Metric Review*

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In engineering, the international system of metric units prevails. Système International (SI) units common to audio engineering are reviewed, and SI equivalents are listed for older units that are vanishing from engineering practice.

A working rule of our *Journal* demands metric units, whenever possible, for the physical quantities discussed in its pages. The rule is not insisted upon merely to appear fashionable—although the United States is the last industrial country to cling to its customary set of nonmetric measures.[1] The Audio Engineering Society is international, and metric language as presented in *The International System of Units (SI)* is the language of choice to guarantee the surest communication of technical subject matter worldwide [1], [2].

Engineers who have entered the profession within the last 20 years may wonder what all the fuss is about. Others, having practiced before then, may still be uneasy. Accustomed to dealing simultaneously with pounds per cubic foot, dynes per square centimeter, oersteds, maxwells per square inch, and watts, sometimes in a single formula, they may not be reassured by language that allows only *one* base unit for length, *one* derived unit for power, *one* unit for pressure, and so on (the only SI unit in this sentence being the watt). But having worked with SI units, most engineers would have it no other way. There are fewer units to remember, large units are decimal multiples of small ones, and physical interrelationships are more easily perceived. An especially felicitous result, for electromagnetic and electromechanical work, is the appearance in frequently used engineering equations of multiplying constants that are unity, 1—no more 10^{-8} or 0.4π, or worse. The price of this convenience is what may seem to be peculiar numbers for some constants of nature,[2] but even these are easily remembered when they appear, as they usually do, in only one or a few places.

In recent years the *Journal* has reprinted pioneering papers on acoustics, microphones, recording, and loudspeaker design. Many of the formulas and experimental results in these early publications are given in non-SI units. For older and younger readers alike, the following tables are intended to facilitate the conver-

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[1] Metrication is the process in which an industry or a society discards nonmetric measures for their metric replacements. Although authorized by Congress, federal leadership of U.S. metrication appears to have fallen to pieces, mostly for lack of money, inspiration, or grass-roots support. Nevertheless, several industries for which metrication provided an immediate economic benefit are already metric; liquor now comes in 1-liter and 1.75-liter bottles, not quarts and half-gallons, and U.S. automobiles are metric, while most of the gasoline pumps are not.

[2] The historic choices of vacuum electric permittivity $\epsilon_0 = 1$ *and* vacuum magnetic permeability $\mu_0 = 1$ unavoidably produced two greatly different units for charge (and current), depending upon whether one were dealing with magnetics or with electrostatics. This fundamental embarrassment was papered over in various ways as different unit systems evolved. The SI, perhaps accepting nature as unlikely to oblige us by making any *natural* constant unity in order to fit *our* choice of units, provides a resolution of the matter by choosing the magnetic constant $\mu_0 = 4\pi/10^7$ henrys per meter, exactly. (In 1983, the same kind of choice was made for the speed of light c = 299 792 458 meters per second, exactly, with the result that the meter is newly *defined* as the distance through which light travels in vacuum in 1/299 792 458 second.) The electric constant, related to μ_0 by the speed of light, is therefore $\epsilon_0 = 1/\mu_0 c^2 = 10^7/4\pi(299\,792\,458)^2$ farads per meter, exactly.

sions between modern units and those of a receding era.[3]

The seven SI base units and two supplementary units are listed in Table 1. Units for all other quantities are *derived*, that is, formed of fractional combinations of these nine. For most electromagnetic and electromechanical formulas, only the first five quantities, in addition to plane angle, are needed.

Table 2 lists some of the derived units that have special names. Although the special names are nearly always used, it is not a requirement to do so; one may just as reasonably specify magnetic flux, for example, in volt-seconds as in webers, and in some cases it may be a more revealing designation. Additional derived units are listed in Table 3. Note that units named after persons are *not* capitalized when spelled out but *are* capitalized in the unit symbols, such as hertz and Hz. Typographical conventions, rules for combining unit symbols, and the particular physical definitions of the unit quantities are all given in [1]. Much useful advice for an author is found in [3].

[3] Tables are based on [1], [2].

Numerical SI prefixes, used to form units that are multiples or submultiples of the base and derived units, are shown in Table 4. Table 5 lists mechanical and magnetic units of other systems and their SI unit equivalents.

Finally, Table 6 shows recent, rounded values for physical constants often needed in electrical engineering and acoustics. All except the defined constants are obtained experimentally and are refined from time to time, so that some constants are known to more decimal places than others. Two quantities in the table, the density of air and the speed of sound, vary with temperature; the values given are simply convenient working numbers.

ACKNOWLEDGMENT

Preparation of this paper followed a suggestion by H. Peter Meisinger, who supplied many helpful comments and amendments as did John G. McKnight.

REFERENCES

[1] "The International System of Units (SI)," NBS

Table 1. SI base and supplementary units.

