United States Department of Commerce
National Institute of Standards and Technology

NIST Special Publication 330
1991 Edition

The International System of Units (SI)

SI

NIST SPECIAL PUBLICATION 330
1991 EDITION

THE INTERNATIONAL SYSTEM OF UNITS (SI)

United States of America Editor:

Barry N. Taylor
National Institute of Standards and Technology
Gaithersburg, MD 20899

Approved translation of the sixth edition (1991) of the International Bureau of Weights and Measures publication *Le Système International d'Unités (SI)*

(Supersedes NBS Special Publication 330 1986 Edition)

Issued August 1991

U.S. DEPARTMENT OF COMMERCE, Robert A. Mosbacher, Secretary

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, John W. Lyons, Director

National Institute of Standards and Technology Special Publication 330, 1991 Edition
Natl. Inst. Stand. Technol. Spec. Publ. 330, 1991 Edition, 62 pages (Aug. 1991)
CODEN: NSPUE2

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1991

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325

Foreword

This booklet is the United States of America edition of the English-language translation of the sixth edition of *Le Système International d'Unités (SI)*, the definitive reference on the SI published in 1991 by the International Bureau of Weights and Measures (BIPM) in the French language. This USA edition conforms in substance with the English-language translation that follows the French-language text in the BIPM publication. That translation was a joint effort of the BIPM, the National Institute of Standards and Technology (NIST) in the United States, and the National Physical Laboratory (NPL) in the United Kingdom. However, to make this booklet helpful to the broadest community of users in the USA, it was necessary to follow current Federal policy, to recognize present USA practices as they are found in the literature of our domestic voluntary standards organizations such as ASTM and IEEE, and to use American spelling of certain words. Thus, this USA edition differs from the English-language version in the BIPM publication in the following details: (1) the dot is used instead of the comma as the decimal marker; (2) the American spellings "meter," "liter," and "deka" are used instead of "metre," "litre," and "deca"; (3) a small number of footnotes are added for explanatory purposes and to identify USA practices that differ from those suggested in the BIPM publication; (4) in a few instances, American rather than British spelling or usage is followed for a few common words; and (5) the index has been moderately expanded.

This English-language edition, the one prepared by U. K. Editor R. J. Bell at the National Physical Laboratory, and the one included in the BIPM publication, represent the best efforts to render an accurate translation of the French-language text. Nevertheless, in case of disagreement it is always the French text that is authoritative.

The SI or modernized metric system, long the language universally used in science, is rapidly becoming the language of international commerce and trade. In recognition of this fact and the increasing global nature of the market place, the Omnibus Trade and Competitiveness Act of 1988, which changed the name of the National Bureau of Standards (NBS) to the National Institute of Standards and Technology (NIST) and assigned to NIST new responsibilities for assisting industry in the development of technology, designates "the metric system of measurement as the preferred system of weights and measures for United States trade and commerce." Further, the Act requires "that each Federal agency, by a date certain and to the extent economically feasible by the end of the fiscal year 1992, use the metric system of measurement in its procurements, grants, and other business related activities."

I am therefore extremely pleased to present this new USA edition of the definitive publication on the foundation and fundamental principles of the International System of Units to the current USA users of the SI, but especially to the many anticipated future users within the United States. It is my sincere hope that this booklet will contribute to a better understanding within our country of the weights and measures language that is rapidly becoming universal.

July 1991

John W. Lyons,
Director,
National Institute of Standards and Technology

Preface to the 6th Edition

Since 1970, the Bureau International des Poids et Mesures (BIPM), has regularly published this document containing Resolutions and Recommendations of the Conférence Générale des Poids et Mesures (CGPM) and the Comité International des Poids et Mesures (CIPM) on the International System of Units. Explanations have been added as well as relevant extracts from the International Standards of the International Organization for Standardization (ISO) for the practical use of the system.

The Comité Consultatif des Unités (CCU) of the CIPM helped to draft the document and has approved the final text.

Appendix I reproduces in chronological order the decisions (Resolutions, Recommendations, Declarations, etc.) promulgated since 1889 by the CGPM and the CIPM on units of measurement and on the International System of Units.

Appendix II outlines the measurements, consistent with the theoretical definitions given here, which metrological laboratories can make to realize the units and to calibrate highest-quality material standards. Unless otherwise specified, uncertainties are given at the level of one standard deviation.

The 6th edition is a revision of the 5th edition (1985); it takes into consideration the decisions of the 18th CGPM (1987) and the CIPM (1988, 1989, 1990), and the amendments made by the CCU (1990).

The early editions of this document have been used as a work of reference in numerous countries. In order to make the contents more readily accessible for a greater number of readers, the CIPM has decided to include an English-language translation. The BIPM has endeavored to publish the most faithful translation possible through collaboration with the National Physical Laboratory (Teddington, United Kingdom) and the National Institute of Standards and Technology (Gaithersburg, USA). A particular difficulty arises from the slight spelling variations that occur in the scientific language of the English-speaking countries (for instance, "metre" and "meter", "litre" and "liter"). In general, translation follows the Recommendations of ISO (1982) as far as the vocabulary and the spelling of the names of quantities and units are concerned, as well as the writing of numbers. This English translation is not to be considered as an official text. In case of dispute, it is always the French text which is authoritative.

February 1991

T. J. Quinn
Director, BIPM

J. de Boer
President, CCU

The International System of Units

Contents

I. INTRODUCTION

I.1 Historical note

In 1948 the 9th General Conference on Weights and Measures (CGPM†), by its Resolution 6, instructed the International Committee for Weights and Measures (CIPM†):

"to study the establishment of a complete set of rules for units of measurement";

"to find out for this purpose, by official inquiry, the opinion prevailing in scientific, technical, and educational circles in all countries"; and

"to make recommendations on the establishment of a *practical system of units of measurement* suitable for adoption by all signatories to the Meter Convention."†

The same General Conference also laid down, by its Resolution 7, general principles for unit symbols and also gave a list of units with special names.

The 10th CGPM (1954), by its Resolution 6, and the 14th CGPM (1971), by its Resolution 3, adopted as base units of this "practical system of units," the units of the following seven quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity.

The 11th CGPM (1960), by its Resolution 12, adopted the name *International System of Units*, with the international abbreviation SI, for this practical system of units of measurement, and laid down rules for the prefixes, the derived and supplementary units, and other matters, thus establishing a comprehensive specification for units of measurement.

I.2 The three classes of SI units

SI units are divided into three classes:

base units, *derived* units, and *supplementary* units.

From the scientific point of view, division of SI units into these three classes is to a certain extent arbitrary, because it is not essential to the physics of the subject.

Nevertheless, the General Conference, considering the advantages of a single, practical, worldwide system of units for international relations, for teaching, and for scientific work, decided to base the International System on a choice of seven well-defined units which by convention are regarded as dimensionally independent: the meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela (see II.1, p. 3). These SI units are called *base units*.

The second class of SI units contains *derived units*, i.e., units that can be formed by combining base units according to the algebraic relations linking the corresponding quantities. The names and symbols of some units thus formed in terms of base units can be replaced by special names and symbols which can themselves be used to form expressions and symbols of other derived units (see II.2, p. 6).

The 11th CGPM (1960) admitted a third class of SI units, called *supplementary units* and containing the SI units of plane and solid angle (see II.3, p. 8).

---

† USA Editor's note: See Appendix III, p. 52, for a discussion of the CGPM, the CIPM, the Meter Convention, and the International Bureau of Weights and Measures (BIPM). In a number of places in the French-language text, CGPM, CIPM, and other organizational names are spelled out while in the English-language text abbreviations are used.

The SI units of these three classes form a coherent set of units in the sense normally attributed to the word "coherent", i.e., a system of units mutually related by rules of multiplication and division without any numerical factor. Following CIPM Recommendation 1 (1969), the units of this coherent set of units are designated by the name *SI units*.

It is important to emphasize that each physical quantity has only one SI unit, even if the name of this unit can be expressed in different forms, but the inverse is not true: the same SI unit name can correspond to several different quantities (see p. 7).

I.3 The SI prefixes

The General Conference has adopted a series of prefixes to be used in forming the decimal multiples and submultiples of SI units (see III.1, p. 10). Following CIPM Recommendation 1 (1969), the set of prefixes is designated by the name *SI prefixes*.

The multiples and submultiples of SI units, which are formed by using the SI prefixes, should be designated by their complete name, *multiples and submultiples of SI units*, in order to make a distinction between them and the coherent set of SI units proper.

I.4 System of quantities

This book does not deal with the system of quantities used with the SI units, an area handled by Technical Committee 12 of the *International Organization for Standardization* (ISO) which, since 1955, has published a series of International Standards on quantities and their units, and which strongly recommends the use of the International System of Units.[1]

In these International Standards, ISO has adopted a system of physical quantities based on the seven base quantities: length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity. The other quantities—the derived quantities—are defined in terms of these seven base quantities; the relationships between the derived quantities and the base quantities are expressed by a system of equations. It is this system of quantities and equations that is properly used with the SI units.

I.5 Legislation on units

Countries have established, through legislation, rules concerning the use of units on a national basis, either for general use, or for specific areas such as commerce, health or public safety, education, etc. In a growing number of countries this legislation is based on the use of the International System of Units.

The *International Organization of Legal Metrology* (OIML), founded in 1955, is concerned with the international harmonization of this legislation.

---

[1] ISO 31, in "Units of measurement," ISO Standards Handbook 2, 2nd Edition, ISO, Geneva, 1982, pp. 17–238.

II. SI UNITS

II.1 SI base units

II.1.1 *Definitions*

(a) unit of length (meter)

The definition of the meter based upon the international prototype of platinum-iridium, in force since 1889, had been replaced by the 11th CGPM (1960) by a definition based upon the wavelength of a krypton-86 radiation. In order to increase the precision of realization of the meter, the 17th CGPM (1983) replaced this latter definition by the following:

The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 *of a second* (17th CGPM (1983), Resolution 1).

The old international prototype of the meter which was sanctioned by the 1st CGPM in 1889 is still kept at the International Bureau of Weights and Measures (BIPM) under the conditions specified in 1889.

(b) unit of mass (kilogram)

The 1st CGPM (1889) sanctioned the international prototype of the kilogram and declared: *this prototype shall henceforth be considered to be the unit of mass.*

The 3d CGPM (1901), in a declaration intended to end the ambiguity which existed as to the meaning of the word "weight" in popular usage, confirmed that the *kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram* (see the complete declaration, p. 17).

This international prototype, made of platinum-iridium, is kept at the BIPM under conditions specified by the 1st CGPM in 1889.

(c) unit of time (second)

The unit of time, the second, was defined originally as the fraction 1/86 400 of the mean solar day. The exact definition of "mean solar day" was left to astronomers, but their measurements have shown that on account of irregularities in the rotation of the Earth, the mean solar day does not guarantee the desired accuracy. In order to define the unit of time more precisely, the 11th CGPM (1960) adopted a definition given by the International Astronomical Union which was based on the tropical year. Experimental work had, however, already shown that an atomic standard of time-interval, based on a transition between two energy levels of an atom or a molecule, could be realized and reproduced much more accurately. Considering that a very precise definition of the unit of time of the International System, the second, is indispensable for the needs of advanced metrology, the 13th CGPM (1967) decided to replace the definition of the second by the following:

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom (13th CGPM (1967), Resolution 1).

(d) unit of electric current (ampere)

Electric units, called "international," for current and resistance had been introduced by the International Electrical Congress held in Chicago in 1893, and the definitions of the "international" ampere and the "international" ohm were confirmed by the International Conference of London in 1908.

Although it was already obvious on the occasion of the 8th CGPM (1933) that there was a unanimous desire to replace those "international" units by so-called "absolute" units, the official decision to abolish them was only taken by the 9th

CGPM (1948), which adopted for the unit of electric current, the ampere, the following definition:

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} *newton per meter of length* (CIPM (1946), Resolution 2 approved by the 9th CGPM, 1948).

The expression "MKS unit of force" which occurs in the original text has been replaced here by "newton," the name adopted for this unit by the 9th CGPM (1948, Resolution 7).

(e) unit of thermodynamic temperature (kelvin)

The definition of the unit of thermodynamic temperature was given in substance by the 10th CGPM (1954, Resolution 3) which selected the triple point of water as the fundamental fixed point and assigned to it the temperature 273.16 K by definition. The 13th CGPM (1967, Resolution 3) adopted the name *kelvin* (symbol K) instead of "degree Kelvin" (symbol °K) and in its Resolution 4 defined the unit of thermodynamic temperature as follows:

The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (13th CGPM (1967), Resolution 4).

The 13th CGPM (1967, Resolution 3) also decided that the unit kelvin and its symbol K should be used to express an interval or a difference of temperature.

Note: In addition to the thermodynamic temperature (symbol T), expressed in kelvins, use is also made of Celsius temperature (symbol t) defined by the equation

$$t = T - T_0$$

where $T_0 = 273.15$ K by definition. To express Celsius temperature, the unit "degree Celsius," which is equal to the unit "kelvin," is used; in this case, "degree Celsius" is a special name used in place of "kelvin." An interval or difference of Celsius temperature can, however, be expressed in kelvins as well as in degrees Celsius.

(f) unit of amount of substance (mole)

Since the discovery of the fundamental laws of chemistry, units of amount of substance called, for instance, "gram-atom" and "gram-molecule," have been used to specify amounts of chemical elements or compounds. These units had a direct connection with "atomic weights" and "molecular weights," which were in fact relative masses. "Atomic weights" were originally referred to the atomic weight of oxygen (by general agreement taken as 16). But whereas physicists separated isotopes in the mass spectrograph and attributed the value 16 to one of the isotopes of oxygen, chemists attributed that same value to the (slightly variable) mixture of isotopes 16, 17, and 18, which was for them the naturally occurring element oxygen. Finally, an agreement between the International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) brought this duality to an end in 1959/60. Physicists and chemists have ever since agreed to assign the value 12 to the isotope 12 of carbon. The unified scale thus obtained gives values of "relative atomic mass."

