of 1 ampere per second is called a henry.

3. *Designations for the multiples and submultiples of* the electrical units (sec. 5c).

The following prefixes to the name of a unit have the following meanings:

Kilo	1000 times
Mega (meg)	1 000 000 times
Milli	One one-thousandth
Micro (mikr)	One millionth

AUSTRIA

ORDINANCE NO. 176, MINISTRY OF COMMERCE, OF JULY 4, 1900

The electrical units are derived from the fundamental metrical units of length, mass, and time, according to the electromagnetic system of measurement, taking the centimeter as the unit of length, the gram as the unit of mass, and the mean solar second, of which there are 86 400 in a mean solar day, as the unit of time. The resulting units are designated as units of the C. G. S. electromagnetic system (centimeter-gram-second system).

Ohm

The unit of resistance is the ohm, which is equal to 10^9 units of resistance of the electromagnetic C. G. S. system. For commercial purposes the ohm may be considered equal to the resistance offered to an unvarying current by a column [22] of mercury having a mass of 14.4521 grams, a length of 106.3 centimeters, at the temperature of melting ice.

Ampere

The unit of current is the ampere, which is equal to the one-tenth part of the electromagnetic unit of current of the C. G. S. system. For commercial purposes the ampere may be considered equal to the value of an unvarying current which when passing through an aqueous solution of silver nitrate deposits 0.001118 gram silver per second.

Volt

The unit of electromotive force is the volt, which is equal to that electromotive force which acting steadily on a conductor having a resistance of 1 ohm produces in the same a current of 1 ampere.

Watt

The unit of power is the watt, which is equal to 10^7 units of power of the C. G. S. system, or equal to the power corresponding to a current of 1 ampere at an electromotive force of 1 volt (voltampere).

Coulomb

The coulomb is equal to the quantity of electricity flowing in one mean solar second through a conductor carrying a current of 1 ampere. One amperehour corresponds to 3600 coulombs.

Watthour

The work done in 3600 seconds in a conductor in which the power is 1 watt is equal to 1 watthour. One hundred watthours are equal to 1 hectowatthour. One thousand watthours are equal to 1 kilowatthour.

FRANCE

DECREE OF THE PRESIDENT, APRIL 25, 1896

Ohm

The unit of electrical resistance—the ohm—is the resistance offered to an unvarying current by a column of mercury at the temperature of melting ice, having a mass of 14.4521 grams, a constant cross section, and a length of 106.3 centimeters.

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[22] No reference is made to a uniform cross section of the mercury column.

Ampere

The electrical unit of current intensity—the ampere—is one-tenth of the electromagnetic unit of current intensity. It is represented sufficiently well for practical purposes by the unvarying current which deposits in one second 0.001118 gram of silver.

Volt

The unit of electromotive force—the volt—is the electromotive force which produces a current of 1 ampere in a conductor having a resistance of 1 ohm. It is represented sufficiently well for practical purposes by 0.6974 (or $\frac{1000}{1434}$), of the electromotive force of the Latimer Clark cell.

SWITZERLAND

FEDERAL LAW ON WEIGHTS AND MEASURES (OF JUNE 24, 1909)—C. ELECTRICAL UNITS

ART. 10. The principal electrical units of legal status are: the international ohm, the international ampere, the international volt, and the international watt.

Ohm

ART. 11. The international ohm is the unit of resistance. It is represented by the resistance offered to an unvarying current by a column of mercury at the temperature of 0° having a mass of 14.4521 grams, a uniform cross section, and a length of 106.300 centimeters.

Ampere

ART. 12. The international ampere is the unit of current intensity. It is represented by the unvarying current the passage of which through a solution of silver nitrate in water causes the deposit of 0.00111800 gram of silver per second.

Amperehour

The quantity of electricity produced by a current of one ampere in one hour is the amperehour.

Volt

ART. 13. The international volt is the unit of electromotive force and of potential difference. It is represented by the unvarying potential difference that, applied to the ends of a circuit containing no electromotive force and having a resistance of one international ohm, produces an unvarying current of one international ampere.

Watt

ART. 14. The international watt is the unit of power. It is the power of an unvarying current of one international ampere under an unvarying potential difference of one international volt.

Watthour

The energy of one international watt during one hour is the watthour.

2. DISCUSSION OF LAWS

Section 2 of the United States act of 1894 required the National Academy of Sciences to prepare specifications for the practical realization of the definitions of the ampere and volt. Accordingly, on February 9, 1895, that body adopted specifications for the silver voltameter and the Clark cell. The specifications were long and have been superseded in practice. Similar specifications, which were written into the laws of other countries, have shared the same fate. Since they are obsolete, the various specifications have not been copied into this appendix, even where they were incorporated in the law.

There has not been much revision of the laws since the London Electrical Conference of 1908. That conference did not introduce any radical changes in the definitions of the electrical units, but did define the "international" units based on specified standards, as distinct from the absolute units from which they are derived. Many of the laws are hazy or contradictory in this matter, most of them having been based on the Chicago definitions of 1893 which were themselves not entirely consistent. A new law, based on the 1908 definitions, has been prepared in France. It passed the French Chamber of Deputies on April 3, 1914, but had not passed the Senate in February, 1915. The only countries which are known to have adopted laws based on the London definitions of 1908 are Great Britain and Switzerland. That of Great Britain supersedes one of 1894 based on the decisions of the Chicago congress. The resolutions of the London conference are generally followed in most countries.

There are no laws upon electric units in Russia, Italy, the Netherlands, Denmark, or Sweden. Definite information has not been obtained regarding countries not mentioned.

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Appendix 4.—SYMBOLS USED IN THIS CIRCULAR

B = magnetic induction
C = electrostatic capacity
c = velocity of light
D = electric displacement
E = electromotive force
$\mathcal{E}$ = electric field intensity
F = force
$\mathfrak{F}$ = magnetomotive force
g = conductance
H = magnetizing force
I = current
J = intensity of magnetization
K = dielectric constant
K_0 = dielectric constant of space
L = l = length
$\mathcal{L}$ = L = self-inductance
M = mass
$\mathcal{M}$ = M = mutual inductance
m = magnetic pole strength
N = number of turns
P = power
Q = quantity of electricity
R = resistance
$\mathcal{R}$ = reluctance
r = distance from a point
S = area
s = length along a path
T = t = time
U = current density
V = electric potential
W = energy
Z = impedance
γ = conductivity
δ = mass resistivity
κ = magnetic susceptibility
μ = permeability
μ_0 = permeability of space
ρ = volume resistivity
σ = strength of a magnetic shell
ϕ = magnetic flux
Ω = magnetic potential