It remained to define the unit of amount of substance by fixing the corresponding mass of carbon 12; by international agreement, this mass has been fixed at 0.012 kg, and the unit of the quantity "amount of substance"[2] has been given the name *mole* (symbol mol).

---

[2] The name of this quantity, adopted by IUPAP, IUPAC, and ISO is in French "quantité de matière" and in English "amount of substance"; the German and Russian translations are "Stoffmenge" and " количество вещества " ("kolichestvo veshchestva"). The French name recalls "quantitas materiae" by which in the past the quantity now called "mass" used to be known; we must forget this old meaning, for mass and amount of substance are entirely different quantities.

Following proposals of IUPAP, IUPAC, and ISO, the CIPM gave in 1967, and confirmed in 1969, a definition of the mole, eventually adopted by the 14th CGPM (1971, Resolution 3):

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

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

In the definition of the mole, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

Note that this definition specifies at the same time the nature of the quantity whose unit is the mole.

(g) unit of luminous intensity (candela) The units of luminous intensity based on flame or incandescent filament standards in use in various countries before 1948 were replaced initially by the "new candle" based on the luminance of a Planckian radiator (a blackbody) at the temperature of freezing platinum. This decision had been prepared by the International Commission on Illumination (CIE) and by the CIPM before 1937, and was promulgated by the CIPM in 1946, and then ratified in 1948 by the 9th CGPM which adopted a new international name for this unit, the *candela* (symbol cd); in 1967 the 13th CGPM gave an amended version of the 1946 definition.

Because of the experimental difficulties in realizing a Planck radiator at high temperatures and the new possibilities offered by radiometry, i.e., the measurement of optical radiation power, the 16th CGPM adopted in 1979 the following new definition:

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} *hertz and that has a radiant intensity in that direction of (1/683) watt per steradian* (16th CGPM (1979), Resolution 3).

II.1.2 *Symbols*

The base units of the International System are collected in table 1 with their names and their symbols (10th CGPM (1954), Resolution 6; 11th CGPM (1960), Resolution 12; 13th CGPM (1967), Resolution 3; 14th CGPM (1971), Resolution 3).

TABLE 1

SI base units

Quantity[a]	SI Unit	
	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

[a] Translator's note: "Quantity" is the technical word for measurable attributes of phenomena or matter.

II.2 SI derived units

Derived units are expressed algebraically in terms of base units by means of the mathematical symbols of multiplication and division (see table 2 for some examples).

TABLE 2

Examples of SI derived units expressed in terms of base units

Quantity	SI Unit	
	Name	Symbol
area	square meter	m^2
volume	cubic meter	m^3
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s^2
wave number	reciprocal meter	m^{-1}
density, mass density	kilogram per cubic meter	kg/m^3
specific volume	cubic meter per kilogram	m^3/kg
current density	ampere per square meter	A/m^2
magnetic field strength	ampere per meter	A/m
concentration (of amount of substance)	mole per cubic meter	mol/m^3
luminance	candela per square meter	cd/m^2

Certain derived units have been given special names and symbols. These names and symbols are given in tables 3 and 3′; they may themselves be used to express other derived units (see table 4 for some examples).

In tables 3, 3′, 4, and 5, the final column gives expressions for the SI units concerned in terms of SI base units. In this column, factors such as m^0, kg^0, etc. that are equal to 1 are not generally shown explicitly.

TABLE 3

SI derived units with special names

Quantity	SI Unit			
	Name	Symbol	Expression in terms of other units	Expression in terms of SI base units
frequency	hertz	Hz		s^{-1}
force	newton	N		$m \cdot kg \cdot s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
power, radiant flux	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
electric charge, quantity of electricity	coulomb	C		$s \cdot A$
electric potential, potential difference, electromotive force	volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
capacitance	farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
electric resistance	ohm	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductance	siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
inductance	henry	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Celsius temperature[(a)]	degree Celsius	°C		K
luminous flux	lumen	lm		$cd \cdot sr$[(b)]
illuminance	lux	lx	lm/m^2	$m^{-2} \cdot cd \cdot sr$[(b)]

[(a)] See p. 4, (e), *Note*.
[(b)] In photometry, the symbol sr is maintained in expressions for units (see II.3., p. 8).

TABLE 3'

SI derived units with special names admitted for reasons of safeguarding human health

Quantity	SI Unit			
	Name	Symbol	Expression in terms of other units	Expression in terms of SI base units
activity (of a radionuclide)	becquerel	Bq		s^{-1}
absorbed dose, specific energy imparted, kerma, absorbed dose index	gray	Gy	J/kg	$m^2 \cdot s^{-2}$
dose equivalent, dose equivalent index	sievert	Sv	J/kg	$m^2 \cdot s^{-2}$

TABLE 4

Examples of SI derived units expressed by means of special names

Quantity	SI Unit		
	Name	Symbol	Expression in terms of SI base units
dynamic viscosity	pascal second	Pa · s	$m^{-1} \cdot kg \cdot s^{-1}$
moment of force	newton meter	N · m	$m^2 \cdot kg \cdot s^{-2}$
surface tension	newton per meter	N/m	$kg \cdot s^{-2}$
heat flux density, irradiance	watt per square meter	W/m^2	$kg \cdot s^{-3}$
heat capacity, entropy	joule per kelvin	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg · K)	$m^2 \cdot s^{-2} \cdot K^{-1}$
specific energy	joule per kilogram	J/kg	$m^2 \cdot s^{-2}$
thermal conductivity	watt per meter kelvin	W/(m · K)	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
energy density	joule per cubic meter	J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
electric field strength	volt per meter	V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
electric charge density	coulomb per cubic meter	C/m^3	$m^{-3} \cdot s \cdot A$
electric flux density	coulomb per square meter	C/m^2	$m^{-2} \cdot s \cdot A$
permittivity	farad per meter	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
permeability	henry per meter	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
molar energy	joule per mole	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
molar entropy, molar heat capacity	joule per mole kelvin	J/(mol · K)	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
exposure (x and γ rays)	coulomb per kilogram	C/kg	$kg^{-1} \cdot s \cdot A$
absorbed dose rate	gray per second	Gy/s	$m^2 \cdot s^{-3}$

A single SI unit name may correspond to several different quantities, as has been mentioned in paragraph I.2 (p. 2). In the above tables, where the list of quantities is not exhaustive, one finds several examples. Thus the joule per kelvin (J/K) is the SI unit for the quantity heat capacity as well as for the quantity entropy; also the ampere (A) is the SI unit for the base quantity electric current as well as for the derived quantity magnetomotive force. The name of the unit is thus not sufficient to define the quantity measured; in particular, measuring instruments should indicate not only the unit but also the measured quantity concerned.

A derived unit can often be expressed in several different ways by using names of base units and special names of derived units: for example, in place of joule one may write newton meter or even kilogram meter squared per second squared. However, this algebraic freedom is governed by common-sense physical considerations.

In practice, with certain quantities one gives preference to using certain special unit names, or certain combinations of units, in order to facilitate the distinction between quantities having the same dimension. For example, one designates the SI unit of frequency as the hertz rather than the reciprocal second, and one designates the SI unit of moment of force as the newton meter rather than the joule.

In the field of ionizing radiation, in the same way one designates the SI unit of activity as the becquerel rather than the reciprocal second and the SI units of absorbed dose and dose equivalent as gray and sievert, respectively, rather than the joule per kilogram.[3]

Note: *Quantities expressed as pure numbers.* Certain so-called dimensionless quantities, as for example refractive index, relative permeability, or friction factor, are defined as the ratio of two comparable quantities. Such quantities have a dimensional product—or dimension— equal to 1 and are therefore expressed by pure numbers. The coherent SI unit is then the ratio of two identical SI units and may be expressed by the number 1.

II.3 SI supplementary units

This class contains two units: the SI unit of plane angle, the *radian,* and the SI unit of solid angle, the *steradian* (11th CGPM (1960), Resolution 12).

Considering that plane angle is generally expressed as the ratio between two lengths and solid angle as the ratio between an area and the square of a length, and in order to maintain the internal coherence of the International System based on only seven base units, the CIPM (1980) specified that, in the International System, the supplementary units radian and steradian are dimensionless derived units. This implies that the quantities plane angle and solid angle are considered as dimensionless derived quantities.

TABLE 5

SI supplementary units

	SI Unit		
Quantity	Name	Symbol	Expression in terms of SI base units
plane angle	radian	rad	$m \cdot m^{-1} = 1$
solid angle	steradian	sr	$m^2 \cdot m^{-2} = 1$

These supplementary units may be used in expressions for derived units to facilitate distinguishing between quantities of different nature but the same dimension. Some examples of the use of supplementary units in forming derived units are given in table 6.

[3] See p. 39, Recommendation 1 (CI-1984) adopted by the CIPM.

TABLE 6

Examples of SI derived units formed by using supplementary units

Quantity	SI Unit	
	Name	Symbol
angular velocity	radian per second	rad/s
angular acceleration	radian per second squared	rad/s^2
radiant intensity	watt per steradian	W/sr
radiance	watt per square meter steradian	$W/(m^2 \cdot sr)$

II.4 Rules for writing and using SI unit symbols

The general principles concerning writing the unit symbols were adopted by the 9th CGPM (1948, Resolution 7):

1. Roman (upright) type, in general lower case, is used for the unit symbols. If, however, the name of the unit is derived from a proper name, the first letter of the symbol is in upper case.

2. Unit symbols are unaltered in the plural.

3. Unit symbols are not followed by a period.

To insure uniformity in the use of the SI unit symbols, ISO International Standards give certain recommendations. Following these recommendations:

a) The product of two or more units may be indicated in either of the following ways,†

for example: N·m or N m.

b) A solidus (oblique stroke, /), a horizontal line, or negative exponents may be used to express a derived unit formed from two others by division,

for example: m/s, $\frac{m}{s}$, or $m \cdot s^{-1}$

c) The solidus must not be repeated on the same line unless ambiguity is avoided by parentheses. In complicated cases negative exponents or parentheses should be used,

for example: m/s^2 or $m \cdot s^{-2}$ *but not*: m/s/s

$m \cdot kg/(s^3 \cdot A)$ or $m \cdot kg \cdot s^{-3} \cdot A^{-1}$ *but not*: $m \cdot kg/s^3/A$

† USA Editor's note: See American National Standard ANSI/IEEE Std 268-1982 Metric Practice, which states that in USA practice only the raised dot is to be commonly used.

III. DECIMAL MULTIPLES AND SUBMULTIPLES OF SI UNITS

III.1 SI prefixes

The 11th CGPM (1960, Resolution 12) adopted a first series of prefixes and symbols of prefixes to form the names and symbols of the decimal multiples and submultiples of SI units. Prefixes for 10^{-15} and 10^{-18} were added by the 12th CGPM (1964, Resolution 8), those for 10^{15} and 10^{18} by the 15th CGPM (1975, Resolution 10), and those for 10^{21}, 10^{24}, 10^{-21}, and 10^{-24} were proposed by the CIPM (1990) for approval by the 19th CGPM (1991).

TABLE 7

SI prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	µ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka†	da	10^{-24}	yocto	y

III.2 Rules for using SI prefixes

In accord with the general principles adopted by the ISO, the CIPM recommends that the following rules for using the SI prefixes be observed:

1. Prefix symbols are printed in roman (upright) type without spacing between the prefix symbol and the unit symbol.

2. The grouping formed by the prefix symbol attached to the unit symbol constitutes a new inseparable symbol (of a multiple or submultiple of the unit concerned) which can be raised to a positive or negative power and which can be combined with other unit symbols to form compound unit symbols,

for example:

$$1\ \mathrm{cm}^3 = (10^{-2}\ \mathrm{m})^3 = 10^{-6}\ \mathrm{m}^3$$
$$1\ \mathrm{cm}^{-1} = (10^{-2}\ \mathrm{m})^{-1} = 10^2\ \mathrm{m}^{-1}$$
$$1\ \mu\mathrm{s}^{-1} = (10^{-6}\ \mathrm{s})^{-1} = 10^6\ \mathrm{s}^{-1}$$
$$1\ \mathrm{V/cm} = (1\ \mathrm{V})/(10^{-2}\ \mathrm{m}) = 10^2\ \mathrm{V/m}$$

3. Compound prefixes, i.e., prefixes formed by the juxtaposition of two or more SI prefixes, are not to be used,

for example: 1 nm *but not*: 1 mµm

4. A prefix should never be used alone

for example: $10^6/\mathrm{m}^3$ *but not*: $\mathrm{M/m}^3$

† USA Editor's note: Outside the USA, the spelling "deca" is extensively used.

III.3 The kilogram

Among the base units of the International System, the unit of mass is the only one whose name, for historical reasons, contains a prefix. Names of decimal multiples and submultiples of the unit of mass are formed by attaching prefixes to the word "gram" (CIPM (1967), Recommendation 2),

for example: 10^{-6} kg = 1 milligram (1 mg) *but not*: 1 microkilogram (1 μkg).

IV. UNITS OUTSIDE THE INTERNATIONAL SYSTEM

IV.1 Units used with the International System

The CIPM (1969) recognized that users of SI will also wish to employ with it certain units not part of it, but which are important and are widely used. These units are given in table 8. The combination of units of this table with SI units to form compound units should be restricted to special cases in order not to lose the advantage of the coherence of SI units.

TABLE 8

Units in use with the International System

Name	Symbol	Value in SI units
minute	min	1 min = 60 s
hour[(a)]	h	1 h = 60 min = 3600 s
day	d	1 d = 24 h = 86 400 s
degree	°	1 ° = (π/180) rad
minute	′	1 ′ = (1/60)° = (π/10 800) rad
second	″	1 ″ = (1/60)′ = (π/648 000) rad
liter[(b)]†	l, L	1 L = 1 dm^3 = 10^{-3} m^3
tonne[(c)(d)]‡	t	1 t = 10^3 kg

[(a)] The symbol of this unit is included in Resolution 7 of the 9th CGPM (1948).
[(b)] This unit and the symbol l were adopted by CIPM in 1879 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1879, p. 41). The alternative symbol, L, was adopted by the 16th CGPM (1979, Resolution 6) in order to avoid the risk of confusion between the letter l and the number 1.† The present definition of the liter is in Resolution 6 of the 12th CGPM (1964).
[(c)] This unit and its symbol were adopted by the International Committee in 1879 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1879, p. 41).
[(d)] In some English-speaking countries this unit is called "metric ton."‡

It is likewise necessary to recognize, outside the International System, some other units that are useful in specialized fields, because their values expressed in SI units must be obtained by experiment, and are therefore not known exactly (table 9).

TABLE 9

Units used with the International System whose values in SI units are obtained experimentally[(a)]

Name	Symbol	Definition
electronvolt	eV	[(b)]
unified atomic mass unit	u	[(c)]

[(a)] 1 eV = 1.602 177 33 (49) × 10^{-19} J,
1 u = 1.660 540 2 (10) × 10^{-27} kg,
values from *CODATA Bulletin*, No. 63, 1986; the uncertainty of the last two figures, at the level of one standard deviation, is shown in parentheses.
[(b)] The electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of 1 volt in vacuum.
[(c)] The unified atomic mass unit is equal to (1/12) of the mass of an atom of the nuclide ^{12}C.

† USA Editor's note: See the Federal Register Notice of December 20, 1990, "Metric System of Measurement; Interpretation of the International System of Units for the United States" (55 FR 522 42-522 45) and American National Standard ANSI/IEEE Std 268-1982 Metric Practice, which state that the recommended symbol for liter in the USA is L.

‡ USA Editor's note: See the above Federal Register Notice and American National Standard which state that the name to be used for this unit in the USA is "metric ton."

IV.2 Units in use temporarily

In view of existing practice in certain fields or countries, the CIPM (1978) considered that it was acceptable for those units listed in table 10 to continue to be used with SI units until the CIPM considers their use no longer necessary. However, these units should not be introduced where they are not used at present.

TABLE 10

Units in use temporarily with the International System

Name	Symbol	Value in SI units
nautical mile[(a)]		1 nautical mile = 1852 m
knot		1 nautical mile per hour = (1852/3600) m/s
ångström	Å	1 Å = 0.1 nm = 10^{-10} m
are[(b)]	a	1 a = 1 dam^2 = 10^2 m^2
hectare[(b)]†	ha	1 ha = 1 hm^2 = 10^4 m^2
barn[(c)]	b	1 b = 100 fm^2 = 10^{-28} m^2
bar[(d)]	bar	1 bar = 0.1 MPa = 100 kPa = 1000 hPa = 10^5 Pa
gal[(e)]	Gal	1 Gal = 1 cm/s^2 = 10^{-2} m/s^2
curie[(f)]	Ci	1 Ci = 3.7×10^{10} Bq
roentgen[(g)]	R	1 R = 2.58×10^{-4} C/kg
rad[(h)]	rad	1 rad = 1 cGy = 10^{-2} Gy
rem[(i)]	rem	1 rem = 1 cSv = 10^{-2} Sv

[(a)] The nautical mile is a special unit employed for marine and aerial navigation to express distances. The conventional value given above was adopted by the First International Extraordinary Hydrographic Conference, Monaco, 1929, under the name "International nautical mile."

[(b)] This unit and its symbol were adopted by the CIPM in 1879 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures,* 1879, p. 41) and are used to express agrarian areas.

[(c)] The barn is a special unit employed in nuclear physics to express effective cross sections.

[(d)] This unit and its symbol are included in Resolution 7 of the 9th CGPM (1948).

[(e)] The gal is a special unit employed in geodesy and geophysics to express the acceleration due to gravity.

[(f)] The curie is a special unit employed in nuclear physics to express activity of radionuclides (12th CGPM (1964), Resolution 7).

[(g)] The roentgen is a special unit employed to express exposure of x or γ radiations.

[(h)] The rad is a special unit employed to express absorbed dose of ionizing radiations. When there is risk of confusion with the symbol for radian, rd may be used as the symbol for rad.

[(i)] The rem is a special unit used in radioprotection to express dose equivalent.

† USA Editor's note: In recommended USA practice, the unit "hectare" is considered to be a unit in use with the International System, i.e., it is considered to be part of table 8. See the Federal Register Notice and American National Standard referred to at the bottom of page 12.

IV.3 CGS units

In the field of mechanics, the CGS system of units was based upon three base units: the centimeter, the gram, and the second. In the field of electricity and magnetism, units were expressed in terms of these three base units; this led to the establishment of several different systems, for example the CGS Electrostatic System, the CGS Electromagnetic System, and the CGS Gaussian System. In these three last-mentioned systems, the system of quantities and the corresponding system of equations are often different from those used with SI units.

The CIPM considers that it is in general preferable not to use, with the units of the International System, CGS units that have special names.[4] Such units are listed in table 11.

TABLE 11

CGS units with special names

Name	Symbol	Value in SI units
erg[a]	erg	1 erg = 10^{-7} J
dyne[a]	dyn	1 dyn = 10^{-5} N
poise[a]	P	1 P = 1 dyn · s/cm² = 0.1 Pa · s
stokes	St	1 St = 1 cm²/s = 10^{-4} m²/s
gauss[b]	Gs, G	1 Gs corresponds to 10^{-4} T
oersted[b]	Oe	1 Oe corresponds to $(1000/4\pi)$ A/m
maxwell[b]	Mx	1 Mx corresponds to 10^{-8} Wb
stilb[b]	sb	1 sb = 1 cd/cm² = 10^4 cd/m²
phot	ph	1 ph = 10^4 lx

[a] This unit and its symbol were included in Resolution 7 of the 9th CGPM (1948).
[b] This unit is part of the so-called "electromagnetic" 3-dimensional CGS system and cannot strictly speaking be compared to the corresponding unit of the International System, which has four dimensions when only mechanical and electric quantities are considered.

[4] The aim of the International System of Units and of the recommendations contained in this document is to secure a greater degree of uniformity, hence a better mutual understanding of the general use of units. Nevertheless, in certain specialized fields of scientific research, in particular in theoretical physics, there may sometimes be very good reasons for using other systems or other units.

Whichever units are used, it is important that the *symbols* employed for them follow current international recommendations.

IV.4 Other units

As regards units outside the International System which do not come under sections IV.1, 2, and 3, the CIPM considers that it is in general preferable to avoid them, and to use instead units of the International System. Some of those units are listed in table 12.

TABLE 12

Other units generally deprecated

Name	Value in SI units
fermi	1 fermi = 1 fm = 10^{-15} m
metric carat[(a)]	1 metric carat = 200 mg = 2×10^{-4} kg
torr	1 torr = (101 325/760) Pa
standard atmosphere (atm)[(b)]	1 atm = 101 325 Pa
kilogram-force (kgf)	1 kgf = 9.806 65 N
calorie (cal)[(c)]	
micron (μ)[(d)]	1 μ = 1 μm = 10^{-6} m
x unit[(e)]	
stere (st)[(f)]	1 st = 1 m^3
gamma (γ)	1 γ = 1 nT = 10^{-9} T
γ[(g)]	1 γ = 1 μg = 10^{-9} kg
λ[(h)]	1 λ = 1 μL = 10^{-6} L = 10^{-9} m^3

[(a)] This name was adopted by the 4th CGPM (1907, pp. 89-91) for commercial dealings in diamonds, pearls, and precious stones.
[(b)] Resolution 4 of the 10th CGPM (1954). The designation "standard atmosphere" for a reference pressure of 101 325 Pa is still acceptable.
[(c)] Several "calories" have been in use:
— a calorie labeled "at 15 °C": 1 cal_{15} = 4.185 5 J [value adopted by the CIPM in 1950 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures* 22, 1950, pp. 79-80)];
— a calorie labeled "IT" (International Table): 1 cal_{IT} = 4.186 8 J (5th International Conference on the Properties of Steam, London, 1956);
— a calorie labeled "thermochemical": 1 cal_{th} = 4.184 J.
[(d)] The name of this unit and its symbol, adopted by the CIPM in 1879 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures,* 1879, p. 41) and repeated in Resolution 7 of the 9th CGPM (1948) were abolished by the 13th CGPM (1967, Resolution 7).
[(e)] This special unit was employed to express wavelengths of x rays; 1 x unit = 1.002×10^{-4} nm approximately.
[(f)] This special unit employed to measure firewood was adopted by the CIPM in 1879 with the symbol "s" (*BIPM Proc.-Verb. Com. Int. Poids et Mesures,* 1879, p. 41). The 9th CGPM (1948, Resolution 7) changed the symbol to "st."
[(g)] This symbol is mentioned in *BIPM Proc.-Verb. Com. Int. Poids et Mesures,* 1880, p. 56.
[(h)] This symbol is mentioned in *BIPM Proc.-Verb. Com. Int. Poids et Mesures,* 1880, p. 30.

APPENDIX I

Decisions of the CGPM and the CIPM

The more important decisions abrogated, modified, or added to, are indicated by an asterisk (*). These references and the footnotes have been added by the BIPM to make understanding of the text easier.

CR: *Comptes rendus des séances de la Conférence Générale des Poids et Mesures* (CGPM)
PV: *Procès-Verbaux des séances du Comité International des Poids et Mesures* (CIPM)

1st CGPM, 1889

meter
kilogram

Sanction of the international prototypes of the meter and the kilogram (CR, pp. 34–38)

The General Conference,

considering

the "Compte rendu of the President of the CIPM" and the "Report of the CIPM," which show that, by the collaboration of the French section of the international Meter Commission and of the CIPM, the fundamental measurements of the international and national prototypes of the meter and of the kilogram have been made with all the accuracy and reliability that the present state of science permits;

that the international and national prototypes of the meter and the kilogram are made of an alloy of platinum with 10 percent iridium, to within 0.0001;

the equality in length of the international Meter and the equality in mass of the international Kilogram with the length of the Meter and the mass of the Kilogram kept in the Archives of France;

that the differences between the national Meters and the international Meter lie within 0.01 millimeter and that these differences are based on a hydrogen thermometer scale which can always be reproduced thanks to the stability of hydrogen, provided identical conditions are secured;

that the differences between the national Kilograms and the international Kilogram lie within 1 milligram;

that the international Meter and Kilogram and the national Meters and Kilograms fulfill the requirements of the Meter Convention,

sanctions

A. As regards international prototypes:

1. The Prototype of the meter chosen by the CIPM.
This prototype, at the temperature of melting ice, shall henceforth represent the metric unit of length.*

2. The Prototype of the kilogram adopted by the CIPM.
This prototype shall henceforth be considered as the unit of mass.

3. The hydrogen thermometer centigrade scale in terms of which the equations of the prototype Meters have been established.

* Definition abrogated in 1960 (see p. 24, 11th CGPM, Resolution 6).

B. As regards national prototypes:

. . . .

3d CGPM, 1901

liter

Declaration concerning the definition of the liter (CR, p. 38)*

. . . .

The Conference declares:

1. The unit of volume, for high accuracy determinations, is the volume occupied by a mass of 1 kilogram of pure water, at its maximum density and at standard atmospheric pressure; this volume is called "liter."*

2. . . . .

* Definition abrogated in 1964 (see p. 27, 12th CGPM, Resolution 6)

mass and weight g_n

Declaration on the unit of mass and on the definition of weight; conventional value of g_n (CR, p. 70)

Taking into account the decision of the CIPM of 15 October 1887, according to which the kilogram has been defined as a unit of mass;[1]

Taking into account the decision contained in the sanction of the prototypes of the Metric System, unanimously accepted by the CGPM on 26 September 1889;

Considering the necessity to put an end to the ambiguity which in current practice still exists on the meaning of the word *weight*, used sometimes for *mass*, sometimes for *mechanical force*;

The Conference declares:

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

"2. The word weight denotes a quantity of the same nature as a *force*; the weight of a body is the product of its mass and the acceleration due to gravity; in particular, the standard weight of a body is the product of its mass and the standard acceleration due to gravity;[†]

"3. The value adopted in the International Service of Weights and Measures for the standard acceleration due to gravity is 980.665 cm/s^2, value already stated in the laws of some countries."[2]

---

[1] "The mass of the international Kilogram is taken as the unit for the International Service of Weights and Measures" (PV, 1887, p. 88).

[2] This conventional reference "standard value" (g_n = 9.806 65 m/s^2) was confirmed in 1913 by the 5th CGPM (CR, p. 44). This value should be used for reduction to standard gravity of measurements made in any location on Earth.

[†] USA Editor's note: In the USA, ambiguity exists in the use of the term weight as a quantity to mean either force or mass. In science and technology this declaration [CGPM (1901)] is usually followed, with the newton the SI unit of force and thus weight. In commercial and everday use, weight is often used in the sense of mass for which the SI unit is the kilogram.

7th CGPM, 1927

meter

Definition of the meter by the international Prototype (CR, p. 49)*

The unit of length is the meter, defined by the distance, at 0°, between the axes of the two central lines marked on the bar of platinum-iridium kept at the BIPM, and declared Prototype of the meter by the 1st CGPM, this bar being subject to standard atmospheric pressure and supported on two cylinders of at least one centimeter diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other.*

* Definition abrogated in 1960 (see p. 24, 11th CGPM, Resolution 6).

CIPM, 1946

photometric units

Definitions of photometric units (PV, **20**, p. 119)

RESOLUTION [3]

. . . .

4. The photometric units may be defined as follows:

New candle (unit of luminous intensity). The value of the new candle is such that the brightness of the full radiator at the temperature of solidification of platinum is 60 new candles per square centimeter.*

New lumen (unit of luminous flux). The new lumen is the luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of 1 new candle.

5. . . . .

* Definition modified in 1967 (see p. 30, 13th CGPM, Resolution 5).

mechanical and electric units

Definitions of electric units (PV, **20**, 131)

RESOLUTION 2 [4]

. . . .

4. A) Definitions of the mechanical units which enter the definitions of electric units:

Unit of force. The unit of force [in the MKS (meter, kilogram, second) system] is the force which gives to a mass of 1 kilogram an acceleration of 1 meter per second, per second.

Joule (unit of energy or work). The joule is the work done when the point of application of 1 MKS unit of force [newton] moves a distance of 1 meter in the direction of the force.

Watt (unit of power). The watt is the power which in one second gives rise to energy of 1 joule.

---

[3] The two definitions contained in this Resolution were ratified by the 9th CGPM (1948), which also approved the name *candela* given to the "new candle" (CR, p. 54). For the lumen the qualifier "new" was later abandoned.

[4] The definitions contained in this Resolution 2 were approved by the 9th CGPM (1948) (CR, p. 49), which moreover adopted the name *newton* (Resolution 7) for the MKS unit of force.

B) Definitions of electric units. The CIPM accepts the following propositions which define the theoretical value of the electric units:

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

Volt (unit of potential difference and of electromotive force). The volt is the difference of electric potential between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

Ohm (unit of electric resistance). The ohm is the electric resistance between two points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force.

Coulomb (unit of quantity of electricity). The coulomb is the quantity of electricity carried in 1 second by a current of 1 ampere.

Farad (unit of capacitance). The farad is the capacitance of a capacitor between the plates of which there appears a potential difference of 1 volt when it is charged by a quantity of electricity of 1 coulomb.

Henry (unit of electric inductance). The henry is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at the rate of 1 ampere per second.

Weber (unit of magnetic flux). The weber is the magnetic flux which, linking a circuit of one turn, would produce in it an electromotive force of 1 volt if it were reduced to zero at a uniform rate in 1 second.

9th CGPM, 1948

thermodynamic scale
unit of quantity of heat

Triple point of water; thermodynamic scale with a single fixed point; unit of quantity of heat (joule) (CR, pp. 55 and 63)

Resolution 3 [5]

1. With present-day techniques, the triple point of water is capable of providing a thermometric reference point with an accuracy higher than can be obtained from the melting point of ice.

In consequence the Consultative Committee for Thermometry and Calorimetry (CCTC) considers that the zero of the centesimal thermodynamic scale must be defined as the temperature 0.0100 degree below that of the triple point of water.

2. The CCTC accepts the principle of an absolute thermodynamic scale with a single fundamental fixed point, at present provided by the triple point of pure water, the absolute temperature of which will be fixed at a later date.

The introduction of this new scale does not affect in any way the use of the International Scale, which remains the recommended practical scale.

[5] The three propositions contained in this Resolution 3 were adopted by the General Conference.

3. The unit of quantity of heat is the joule.

Note: It is requested that the results of calorimetric experiments be as far as possible expressed in joules.

If the experiments are made by comparison with the rise of temperature of water (and that, for some reason, it is not possible to avoid using the calorie), the information necessary for conversion to joules must be provided.

The CIPM, advised by the CCTC, should prepare a table giving, in joules per degree, the most accurate values that can be obtained from experiments on the specific heat of water.[6]

degree Celsius

Adoption of "degree Celsius"

From three names ("degree centigrade," "centesimal degree," "degree Celsius") proposed to denote the degree of temperature, the CIPM has chosen "degree Celsius" (PV, **21**, 1948, p. 88).

This name is also adopted by the General Conference (CR, p. 64).

practical system of units of measurement

Proposal for establishing a practical system of units of measurement (CR, p. 64)

RESOLUTION 6

The General Conference,

considering

that the CIPM has been requested by the International Union of Physics to adopt for international use a practical international system of units; that the International Union of Physics recommends the MKS system and one electric unit of the absolute practical system, but does not recommend that the CGS system be abandoned by physicists;

that the CGPM has itself received from the French Government a similar request, accompanied by a draft to be used as basis of discussion for the establishment of a complete specification of units of measurement;

instructs the CIPM:

to seek by an energetic, active, official enquiry the opinion of scientific, technical, and educational circles of all countries (offering them, in fact, the French document as basis);

to gather and study the answers;

to make recommendations for a single practical system of units of measurement, suitable for adoption by all countries adhering to the Meter Convention.

[6] A table, prepared in response to this request, was approved and published by the CIPM in 1950 (PV, **22**, p. 92).

symbols and numbers

Writing and printing of unit symbols and of numbers (CR, p. 70)

RESOLUTION 7

Principles

Roman (upright) type, in general lower case, is used for symbols of units; if, however, the symbols are derived from proper names, capital roman type is used. These symbols are not followed by a full stop.

In numbers, the comma (French practice) or the dot (British practice) is used only to separate the integral part of numbers from the decimal part. Numbers may be divided in groups of three in order to facilitate reading; neither dots nor commas are ever inserted in the spaces between groups.

Unit	Symbol	Unit	Symbol
· meter	m	ampere	A
· square meter	m^2	volt	V
· cubic meter	m^3	watt	W
· micron*	μ	ohm	Ω
· liter**	l	coulomb	C
· gram	g	farad	F
· tonne†	t	henry	H
second	s	hertz	Hz
erg	erg	poise	P
dyne	dyn	newton	N
degree Celsius	°C	· candela (new candle*)	cd
· degree absolute***	°K	lux	lx
calorie	cal	lumen	lm
bar	bar	stilb	sb
hour	h		

Notes

I. The symbols whose unit names are preceded by dots are those which had already been adopted by a decision of the CIPM.

II. The symbol for the stere, the unit of volume for firewood, shall be "st" and not "s," which had been previously assigned to it by the CIPM.

III. To indicate a temperature interval or difference, rather than temperature, the word "degree" in full, or the abbreviation "deg," must be used.****

* See p. 31, Resolution 7 of the 13th CGPM (1967).

** An alternative symbol, L, was adopted in 1979 (see p. 37, 16th CGPM, Resolution 6).

*** Name and symbol changed in 1967 (see p. 29, 13th CGPM, Resolution 3).

**** Decision abrogated in 1967 (see p. 29, 13th CGPM, Resolution 3).

† USA Editor's note: See the second footnote at the bottom of p. 12.

thermodynamic scale

Definition of the thermodynamic temperature scale (CR, p. 79)

Resolution 3

The 10th CGPM decides to define the thermodynamic temperature scale by choosing the triple point of water as the fundamental fixed point, and assigning to it the temperature 273.16 degrees Kelvin, exactly.[7]

standard atmosphere

Definition of the standard atmosphere (CR, p. 79)

Resolution 4

The 10th CGPM, having noted that the definition of the standard atmosphere given by the 9th CGPM when defining the International Temperature Scale led some physicists to believe that this definition of the standard atmosphere was valid only for accurate work in thermometry,

declares that it adopts, for general use, the definition:

1 standard atmosphere = 1 013 250 dynes per square centimeter, i.e., 101 325 newtons per square meter.

practical system of units

Practical system of units (CR, p. 80)

Resolution 6

In accordance with the wish expressed by the 9th CGPM in its Resolution 6 concerning the establishment of a practical system of units of measurement for international use, the 10th CGPM

decides to adopt as base units of the system, the following units:

length	meter
mass	kilogram
time	second
electric current	ampere
thermodynamic temperature	degree Kelvin*
luminous intensity	candela

* Name changed to "kelvin" in 1967 (see p. 29, 13th CGPM, Resolution 3).

[7] See p. 29, Resolution 4 of the 13th CGPM (1967) which explicity defines the kelvin.

second *Definition of the unit of time* (PV, **25**, p. 77)*

RESOLUTION 1

In virtue of the powers invested in it by Resolution 5 of the 10th CGPM, the CIPM

considering

1. that the 9th General Assembly of the International Astronomical Union (Dublin, 1955) declared itself in favor of linking the second to the tropical year;

2. that, according to the decisions of the 8th General Assembly of the International Astronomical Union (Rome, 1952), the second of ephemeris time (ET) is the fraction

$$\frac{12\,960\,276\,813}{408\,986\,496} \times 10^{-9}$$ of the tropical year for 1900 January 0 at 12 h ET,

decides

"The second is the fraction 1/31 556 925.974 7 of the tropical year for 1900 January 0 at 12 hours ephemeris time."*

* Definition abrogated in 1967 (see p. 28, 13th CGPM, Resolution 1).

SI *International System of Units* (PV, **25**, p. 83)

RESOLUTION 3

The CIPM,

considering

the task entrusted to it by Resolution 6 of the 9th CGPM concerning the establishment of a practical system of units of measurement suitable for adoption by all countries adhering to the Meter Convention,

the documents received from twenty-one countries in reply to the enquiry requested by the 9th CGPM,

Resolution 6 of the 10th CGPM, fixing the base units of the system to be established,

recommends

1. that the name "International System of Units" be given to the system founded on the base units adopted by the 10th CGPM, viz.:
[There follows the list of the six base units with their symbols, reproduced in Resolution 12 of the 11th CGPM (1960)];

2. that the units listed in the table below be used, without excluding others which might be added later:
[There follows the table of units reproduced in paragraph 4 of Resolution 12 of the 11th CGPM (1960)].

meter

Definition of the meter (CR, p. 85)*

RESOLUTION 6

The 11th CGPM,

considering

that the international Prototype does not define the meter with an accuracy adequate for the present needs of metrology,

that it is moreover desirable to adopt a natural and indestructible standard,

decides

1. The meter is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton 86 atom.*

2. The definition of the meter in force since 1889, based on the international Prototype of platinum-iridium, is abrogated.

3. The international Prototype of the meter sanctioned by the 1st CGPM in 1889 shall be kept at the BIPM under the conditions specified in 1889.

* Definition abrogated in 1983 (see p. 38, 17th CGPM, Resolution 1).

second

Definition of the unit of time (CR, p. 86)*

RESOLUTION 9

The 11th CGPM,

considering

the powers given to the CIPM by the 10th CGPM to define the fundamental unit of time,

the decision taken by the CIPM in 1956,

ratifies the following definition:

"The second is the fraction 1/31 556 925.974 7 of the tropical year for 1900 January 0 at 12 hours ephemeris time."*

* Definition abrogated in 1967 (see p. 28, 13th CGPM, Resolution 1).

Resolution 12

The 11th CGPM,

considering

Resolution 6 of the 10th CGPM, by which it adopted six base units on which to establish a practical system of measurement for international use:

length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	degree Kelvin	°K*
luminous intensity	candela	cd

Resolution 3 adopted by the CIPM in 1956,

the recommendations adopted by the CIPM in 1958 concerning an abbreviation for the name of the system, and prefixes to form multiples and submultiples of the units,

decides

1. the system founded on the six base units above is called the "International System of Units";**

2. the international abbreviation of the name of the system is: SI;

3. names of multiples and submultiples of the units are formed by means of the following prefixes:*** †

Multiplying factor	Prefix	Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto	h
10 = 10^{1}	deka ‡	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p

4. the units listed below are used in the system, without excluding others which might be added later:

Supplementary Units

plane angle	radian	rad
solid angle	steradian	sr

* Name and symbol of unit modified in 1967 (see p. 29, 13th CGPM, Resolution 3).
** A seventh base unit, the mole, was adopted in 1971 by the 14th CGPM, Resolution 3; see p. 33.
*** See pp. 28 and 35 for the four new prefixes adopted by the 12th CGPM (1964), Resolution 8, and the 15th CGPM (1975), Resolution 10.

† USA Editor's note: See p. 40 for the four new prefixes submitted for approval to the 19th CGPM.

‡ USA Editor's note: Outside the USA, the spelling "deca" is extensively used.

DERIVED UNITS *

area	square meter	m^2	
volume	cubic meter	m^3	
frequency	hertz	Hz	1/s
mass density (density)	kilogram per cubic meter	kg/m^3	
speed, velocity	meter per second	m/s	
angular velocity	radian per second	rad/s	
acceleration	meter per second squared	m/s^2	
angular acceleration	radian per second squared	rad/s^2	
force	newton	N	$kg \cdot m/s^2$
pressure (mechanical stress)	newton per square meter	N/m^2	
kinematic viscosity	square meter per second	m^2/s	
dynamic viscosity	newton-second per square meter	$N \cdot s/m^2$	
work, energy, quantity of heat	joule	J	$N \cdot m$
power	watt	W	J/s
quantity of electricity	coulomb	C	$A \cdot s$
potential difference, electromotive force	volt	V	W/A
electric field strength	volt per meter	V/m	
electric resistance	ohm	Ω	V/A
capacitance	farad	F	$A \cdot s/V$
magnetic flux	weber	Wb	$V \cdot s$
inductance	henry	H	$V \cdot s/A$
magnetic flux density	tesla	T	Wb/m^2
magnetic field strength	ampere per meter	A/m	
magnetomotive force	ampere	A	
luminous flux	lumen	lm	$cd \cdot sr$
luminance	candela per square meter	cd/m^2	
illuminance	lux	lx	lm/m^2

* See page 30 for the other units added by the 13th CGPM (1967), Resolution 6.

cubic decimeter and liter

Cubic decimeter and liter (CR, p. 88)

RESOLUTION 13

The 11th CGPM,

considering

that the cubic decimeter and the liter are unequal and differ by about 28 parts in 10^6,

that determination of physical quantities which involve measurements of volume are being made more and more accurately, thus increasing the risk of confusion between the cubic decimeter and the liter,

requests the CIPM to study the problem and submit its conclusions to the 12th CGPM.

CIPM, 1961

cubic decimeter and liter (PV, **29**, p. 34)

RECOMMENDATION

The CIPM recommends that the results of accurate measurements of volume be expressed in units of the International System and not in liters.

frequency standard

Atomic standard of frequency (CR, p. 93)

RESOLUTION 5

The 12th CGPM,

considering

that the 11th CGPM noted in its Resolution 10 the urgency, in the interests of accurate metrology, of adopting an atomic or molecular standard of time interval,

that, in spite of the results already obtained with cesium atomic frequency standards, the time has not yet come for the CGPM to adopt a new definition of the second, base unit of the International System of Units, because of the new and considerable improvements likely to be obtained from work now in progress,

considering also that it is not desirable to wait any longer before time measurements in physics are based on atomic or molecular frequency standards,

empowers the CIPM to name the atomic or molecular frequency standards to be employed for the time being,

requests the Organizations and Laboratories knowledgeable in this field to pursue work connected with a new definition of the second.

DECLARATION OF THE CIPM (1964) (PV, **32**, p. 26, and CR, p. 93)

The CIPM,

empowered by Resolution 5 of the 12th CGPM to name atomic or molecular frequency standards for temporary use for time measurements in physics,

declares that the standard to be employed is the transition between the hyperfine levels $F = 4, M = 0$ and $F = 3, M = 0$ of the ground state $^2S_{1/2}$ of the cesium 133 atom, unperturbed by external fields, and that the frequency of this transition is assigned the value 9 192 631 770 hertz.

liter

Liter (CR, p. 93)

RESOLUTION 6

The 12th CGPM,

considering Resolution 13 adopted by the 11th CGPM in 1960 and the Recommendation adopted by the CIPM in 1961,

1. *abrogates* the definition of the liter given in 1901 by the 3d CGPM,

2. *declares* that the word "liter" may be employed as a special name for the cubic decimeter,

3. *recommends* that the name liter should not be employed to give the results of high accuracy volume measurements.

curie *Curie* (CR, p. 94)

RESOLUTION 7

The 12th CGPM,

considering that the curie has been used for a long time in many countries as a unit of activity for radionuclides,

recognizing that in the International System of Units (SI), the unit of this activity is the second to the power of minus one (s^{-1}),*

accepts that the curie be still retained, outside SI, as unit of activity, with the value 3.7×10^{10} s^{-1}. The symbol for this unit is Ci.

* In 1975 the name "becquerel" (Bq) was adopted for the SI unit of activity (see p. 34, 15th CGPM, Resolution 8): 1 Ci = 3.7×10^{10} Bq.

femto and atto *SI prefixes femto and atto* (CR, p. 94)

RESOLUTION 8

The 12th CGPM,

decides to add to the list of prefixes for the formation of names of multiples and submultiples of units, adopted by the 11th CGPM, Resolution 12, paragraph 3, the following two new prefixes:

Multiplying factor	Prefix	Symbol
10^{-15}	femto	f
10^{-18}	atto	a

13th CGPM, 1967–1968

second *SI unit of time (second)* (CR, p. 103)

RESOLUTION 1

The 13th CGPM,

considering

that the definition of the second adopted by the CIPM in 1956 (Resolution 1) and ratified by Resolution 9 of the 11th CGPM (1960), later upheld by Resolution 5 of the 12th CGPM (1964), is inadequate for the present needs of metrology,

that at its meeting of 1964 the CIPM, empowered by Resolution 5 of the 12th CGPM (1964), recommended, in order to fulfill these requirements, a cesium atomic frequency standard for temporary use,

that this frequency standard has now been sufficiently tested and found sufficiently accurate to provide a definition of the second fulfilling present requirements,

that the time has now come to replace the definition now in force of the unit of time of the International System of Units by an atomic definition based on that standard, *decides*

1. The SI unit of time is the second defined as follows:

"The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom."

2. Resolution 1 adopted by the CIPM at its meeting of 1956 and Resolution 9 of the 11th CGPM are now abrogated.

kelvin (degree Celsius)

SI unit of thermodynamic temperature (kelvin) (CR, p. 104)

Resolution 3

The 13th CGPM,

considering

the names "degree Kelvin" and "degree," the symbols "°K" and "deg," and the rules for their use given in Resolution 7 of the 9th CGPM (1948), in Resolution 12 of the 11th CGPM (1960), and the decision taken by the CIPM in 1962 (PV, **30**, p. 27),

that the unit of thermodynamic temperature and the unit of temperature interval are one and the same unit, which ought to be denoted by a single name and single symbol,

decides

1. the unit of thermodynamic temperature is denoted by the name "kelvin" and its symbol is "K";

2. the same name and the same symbol are used to express a temperature interval;

3. a temperature interval may also be expressed in degrees Celsius;

4. the decisions mentioned in the opening paragraph concerning the name of the unit of thermodynamic temperature, its symbol, and the designation of the unit to express an interval or a difference of temperatures are abrogated, but the usages which derive from these decisions remain permissible for the time being.*

*At its 1980 meeting the CIPM approved the report of the 7th meeting of the CCU which requested that the use of the symbols "°K" and "deg" no longer be permitted.

kelvin

Resolution 4

The 13th CGPM,

considering that it is useful to formulate more explicitly the definition of the unit of thermodynamic temperature contained in Resolution 3 of the 10th CGPM (1954),

decides to express this definition as follows:

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

candela *SI unit of luminous intensity (candela)* (CR, p. 104)*

RESOLUTION 5

The 13th CGPM,

considering

the definition of the unit of luminous intensity ratified by the 9th CGPM (1948) and contained in the "Resolution concerning the change of photometric units" adopted by CIPM in 1946 (PV, **20**, p. 119) in virtue of the powers conferred by the 8th CGPM (1933),

that this definition fixes satisfactorily the unit of luminous intensity, but that its wording may be open to criticism,

decides to express the definition of the candela as follows:

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

* Definition abrogated in 1979 (see p. 35, 16th CGPM, Resolution 3).

SI derived units *SI derived units* (CR, p. 105)

RESOLUTION 6

The 13th CGPM,

considering that it is useful to add some derived units to the list of paragraph 4 of Resolution 12 of the 11th CGPM (1960),

decides to add:

wave number	1 per meter	m^{-1}
entropy	joule per kelvin	J/K
specific heat capacity	joule per kilogram kelvin	J/(kg · K)
thermal conductivity	watt per meter kelvin	W/(m · K)
radiant intensity	watt per steradian	W/sr
activity (of a radioactive source)	1 per second	s^{-1} *

* The unit of activity received a special name and symbol in 1975 (see p. 34, 15th CGPM, Resolution 8).

micron (μ) new candle *Abrogation of earlier decisions (micron, new candle)* (CR, p. 105)

RESOLUTION 7

The 13th CGPM,

considering that subsequent decisions of the General Conference concerning the International System of Units are incompatible with parts of Resolution 7 of the 9th CGPM (1948),

decides accordingly to remove from Resolution 7 of the 9th Conference:

1. the unit name "micron," and the symbol "μ" which had been given to that unit, but which has now become a prefix;

2. the unit name "new candle."

CIPM, 1967

multiples of kilogram *Decimal multiples and submultiples of the unit of mass* (PV, **35**, p. 29)

RECOMMENDATION 2

The CIPM,

considering that the rule for forming names of decimal multiples and submultiples of the units of paragraph 3 of Resolution 12 of the 11th CGPM (1960) might be interpreted in different ways when applied to the unit of mass,

declares that the rules of Resolution 12 of the 11th CGPM apply to the kilogram in the following manner: the names of decimal multiples and submultiples of the unit of mass are formed by attaching prefixes to the word "gram."

CIPM, 1969

SI *International System of Units: Rules for application of Resolution 12 of the 11th CGPM (1960)* (PV, **37**, p. 30)

RECOMMENDATION 1 (1969)

The CIPM,

considering that Resolution 12 of the 11th CGPM (1960) concerning the International System of Units, has provoked discussions on certain of its aspects,

declares

1. the base units, the supplementary units, and the derived units of the International System of Units, which form a coherent set, are denoted by the name "SI units";

2. the prefixes adopted by the CGPM for the formation of decimal multiples and submultiples of SI units are called "SI prefixes";

and *recommends*

3. the use of SI units, and of their decimal multiples and submultiples whose names are formed by means of SI prefixes.

Note: The name "supplementary units," appearing in Resolution 12 of the 11th CGPM (and in the present Recommendation) is given to SI units for which the General Conference declines to state whether they are base units or derived units.*

* See p. 37, Recommendation 1 (CI-1980) of the CIPM.

14th CGPM, 1971

pascal
siemens

Pascal; siemens

The 14th CGPM (CR, p. 59) adopted the special names "pascal" (symbol Pa), for the SI unit newton per square meter, and "siemens" (symbol S), for the SI unit of electric conductance (reciprocal ohm).

TAI

International Atomic Time; function of CIPM (CR, p. 77)

Resolution 1

The 14th CGPM,

considering

that the second, unit of time of the International System of Units, has since 1967 been defined in terms of a natural atomic frequency, and no longer in terms of the time scales provided by astronomical motions,

that the need for an International Atomic Time (TAI) scale is a consequence of the atomic definition of the second,

that several international organizations have ensured and are still successfully ensuring the establishment of time scales based on astronomical motions, particularly thanks to the permanent services of the Bureau International de l'Heure (BIH),

that the BIH has started to establish an atomic time scale of recognized quality and proven usefulness,

that the atomic frequency standards for realizing the second have been considered and must continue to be considered by the CIPM, helped by a Consultative Committee, and that the unit interval of the International Atomic Time scale must be the second realized according to its atomic definition,

that all the competent international scientific organizations and the national laboratories active in this field have expressed the wish that the CIPM and the CGPM should give a definition of International Atomic Time, and should contribute to the establishment of the International Atomic Time scale,

that the usefulness of International Atomic Time entails close coordination with the time scales based on astronomical motions, *requests* the CIPM

1. to give a definition of International Atomic Time; [8] [†]

2. to take the necessary steps, in agreement with the international organizations concerned, to ensure that available scientific competence and existing facilities are used in the best possible way to realize the International Atomic Time scale and to satisfy the requirements of users of International Atomic Time.

mole *SI unit of amount of substance (mole)* (CR, p. 78)

RESOLUTION 3

The 14th CGPM,

considering the advice of the International Union of Pure and Applied Physics, of the International Union of Pure and Applied Chemistry, and of the International Organization for Standardization, concerning the need to define a unit of amount of substance,

decides

1. The mole is the amount of substance of a system that contains as many elementary entities as there are atoms* in 0.012 kilogram of carbon 12; its symbol is "mol."

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

3. The mole is a base unit of the International System of Units.

* At its 1980 meeting, the CIPM approved the report of the 7th meeting of the CCU (1980) specifying that "in this definition, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to."

---

[8] See p. 44.

[†] USA Editor's note: In anticipation of this request, the CIPM had asked the Consultative Committee for the Definition of the Second (CCDS) to prepare a definition of International Atomic Time. This definition, approved by the CIPM at its 59th session (October 1970), is that given on p. 44.

speed of light

Recommended value (CR, p. 103)

RESOLUTION 2

The 15th CGPM,

considering the excellent agreement among the results of wavelength measurements on the radiations of lasers locked on a molecular absorption line in the visible or infrared region, with an uncertainty estimated at $\pm 4 \times 10^{-9}$ which corresponds to the uncertainty of the realization of the meter,*

considering also the concordant measurements of the frequencies of several of these radiations,

recommends the use of the resulting value for the speed of propagation of electromagnetic waves in vacuum $c = 299\,792\,458$ meters per second.

* The uncertainty given here corresponds to three standard deviations.

UTC

Universal Coordinated Time (CR, p. 104)

RESOLUTION 5

The 15th CGPM,

considering that the system called "Coordinated Universal Time" (UTC) is widely used, that it is broadcast in most radio transmissions of time signals, that this wide diffusion makes available to the users not only frequency standards but also International Atomic Time and an approximation to Universal Time (or, if one prefers, mean solar time),

notes that Coordinated Universal Time provides the basis of civil time, the use of which is legal in most countries,

judges that this usage can be strongly endorsed.

bequerel
gray

SI units for ionizing radiations (CR, p. 105)

RESOLUTIONS 8 and 9

The 15th CGPM,

by reason of the pressing requirement, expressed by the International Commission on Radiation Units and Measurements (ICRU), to extend the use of the International System of Units to radiological research and applications,

by reason of the need to make as easy as possible the use of the units for nonspecialists,

taking into consideration also the grave risk of errors in therapeutic work,

adopts the following special name for the SI unit of activity:
becquerel, symbol Bq, equal to one reciprocal second — RESOLUTION 8

adopts the following special name for the SI unit of ionizing radiation:
gray, symbol Gy, equal to one joule per kilogram. — RESOLUTION 9

Note: The gray is the SI unit of absorbed dose. In the field of ionizing radiation the gray may also be used with other physical quantities also expressed in joules per kilogram; the Consultative Committee for Units (CCU) is made responsible for studying this matter in collaboration with the competent international organizations.[9]

peta
exa

SI prefixes peta and exa (CR, p. 106)

RESOLUTION 10

The 15th CGPM,

decides to add to the list of SI prefixes to be used for multiples, which was adopted by the 11th CGPM, Resolution 12, paragraph 3, the two following prefixes:

Multiplying factor	Prefix	Symbol
10^{15}	peta	P
10^{18}	exa	E

16th CGPM, 1979

candela

SI unit of luminous intensity (candela) (CR, p. 100)

RESOLUTION 3

The 16th CGPM,

considering

that despite the notable efforts of some laboratories there remain excessive divergences between the results of realizations of the candela based upon the present blackbody primary standard,

that radiometric techniques are developing rapidly, allowing precisions that are already equivalent to those of photometry and that these techniques are already in use in national laboratories to realize the candela without having to construct a blackbody,

that the relation between luminous quantities of photometry and radiometric quantities, namely the value of 683 lumens per watt for the spectral luminous efficacy of monochromatic radiation of frequency 540×10^{12} hertz, has been adopted by the CIPM in 1977,

that this value has been accepted as being sufficiently accurate for the system of luminous photopic quantities, that it implies a change of only about 3% for the system of luminous scotopic quantities, and that it therefore ensures satisfactory continuity,

[9] At its 1976 meeting, the CIPM approved the report of the 5th meeting of the CCU (1976), specifying that, following the advice of the ICRU, the gray may also be used to express specific energy imparted, kerma, and absorbed dose index.

that the time has come to give the candela a definition that will allow an improvement in both the ease of realization and the precision of photometric standards, and that applies to both photopic and scotopic photometric quantities and to quantities yet to be defined in the mesopic field,

decides

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

2. The definition of the candela (at the time called new candle) adopted by the CIPM in 1946 by reason of the powers conferred by the 8th CGPM in 1933, ratified by the 9th CGPM in 1948, then amended by the 13th CGPM in 1967, is abrogated.

sievert *Special name for the SI unit of dose equivalent* (CR, p. 100)

RESOLUTION 5

The 16th CGPM,

considering

the effort made to introduce SI units into the field of ionizing radiations,

the risk to human beings of an underestimated radiation dose, a risk that could result from a confusion between absorbed dose and dose equivalent,

that the proliferation of special names represents a danger for the International System of Units and must be avoided in every possible way, but that this rule can be broken when it is a matter of safeguarding human health,

adopts the special name *sievert*, symbol Sv, for the SI unit of dose equivalent in the field of radioprotection. The sievert is equal to the joule per kilogram.[10]

---

[10] At its 1984 meeting the CIPM decided to accompany this Resolution with the following explanation (see Recommendation 1 (CI-1984), p. 39):

"The quantity dose equivalent H is the product of the absorbed dose D of ionizing radiation and the dimensionless factors Q (quality factor) and N (product of any other multiplying factors) stipulated by the International Commission on Radiological Protection:

$$H = Q \cdot N \cdot D.$$

Thus, for a given radiation, the numerical value of H in joules per kilogram may differ from that of D in joules per kilogram depending upon the values of Q and N. In order to avoid any risk of confusion between the absorbed dose D and the dose equivalent H, the special names for the respective units should be used, that is, the name gray should be used instead of joules per kilogram for the unit of absorbed dose D and the name sievert instead of joules per kilogram for the unit of dose equivalent H."

liter *Symbols for the liter* (CR, p. 101)

RESOLUTION 6

The 16th CGPM,

recognizing the general principles adopted for writing the unit symbols in Resolution 7 of the 9th CGPM (1948),

considering that the symbol l for the unit liter was adopted by the CIPM in 1879 and confirmed in the same Resolution of 1948,

considering also that, in order to avoid the risk of confusion between the letter l and the number 1, several countries have adopted the symbol L instead of l for the unit liter,

considering that the name liter, although not included in the International System of Units, must be admitted for general use with the System,

decides, as an exception, to adopt the two symbols l and L as symbols to be used for the unit liter,

considering further that in the future only one of these two symbols should be retained,

invites the CIPM to follow the development of the use of these two symbols and to give the 18th CGPM its opinion as to the possibility of suppressing one of them.[11]

CIPM, 1980

SI supplementary units *SI supplementary units (radian and steradian)* (PV, **48**, p. 24)

RESOLUTION 1 (CI-1980)

The CIPM,

taking into consideration Resolution 3 adopted by ISO/TC12 in 1978 and Recommendation U1 (1980) adopted by the Consultative Committee for Units (CCU) at its 7th meeting,

considering

that the units radian and steradian are usually introduced into expressions for units when there is need for clarification, especially in photometry where the steradian plays an important role in distinguishing between units corresponding to different quantities,

that in the equations used one generally expresses plane angle as the ratio of two lengths and solid angle as the ratio between an area and the square of a length, and consequently that these quantities are treated as dimensionless quantities,

that the study of the formalisms in use in the scientific field shows that none exists which is at the same time coherent and convenient and in which the quantities plane angle and solid angle might be considered as base quantities,

considering also

that the interpretation given by the CIPM in 1969 for the class of supplementary units introduced in Resolution 12 of the 11th CGPM in 1960 allows the freedom of treating the radian and the steradian as SI base units,

---

[11] The CIPM, at its 79th meeting in 1990, considered that it was still too early to make a final choice.

that such a possibility compromises the internal coherence of the SI based on only seven base units,

decides to interpret the class of supplementary units in the International System as a class of dimensionless derived units for which the CGPM allows the freedom of using or not using them in expressions for SI derived units.

17th CGPM, 1983

meter *Definition of the meter* (CR, p. 97)

Resolution 1

The 17th CGPM,

considering

that the present definition does not allow a sufficiently precise realization of the meter for all requirements,

that progress made in the stabilization of lasers allows radiations to be obtained that are more reproducible and easier to use than the standard radiation emitted by a krypton 86 lamp,

that progress made in the measurement of the frequency and wavelength of these radiations has resulted in concordant determinations of the speed of light whose accuracy is limited principally by the realization of the present definition of the meter,

that wavelengths determined from frequency measurements and a given value for the speed of light have a reproducibility superior to that which can be obtained by comparison with the wavelength of the standard radiation of krypton 86,

that there is an advantage, notably for astronomy and geodesy, in maintaining unchanged the value of the speed of light recommended in 1975 by the 15th CGPM in its Resolution 2 (c = 299 792 458 m/s),

that a new definition of the meter has been envisaged in various forms all of which have the effect of giving the speed of light an exact value, equal to the recommended value, and that this introduces no appreciable discontinuity into the unit of length, taking into account the uncertainty* of $\pm 4 \times 10^{-9}$ of the best realizations of the present definition of the meter,

that these various forms, making reference either to the path travelled by light in a specified time interval or to the wavelength of a radiation of measured or specified frequency, have been the object of consultations and deep discussions, have been recognized as being equivalent and that a consensus has emerged in favor of the first form,

that the Consultative Committee for the Definition of the Meter (CCDM) is now in a position to give instructions for the practical realization of such a definition, instructions which could include the use of the orange radiation of krypton 86 used as standard up to now, and which may in due course be extended or revised,

* *Note*: In this case, the uncertainty represents three standard deviations.

decides

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

2. The definition of the meter in force since 1960, based upon the transition between the levels $2p_{10}$ and $5d_5$ of the atom of krypton 86, is abrogated.

meter

On the realization of the definition of the meter (CR, p. 98)

RESOLUTION 2

The 17th CGPM

invites the CIPM

to draw up instructions for the practical realization of the new definition of the meter,[12]

to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and to draw up instructions for their use,

to pursue studies undertaken to improve these standards.

CIPM, 1984

gray
sievert

Concerning the sievert (PV, **52**, p. 31)

RECOMMENDATION 1 (CI-1984)

The CIPM,

considering the confusion which continues to exist on the subject of Resolution 5, approved by the 16th CGPM (1979),

decides to introduce the following explanation in the brochure "Le Système International d'Unités (SI)":

"The quantity dose equivalent H is the product of the absorbed dose D of ionizing radiation and the dimensionless factors Q (quality factor) and N (product of any other multiplying factors) stipulated by the International Commission on Radiological Protection:

$$H = Q \cdot N \cdot D \ .$$

Thus, for a given radiation, the numerical value of H in joules per kilogram may differ from that of D in joules per kilogram depending upon the values of Q and N. In order to avoid any risk of confusion between the absorbed dose D and the dose equivalent H, the special names for the respective units should be used, that is, the name gray should be used instead of joules per kilogram for the unit of absorbed dose D and the name sievert instead of joules per kilogram for the unit of dose equivalent H."

---

[12] See Appendix II, p. 41, Recommendation 1 (CI-1983) adopted by the CIPM in 1983.

zetta, zepto
yotta, yocto

SI prefixes zetta, zepto, yotta, and yocto[13]

DRAFT RESOLUTION D TO THE 19th CGPM

The 19th Conférence Générale des Poids et Mesures,

decides to add to the list of SI prefixes to be used for multiples and submultiples of units, adopted by the 11th Conférence Générale des Poids et Mesures (CGPM), Resolution 12, paragraph 3, the 12th CGPM, Resolution 8, and the 15th CGPM, Resolution 10, the following prefixes:

Multiplying factor	Prefix	Symbol
10^{21}	zetta	Z
10^{-21}	zepto	z
10^{24}	yotta	Y
10^{-24}	yocto	y

---

[13] The names zepto and zetta are derived from septo suggesting the number seven (the seventh power of 10^3) and the letter "z" is substituted for the letter "s" to avoid the duplicate use of the letter "s" as a symbol.

The names yocto and yotta are derived from octo, suggesting the number eight (the eighth power of 10^3); the letter "y" is added to avoid the use of the letter "o" as a symbol because it may be confused with the number zero.

APPENDIX II

Practical Realization of the Definitions of Some Important Units

1. Length

The Recommendation 1 (CI-1983) was adopted by the CIPM in 1983 to specify the rules for the practical realization of the definition of the meter:

The CIPM

recommends

that the meter be realized by one of the following methods:

a) by means of the length l of the path travelled in vacuum by a plane electromagnetic wave in a time t; this length is obtained from the measured time t, using the relation $l = c \cdot t$ and the value of the speed of light in vacuum c = 299 792 458 m/s;

b) by means of the wavelength in vacuum λ of a plane electromagnetic wave of frequency f; this wavelength is obtained from the measured frequency f, using the relation $\lambda = c/f$ and the value of the speed of light in vacuum c = 299 792 458 m/s;

c) by means of one of the radiations from the list below, whose stated wavelength in vacuum or whose stated frequency can be used with the uncertainty shown, provided that the given specifications and accepted good practice are followed;

and that in all cases any necessary corrections be applied to take account of actual conditions such as diffraction, gravitation, or imperfection in the vacuum.

LIST OF RECOMMENDED RADIATIONS, 1983

In this list, the values of the frequency f and of the wavelength λ should be related exactly by the relation $\lambda f = c$, with c = 299 792 458 m/s but the values of λ are rounded.

1. *Radiations of Lasers Stabilized by Saturated Absorption* * †

1.1 Absorbing molecule CH_4, transition ν_3, P(7), component $F_2^{(2)}$.

The values f = 88 376 181 608 kHz
λ = 3 392 231 397.0 fm

with an estimated overall relative uncertainty of $\pm\ 1.3 \times 10^{-10}$ [which results from an estimated relative standard deviation of 0.44×10^{-10}] apply to the radiation of a He-Ne laser stabilized with a cell of methane, within or external to the laser, subject to the conditions:

- methane pressure $\leqslant$ 3 Pa
- mean one-way axial intracavity surface power density** $\leqslant 10^4\ W \cdot m^{-2}$
- radius of wavefront curvature $\geqslant$ 1 m
- inequality of power between counter-propagating waves $\leqslant$ 5%.

---

† USA Editor's note: See the bottom of p. 42 for notes.

1.2. Absorbing molecule $^{127}I_2$, transition 17-1, P(62), component o.

The values f = 520 206 808.51 MHz
λ = 576 294 760.27 fm

with an estimated*** overall relative uncertainty of $\pm\ 6\times10^{-10}$ [which results from an estimated relative standard deviation of 2×10^{-10}] apply to the radiation of a dye laser (or frequency-doubled He-Ne laser) stabilized with a cell of iodine, within or external to the laser, having a cold-finger temperature of 6 °C ± 2 °C.

1.3. Absorbing molecule $^{127}I_2$, transition 11-5, R(127), component i.

The values f = 473 612 214.8 MHz
λ = 632 991 398.1 fm

with an estimated overall relative uncertainty of $\pm\ 1\times10^{-9}$ [which results from an estimated relative standard deviation of 3.4×10^{-10}] apply to the radiation of a stabilized He-Ne laser containing an iodine cell, subject to the conditions:

– cell-wall temperature between 16 °C and 50 °C with a cold-finger temperature of 15 °C ± 1 °C
– one-way intracavity beam power** 15 mW ± 10 mW
– frequency modulation amplitude, peak to peak, 6 MHz ± 1 MHz.

1.4. Absorbing molecule $^{127}I_2$, transition 9-2, R(47), component o.

The values f = 489 880 355.1 MHz
λ = 611 970 769.8 fm

with an estimated overall relative uncertainty of $\pm\ 1.1\times10^{-9}$ [which results from an estimated relative standard deviation of 3.7×10^{-10}] apply to the radiation of a He-Ne laser stabilized with a cell of iodine, within or external to the laser, having a cold-finger temperature of −5 °C ± 2 °C.

1.5. Absorbing molecule $^{127}I_2$, transition 43-0, P(13), component a_3 (sometimes called component s).

The values f = 582 490 603.6 MHz
λ = 514 673 466.2 fm

with an estimated overall relative uncertainty of $\pm\ 1.3\times10^{-9}$ [which results from an estimated relative standard deviation of 4.3×10^{-10}] apply to the radiation of an Ar^+ laser stabilized with a cell of iodine, within or external to the laser, having a cold-finger temperature of −5 °C ± 2 °C.

Notes

* Each of these radiations can be replaced, without degrading the accuracy, by a radiation corresponding to another component of the same transition or by another radiation, when the frequency difference is known with sufficient accuracy. Details of methods of stabilization are described in numerous scientific and technical publications. References to appropriate articles, illustrating accepted good practice for a particular radiation, may be obtained by application to a member laboratory of the CCDM, or the BIPM.

** The one-way intracavity beam power is obtained by dividing the output power by the transmittance of the output mirror.

*** This uncertainty, and the frequency and wavelength values, are based on the weighted mean of only two determinations. The more precise of the two, however, was a measurement dependent only on frequency mixing and multiplication techniques relative to the radiation in 1.1. above.

2. *Radiations of Spectral Lamps*

2.1. Radiations corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the atom of ^{86}Kr.

The value $\lambda = 605\,780\,210$ fm

with an estimated overall relative uncertainty of $\pm\, 4 \times 10^{-9}$ [which results from an estimated relative standard deviation of 1.3×10^{-9}] applies to the radiation emitted by a lamp operated under the conditions recommended by the CIPM (*Procès-Verbaux CIPM,* 49th session, 1960, pp. 71-72 and *Comptes Rendus, 11th CGPM,* 1960, p. 85).

2.2. Radiations of the atoms ^{86}Kr, ^{198}Hg and ^{114}Cd recommended by the CIPM in 1963 (*Comité Consultatif pour la Définition du Mètre,* 3rd session, 1962, pp. 18-19 and *Procès-Verbaux CIPM,* 52nd session, 1963, pp. 26-27), with the indicated values for the wavelengths and the corresponding uncertainties.

2. Mass

The unit of mass, the kilogram, is the mass of the international prototype of the kilogram kept at the BIPM. The masses of 1 kg secondary standards of platinum-iridium or of stainless-steel are compared with the mass of the prototype by means of balances whose precision can reach 1 in 10^8 or better. In the case of stainless-steel standards, the accuracy of comparison depends upon the accuracy with which the correction due to air-buoyancy is known.

By an easy operation a series of masses can be standardized to obtain multiples and submultiples of the kilogram.

3. Time

Unit of time, frequency

Some research laboratories are able to construct the equipment required to produce electric oscillations at a frequency whose relationship to the transition frequency of the atom of cesium 133 which defines the second is known. It is possible thus to obtain both the second and pulses at desired frequencies, 1 Hz, 1 kHz, etc. In the best equipment, the uncertainty is at present estimated to be a few parts in 10^{14} for averages extending over periods from a few hours to a few days. Commercial cesium-beam time standards are also available having uncertainties of about 3 parts in 10^{12}.

There exist very stable clocks and frequency generators besides those using cesium, including the hydrogen maser, and rubidium and quartz clocks. Their frequencies have to be standardized by comparison with a cesium time standard, either directly, or by means of radio transmissions. Some of these transmissions emit signals whose frequencies are known with uncertainties (standard deviations) from 1 part in 10^{11} to 5 parts in 10^{13}. These transmissions cover the whole surface of the Earth, but reception may sometimes be difficult owing to uneven propagation. When a higher accuracy is required it is better to use time comparisons, as explained below.

Some cesium-beam standards made in national laboratories operate continuously as time standards. However, many national time services use continuously-running commercial cesium standards that are maintained under careful environmental control. Since 1969 it has been possible to compare these various instruments, over intercontinental distances, with uncertainties of only a few hundred nanoseconds. It has thus been possible to establish a mean atomic-time scale sufficiently secure for it to serve as the basis of the world's time reference. This scale, approved by Resolution 1 of the 14th CGPM in 1971, was given the name International Atomic Time (TAI).[1] Through the use of the satellite system "Global Positioning System" (GPS) TAI is now accessible worldwide to within about twenty nanoseconds.

TAI is not directly distributed. Time signals broadcast by radio waves are given on a time scale called Coordinated Universal Time (UTC) as recommended by the 15th CGPM (Resolution 5) in 1975. UTC is defined in such a manner that it differs from International Atomic Time (TAI) by a whole number of seconds. The difference UTC − TAI was set equal to −10 s starting the first of January 1972, the date of application of the reformulation of UTC which previously involved a frequency offset; this difference can be modified by 1 second by the use of a positive or negative leap second at the end of a month of UTC, preferably in the first instance at the end of December or of June, and in the second instance at the end of March or of September, in order to keep UTC in agreement with the time defined by the rotation of the Earth with an approximation better than 0.9 s.[2] Furthermore, the legal times of most countries are offset from UTC by a whole number of hours (time zones and "summer" time).

National time-service laboratories maintain an approximation to UTC known as UTC(k) for laboratory k. The differences between UTC(k) and UTC are in general no more than a few microseconds.

The precision and accuracy of time measurement sometimes require relativistic effects to be taken into account. The definition of the second must be understood as the definition of the unit of proper time, i.e., strictly speaking the user must be in the neighborhood of the clock and at rest with respect to it. In general, within the expanse of a laboratory, only the effects of special relativity are significant, if the clock is in the laboratory. But, in applications which bring into play distant clocks, it may be necessary to take general relativity into account. In particular, TAI is based upon a worldwide network of clocks and its definition* has been completed as follows (declaration of the CCDS : *BIPM Com. Cons. Déf. Seconde* **9**, 1980, p. S 15):

> *"TAI is a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit."*

For all clocks fixed in relation to the Earth, situated at sea level, the scale unit of TAI has a time interval equal to that of the unit of time as realized locally, but compared to a clock at 2000 m altitude, for example, the scale unit of TAI appears to be longer by 2.2×10^{-13} s. In long-distance time links using geostationary satellites, the relativistic effect can reach a few hundred nanoseconds.

* The definition of TAI approved by the CIPM at its 59th session (October 1970) is as follows:

> *"International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units."*

---

[1] See * at the bottom of this page for the definition of TAI given by CIPM at the request of the 14th CGPM (1971, Resolution 1).

[2] The difference UTC − TAI was −26 s on 1 January 1991.

The scale unit of TAI (and that of UTC) conforms to its definition to within 2 or 3×10^{-14} s averaged over 10 or 20 days. By means of the signals emitted by GPS satellites, TAI and the time scale of a local clock may be compared so that the frequency of the local clock can be established to within 2 or 3 parts in 10^{14}.

4. Electrical quantities

The realization to high accuracy of the ampere (a base unit of the SI), the ohm, and the volt directly in terms of their definitions is difficult and time consuming. The best such realizations of the ampere are now obtained through combinations of realizations of the watt, the ohm, and the volt. The watt realized electrically is compared by beam-balance experiments with the watt realized mechanically. These experiments employ a coil in a magnetic field and are devised in such a way that it is not necessary to know either the dimensions of the coil or the magnitude of the magnetic field. The ohm is realized using a Thompson-Lampard capacitor whose value can be changed by an amount that depends only on the magnitude of a linear displacement of a guard electrode. The volt is realized by means of a balance in which an electrostatic force is measured in terms of a mechanical force. The ampere may thus be deduced from combinations of any two of these units. The uncertainty in the value of the ampere obtained in this way is estimated to be a few parts in 10^7. The ampere, ohm, and volt may also be determined from measurements of various combinations of physical constants. Laboratory reference standards for the volt and the ohm based upon the Josephson and quantum-Hall effects are, however, significantly more reproducible and stable than a few parts in 10^7. In order to take advantage of these highly stable methods of maintaining laboratory reference standards of the electrical units while at the same time taking care not to change their SI definitions, the 18th CGPM in 1987 adopted Resolution 6.

Forthcoming adjustment to the representations of the volt and of the ohm

Resolution 6

The 18th Conférence Générale des Poid et Mesures,

considering

that worldwide uniformity and long-term stability of national representations of the electrical units are of major importance for science, commerce, and industry from both the technical and economic points of view,

that many national laboratories use the Josephson effect and are beginning to use the quantum Hall effect to maintain, respectively, representations of the volt and of the ohm, as these offer the best guarantees of long-term stability,

that because of the importance of coherence among the units of measurement of the various physical quantities the values adopted for these representations must be as closely as possible in agreement with the SI,

that the results of recent and current experiment will permit the establishment of an acceptable value, sufficiently compatible with the SI, for the coefficient which relates each of these effects to the corresponding electrical unit, *invites* the laboratories whose work can contribute to the establishment of the quotient voltage/frequency in the case of the Josephson effect and of the quotient voltage/current for the quantum Hall effect to vigorously pursue these efforts and to communicate their results without delay to the Comité International des Poids et Mesures, and

instructs the Comité International des Poids et Mesures to recommend as soon as it considers it possible, a value for each of these quotients together with a date for them to be put into practice simultaneously in all countries; these values should be announced at least one year in advance and would be adopted on January 1st 1990.

In 1988 the CIPM adopted Recommendations 1 (CI-1988) and 2 (CI-1988):

Representation of the volt by means of the Josephson effect

RECOMMENDATION 1 (CI-1988)

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

that a detailed study of the results of the most recent determinations leads to a value of 483 597.9 GHz/V for the Josephson constant, K_J, that is to say, for the quotient of frequency divided by the potential difference corresponding to the $n = 1$ step in the Josephson effect,

that the Josephson effect together with this value of K_J can be used to establish a reference standard of electomotive force having a one-standard-deviation uncertainty with respect to the volt estimated to be 4 parts in 10^7, and a reproducibility which is significantly better,

recommends

that 483 597.9 GHz/V exactly be adopted as a conventional value, denoted by K_{J-90}, for the Josephson constant, K_J,

that this new value be used from 1st January 1990, and not before, to replace the values currently in use,

that this new value be used from this same date by all laboratories which base their measurements of electromotive force on the Josephson effect, and

that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with the new adopted value,

is of the opinion

that no change in this recommended value of the Josephson constant will be necessary in the foreseeable future, and

draws the attention of laboratories to the fact that the new value is greater by 3.9 GHz/V, or about 8 parts in 10^6, than the value given in 1972 by the Comité Consultatif d'Électricité in its Declaration E-72.

Recommendation 2 (CI-1988)

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

that most existing laboratory reference standards of resistance change significantly with time,

that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,

that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau $i = 1$ in the quantum Hall effect,

that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

that 25 812.807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,

that this value be used from 1st January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,

that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},

that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the technical guidelines for reliable measurements of the quantized Hall resistance drawn up by the Comité Consultatif d'Électricité and published by the Bureau International des Poids et Mesures, and

is of the opinion

that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

The CCE at its meeting in 1988 considered very carefully the way in which the recommended conventional values K_{J-90} and R_{K-90} should be used and made additional statements to clarify these implications of the Recommendations. These statements may be summarized as follows:

(1) Recommendations 1 (CI-1988) and 2 (CI-1988) do not constitute a redefinition of SI units. The conventional values K_{J-90} and R_{K-90} cannot be used as bases for defining the volt and the ohm [meaning the present units of electromotive force and electrical resistance in the Système International d'Unités (SI)]. To do so would change the status of μ_0 from that of a constant having an exactly defined value (and would therefore abrogate the definition of the ampere) and would also produce electrical units which would be incompatible with the definition of the kilogram and units derived from it.

(2) Concerning the use of subscripts on symbols for quantities or units, the CCE considers that symbols for electromotive force (electric potential, electric potential difference) and electric resistance, and for the volt and the ohm, should not be modified by adding subscripts to denote particular laboratories or dates.

These statements were subsequently supported by the CIPM at its 78th Meeting in 1988.

5. Temperature

Direct measurements of thermodynamic temperature can only be made by using one of only a small number of so-called primary thermometers. These are thermometers whose equation of state can be written down explicitly without having to introduce unknown temperature-dependent constants. Primary thermometers that have been used to provide accurate values of thermodynamic temperature include the constant-volume gas thermometer, the acoustic gas thermometer, the spectral and total radiation thermometers, and the electronic noise thermometer. Uncertainties of 1 or 2 millikelvins have been achieved with such thermometers up to about 373 K beyond which the uncertainties increase progressively. The use of such thermometers to high accuracy is difficult and time-consuming and there exist secondary thermometers, such as the platinum resistance thermometer, whose reproducibility can be of the order of ten times better than that of any primary thermometer. In order to allow the maximum advantage to be taken of these secondary thermometers the CGPM has, in the course of time, adopted successive versions of an international temperature scale. The first of these was the International Temperature Scale of 1927 (ITS-27); this was replaced by the International Practical Temperature Scale of 1948 (IPTS-48) which in turn was replaced by the International Practical Temperature Scale of 1968 (IPTS-68). In 1976 the CIPM adopted, for use at low temperatures, the 1976 Provisional 0.5 K to 30 K Temperature Scale (EPT-76). On 1 January 1990 the IPTS-68 and the EPT-76 were replaced by the International Temperature Scale of 1990 (ITS-90) adopted by the CIPM in 1989 in its Recommendation 5 (CI-1989).

The International Temperature Scale of 1990

RECOMMENDATION 5 (CI-1989)

The Comité International des Poids et Mesures (CIPM) acting in accordance with Resolution 7 of the 18th Conférence Générale des Poids et Mesures (1987) has adopted the International Temperature Scale of 1990 (ITS-90) to supersede the International Practical Temperature Scale of 1968 (IPTS-68).

The CIPM *notes* that, by comparison with the IPTS-68, the ITS-90

extends to lower temperatures, down to 0.65 K, and hence also supersedes the EPT-76,

is in substantially better agreement with corresponding thermodynamic temperatures,

has much improved continuity, precision, and reproducibility throughout its range, and

has subranges and alternative definitions in certain ranges which greatly facilitate its use.

The CIPM also *notes* that, to accompany the text of the ITS-90 there will be two further documents, the "Supplementary Information for the ITS-90" and "Techniques for Approximating the ITS-90." These documents will be published by the BIPM and periodically updated.

The CIPM *recommends*

that on 1 January 1990 the ITS-90 come into force and

that from this same date the IPTS-68 and the EPT-76 be abrogated.

The ITS-90 extends upwards from 0.65 K to the highest temperature measurable using an optical pyrometer. The Scale is defined in terms of the helium vapor-pressure equations from 0.65 K to 5 K, interpolating constant-volume gas thermometers from 3 K to 24.5561 K, platinum resistance thermometers from 13.8033 K to 961.78 °C, and the Planck radiation law at higher temperatures, together with a set of defining fixed points and methods of interpolating between them. These defining fixed points are the temperatures assigned by agreement to a number of experimentally realizable thermodynamic states. In several ranges of temperature more than one definition of T_{90}, the temperature defined by the Scale, exists. The various definitions have equal validity.

Advice on the realization and implementation of the ITS-90 is given in the two documents "Supplementary Information for the ITS-90" and "Techniques for Approximating the ITS-90," which are approved and updated periodically by the Consultative Committee on Thermometry (CCT) and published by the BIPM.

6. Amount of substance

All quantitative results of chemical analysis or of dosages can be expressed in moles, in other words in units of amount of substance of the elementary entities. The principle of physical measurement based on the definition of this unit is explained below.

The simplest case is that of a sample of a pure substance that is considered to be formed of atoms; call X the chemical symbol of these atoms. A mole of atoms X contains by definition as many atoms as there are ^{12}C atoms in 0.012 kilogram of carbon 12. As neither the mass $m(^{12}C)$ of an atom of carbon 12 nor the mass $m(X)$ of an atom X can be measured accurately, we use the ratio of these masses, $m(X)/m(^{12}C)$, which can be accurately determined.[3] The mass corresponding to 1 mole of

[3] There are many methods of measuring this ratio, the most direct one being by the mass spectrograph.

X is then $[m(\mathrm{X})/m(^{12}\mathrm{C})]\times 0.012$ kg, which is expressed by saying that the molar mass $M(\mathrm{X})$ of X (quotient of mass by amount of substance) is

$$M(\mathrm{X}) = [m(\mathrm{X})/m(^{12}\mathrm{C})]\times 0.012\ \mathrm{kg/mol}.$$

For example, the atom of fluorine $^{19}\mathrm{F}$ and the atom of carbon $^{12}\mathrm{C}$ have masses that are in the ratio 18.9984/12. The molar mass of the molecular gas F_2 is

$$M(\mathrm{F_2}) = \frac{2\times 18.9984}{12}\times 0.012\ \mathrm{kg/mol} = 0.037\,996\,8\ \mathrm{kg/mol}.$$

The amount of substance corresponding to a given mass of gas F_2, 0.05 kg for example, is:

$$\frac{0.05\ \mathrm{kg}}{0.037\,996\,8\ \mathrm{kg\cdot mol^{-1}}} = 1.315\,90\ \mathrm{mol}.$$

In the case of a pure substance that is supposedly made up of molecules B, which are combinations of atoms X, Y, ... according to the chemical formula $\mathrm{B} = \mathrm{X}_\alpha \mathrm{Y}_\beta \ldots$, the mass of one molecule is $m(\mathrm{B}) = \alpha m(\mathrm{X}) + \beta m(\mathrm{Y}) + \ldots$.

This mass is not known with accuracy, but the ratio $m(\mathrm{B})/m(^{12}\mathrm{C})$ can be determined accurately. The molar mass of a molecular substance B is then

$$M(\mathrm{B}) = \frac{m(\mathrm{B})}{m(^{12}\mathrm{C})}\times 0.012\ \mathrm{kg/mol} = \left(\alpha\frac{m(\mathrm{X})}{m(^{12}\mathrm{C})} + \beta\frac{m(\mathrm{Y})}{m(^{12}\mathrm{C})} + \ldots\right)\times 0.012\ \mathrm{kg/mol}.$$

The same procedure is used in the more general case when the composition of the substance B is specified as $\mathrm{X}_\alpha \mathrm{Y}_\beta \ldots$, even if α, β, ... are not integers. If we denote the mass ratios $m(\mathrm{X})/m(^{12}\mathrm{C})$, $m(\mathrm{Y})/m(^{12}\mathrm{C})$, ... by $r(\mathrm{X})$, $r(\mathrm{Y})$, ..., the molar mass of the substance B is given by the formula:

$$M(\mathrm{B}) = [\alpha r(\mathrm{X}) + \beta r(\mathrm{Y}) + \ldots]\times 0.012\ \mathrm{kg/mol}.$$

There are other methods based on the laws of physics and physical chemistry for measuring amounts of substance; three examples are given below:

With perfect gases, 1 mole of particles of any gas occupies the same volume at a temperature T and a pressure p (approximately $0.0224\ \mathrm{m^3}$ at $T = 273.16$ K and $p = 101\,325$ Pa); hence a method of measuring the ratio of amounts of substance for any two gases (the corrections to apply if the gases are not perfect are well known).

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

Application of the laws of Raoult is yet another method of determining ratios of amounts of substance in extremely dilute solutions.

7. Photometric quantities

The method approved by the CIPM in 1937 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures* **18**, p. 237) for determining the value of photometric quantities for luminous sources whose radiation does not have the same spectral composition, utilizes a procedure taking account of the "spectral luminous efficiencies" $V(\lambda)$. By its Recommendation 1 (CI-1972), the CIPM recommends the use of the $V(\lambda)$ values adopted by the International Commission on Illumination (CIE) in 1971.[4] The weighting function $V(\lambda)$ was obtained for photopic vision, i.e., for retinas adapted to light. For retinas adapted to darkness, another function $V'(\lambda)$ gives the spectral luminous efficiency for scotopic vision (CIE 1951); this function $V'(\lambda)$ was ratified by the CIPM in September 1976.

Photometric quantities are thereby defined in purely physical terms as quantities proportional to the sum or integral of a spectral power distribution, weighted according to a specified function of wavelength.

Before 1979, the standard lamps then in use were calibrated by comparison with the luminance of a Planckian radiator (a blackbody) at the temperature of freezing platinum. Since the adoption of the new definition of the candela in 1979, this measurement is carried out by comparison with the monochromatic radiation specified in the definition, or with some other radiation by taking account of $V(\lambda)$ or $V'(\lambda)$.

The standard lamps are incandescent lamps powered by a specified direct current; they provide either a known luminous flux or, in a given direction, a known luminous intensity.

[4] CIE Publications No. 18 (1970), p. 43, and No. 15 (1971), p. 93; *BIPM Proc.-Verb. Com. Int. Poids et Mesures* **40**, 1972, Annexe 1. The $V(\lambda)\,[=\bar{y}(\lambda)]$ values are given for wavelengths in 1 nm steps from 360 to 830 nm; they are an improvement on the values in 10 nm steps adopted by the CIPM in 1933, and previously by the CIE in 1924.

APPENDIX III

The BIPM and the Meter Convention

The International Bureau of Weights and Measures (BIPM, Bureau Internantional des Poids et Mesures) was set up by the *Meter Convention* (Convention du Mètre) signed in Paris on 20 May 1875 by seventeen States during the final session of the Diplomatic Conference of the Meter. This Convention was amended in 1921.

The BIPM has its headquarters near Paris, in the grounds (43 520 m^2) of the Pavillon de Breteuil (Parc de Saint-Cloud), placed at its disposal by the French Government; its upkeep is financed jointly by the Member States of the Meter Convention.[1]

The task of the BIPM is to ensure worldwide unification of physical measurements; it is responsible for:

establishing the fundamental standards and scales for measurement of the principal physical quantities and maintaining the international prototypes;

carrying out comparisons of national and international standards;

ensuring the coordination of corresponding measuring techniques;

carrying out and coordinating determinations relating to the fundamental physical constants that are involved in the above-mentioned activities.

The BIPM operates under the exclusive supervision of the *International Committee for Weights and Measures* (CIPM, Comité International des Poids et Mesures), which itself comes under the authority of the *General Conference on Weights and Measures* (CGPM, Conférence Générale des Poids et Mesures).

The General Conference consists of delegates from all the Member States of the Meter Convention and meets at present every four years. At each meeting it receives the Report of the International Committee on the work accomplished, and it is responsible for:

discussing and instigating the arrangements required to ensure the propagation and improvement of the International System of Units (SI, Système International d'Unités), which is the modern form of the metric system;

confirming the results of new fundamental metrological determinations and the various scientific resolutions of international scope;

adopting the important decisions concerning the organization and development of the BIPM.

The International Committee consists of eighteen members each belonging to a different State; it meets at present every year. The officers of this Committee issue an Annual Report on the administrative and financial position of the BIPM to the Governments of the Member States of the Meter Convention.

---

[1] In March 1991 forty-six States were members of this Convention: Argentina (Rep. of), Australia, Austria, Belgium, Brazil, Bulgaria, Cameroon, Canada, Chile, China (People's Rep. of), Czechoslovakia, Denmark, Dominican Republic, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Korea (Dem. People's Rep.), Korea (Rep. of), Mexico, Netherlands, Norway, Pakistan, Poland, Portugal, Romania, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, U.S.S.R., United Kingdom, U.S.A., Uruguay, Venezuela, Yugoslavia.

The activities of the BIPM, which in the beginning were limited to the measurement of length and mass and to metrological studies in relation to these quantities, have been extended to standards of measurement for electricity (1927), photometry (1937), ionizing radiations (1960), and to time scales (1988). To this end the original laboratories, built in 1876-1878, were enlarged in 1929, new buildings were constructed in 1963-1964 for the ionizing radiation laboratories, in 1984 for laser work, and in 1988 a new building for a library and offices was opened.

Some forty physicists or technicians are working in the BIPM laboratories. They are mainly conducting metrological research, international comparisons of realizations of units, and the checking of standards used in the above-mentioned areas. An annual report in *Procès-Verbaux des séances du Comité International des Poids et Mesures* gives the details of the work in progress.

In view of the extension of the work entrusted to the BIPM, the CIPM has set up since 1927, under the name of *Consultative Committees* (Comités Consultatifs), bodies designed to provide it with information on matters that it refers to them for study and advice. These Consultative Committees, which may form temporary or permanent Working Groups to study special subjects, are responsible for coordinating the international work carried out in their respective fields and proposing recommendations concerning units. In order to ensure worldwide uniformity in units of measurement, the International Committee accordingly acts directly or submits proposals for sanction by the General Conference.

The Consultative Committees have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures* **31**, 1963, p. 97). Each Consultative Committee, the chairman of which is normally a member of the CIPM, is composed of delegates from the major metrology laboratories and specialized institutes, a list of which is drawn up by the CIPM, as well as individual members also appointed by the CIPM and one representative of the BIPM. These committees hold their meetings at irregular intervals; at present there are eight of them in existence.

1. *The Consultative Committee for Electricity* (CCE, Comité Consultatif d'Électricité), set up in 1927.
2. *The Consultative Committee for Photometry and Radiometry* (CCPR, Comité Consultatif de Photométrie et Radiométrie), new name given in 1971 to the Consultative Committee for Photometry set up in 1933 (between 1930 and 1933 the preceding Committee (CCE) dealt with matters concerning photometry).
3. *The Consultative Committee for Thermometry* (CCT, Comité Consultatif de Thermométrie), which for a time was called Consultative Committee for Thermometry and Calorimetry (CCTC) set up in 1937.
4. *The Consultative Committee for the Definition of the Meter* (CCDM, Comité Consultatif pour la Définition du Mètre), set up in 1952.
5. *The Consultative Committee for the Definition of the Second* (CCDS, Comité Consultatif pour la Définition de la Seconde), set up in 1956.
6. *The Consultative Committee for the Standards of Measurement of Ionizing Radiations* (CCEMRI, Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants), set up in 1958. In 1969 this Consultative Committee established four sections: Section I (Measurement of x and γ rays, electrons); Section II (Measurement of radionuclides); Section III (Neutron measurements); Section IV (α-energy standards). In 1975 this last section was dissolved and Section II made responsible for its field of activity.
7. *The Consultative Committee for Units* (CCU, Comité Consultatif des Unités), set up in 1964 (this Consultative Committee replaced the "Commission for the System of Units" set up by the CIPM in 1954).
8. *The Consultative Committee for Mass and Related Quantities* (CCM, Comité Consultatif pour la Masse et les grandeurs apparentées), set up in 1980.

The proceedings of the General Conference, the International Committee, the Consultative Committees, and the International Bureau are published under the auspices of the latter in the following series:

Comptes rendus des séances de la Conférence Générale des Poids et Mesures;

Procès-Verbaux des séances du Comité International des Poids et Mesures;

Sessions des Comités Consultatifs;

Recueil de Travaux du Bureau International des Poids et Mesures.
(This collection for private distribution brings together articles published in scientific and technical journals and books, as well as certain work published in the form of duplicated reports.)

The collection of the *Travaux et Mémoires du Bureau International des Poids et Mesures* (22 volumes published between 1881 and 1966) ceased in 1966 by a decision of the CIPM.

Since 1965 the international journal *Metrologia*, edited under the auspices of CIPM, has published articles on the more important work on scientific metrology carried out throughout the world, on the improvement in measuring methods and standards, on units, etc., as well as reports concerning the activities, decisions, and recommendations of the various bodies created under the Meter Convention.

Index

(Numbers in boldface indicate the pages where the definitions of the SI base units are to be found)

* U.S. G.P.O.:1991-281-557:40298

NIST *Technical Publications*

Periodical

Journal of Research of the National Institute of Standards and Technology—Reports NIST research and development in those disciplines of the physical and engineering sciences in which the Institute is active. These include physics, chemistry, engineering, mathematics, and computer sciences.
Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Institute's technical and scientific programs. Issued six times a year.

Nonperiodicals

Monographs—Major contributions to the technical literature on various subjects related to the Institute's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NIST, NIST annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NIST under the authority of the National Standard Data Act (Public Law 90-396). NOTE: The Journal of Physical and Chemical Reference Data (JPCRD) is published bi-monthly for NIST by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements are available from ACS, 1155 Sixteenth St., NW., Washington, DC 20056.

Building Science Series—Disseminates technical information developed at the Institute on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NIST under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The standards establish nationally recognized requirements for products, and provide all concerned interests with a basis for common understanding of the characteristics of the products. NIST administers this program as a supplement to the activities of the private sector standardizing organizations.

Consumer Information Series—Practical information, based on NIST research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

Order the **above** *NIST publications from: Superintendent of Documents, Government Printing Office, Washington, DC 20402.*

Order the **following** *NIST publications—FIPS and NISTIRs—from the National Technical Information Service, Springfield, VA 22161.*

Federal Information Processing Standards Publications (FIPS PUB)—Publications in this series collectively constitute the Federal Information Processing Standards Register. The Register serves as the official source of information in the Federal Government regarding standards issued by NIST pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NIST Interagency Reports (NISTIR)—A special series of interim or final reports on work performed by NIST for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Service, Springfield, VA 22161, in paper copy or microfiche form.

U.S. Department of Commerce
National Institute of Standards and Technology
Gaithersburg, MD 20899