Quantity	Unit Name	Unit Symbol
SI base units		
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
SI supplementary units		
Plane angle	radian	rad
Solid angle	steradian	sr

Table 2. Some SI-derived units with special names.

Quantity	Unit Name	Unit Symbol	Definition in Other SI Units
Frequency	hertz	Hz	1/s
Force	newton	N	$m \cdot kg/s^2$
Pressure, stress	pascal	Pa	N/m^2
Energy, work, quantity of heat	joule	J	$N \cdot m$
Power, radiant flux	watt	W	J/s
Quantity of electricity, electric charge	coulomb	C	$A \cdot s$
Electric potential, potential difference, electromotive force	volt	V	J/C, W/A
Capacitance	farad	F	C/V
Electric resistance	ohm	Ω	V/A
Conductance	siemens	S	A/V
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	Wb/m^2
Inductance	henry	H	Wb/A
Celsius temperature	degree Celsius	°C	K
Luminous flux	lumen	lm	$cd \cdot sr$
Illuminance	lux	lx	lm/m^2
Volume	liter	L, l	$10^{-3}m^3$

Spec. Publ. 330, 1981. (For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402; price $3.25.)

[2] ANSI/IEEE Std. 268-1982, "American National Standard Metric Practice," Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, NY 10017.

[3] J. G. McKnight, "Quantities, Units, Letter Symbols, and Abbreviations," *J. Audio Eng. Soc.*, vol. 24, pp. 40–44 (1976 Jan./Feb).

Table 3. Some additional SI-derived units.

Quantity	Unit Name	Unit Symbol
Area	square meter	m^2
Volume	cubic meter	m^3
Speed, velocity	meter per second	m/s
Angular frequency	radian per second	rad/s
Acceleration	meter per second squared	m/s^2
Compliance	meter per newton	m/N
Torque*	newton meter	N·m
Dynamic viscosity	pascal second	Pa·s
Acoustic impedance	pascal second per meter	Pa·s/m
Density	kilogram per cubic meter	kg/m^3
Young's modulus	newton per square meter	N/m^2
Energy density	joule per cubic meter	J/m^3
Power density, acoustic intensity	watt per square meter	W/m^2
Specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg·K)
Electric field strength	volt per meter	V/m
Electric flux density	coulomb per square meter	C/m^2
Permittivity	farad per meter	F/m
Relative permittivity	(pure number)	
Resistivity	ohm meter	Ω·m
Conductivity	siemens per meter	S/m
Magnetomotive force	ampere	A
Magnetic field strength	ampere per meter	A/m
Permeance	henry	H
Reluctance	reciprocal henry	1/H
Permeability	henry per meter	H/m
Relative permeability	(pure number)	

* While SI specifies the newton meter as the unit for "moment of force," a reading of reference [2], paragraph 3.4.4, reveals that a more consistent unit for torque as an energetic quantity may be newton meter per radian (N·m/rad) or joule per radian (J/rad).

Table 4. SI prefixes

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

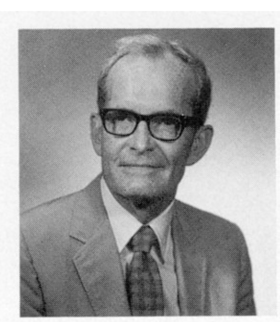
Table 5. SI equivalents of some non-SI units.

Unit Name	Unit Symbol	Equivalent in SI Units
angstrom	Å	10^{-10} m
inch	in	2.54×10^{-2} m
micron	μ	10^{-6} m
degree (angle)	°	$\pi/180$ rad
pound (avoirdupois)	lb	0.453 592 37 kg
metric ton (tonne)	t	10^3 kg
dyne	dyn	10^{-5} N
gram-force	gf	$9.806\,65 \times 10^{-3}$ N
pound-force	lbf	4.448 222 N
kilogram-force	kgf	9.806 65 N
dyne per square centimeter	dyn/cm^2	10^{-1} Pa
torr	Torr	(101 325)/760 Pa
millimeter of mercury at 0°C	mmHg	133.322 Pa
pound-force per square inch	lbf/in^2	6894.757 Pa
bar	bar	10^5 Pa
atmosphere	atm	101 325 Pa
erg	erg	10^{-7} J
foot pound-force	ft·lbf	1.355 818 J
calorie (thermochemical)	cal	4.184 J
British thermal unit	Btu	1055.056 J
kilowatt-hour	kWh	3.6×10^6 J
maxwell	Mx	10^{-8} Wb
maxwell per square inch, line per square inch	Mx/in^2	1.55×10^{-5} T
gauss, maxwell per square centimeter, line per square centimeter	Gs, G	10^{-4} T
gamma	γ	10^{-9} T
gilbert	Gb	$10/4\pi$ A
oersted	Oe	$1000/4\pi$ A/m

Table 6. Some physical constants useful in engineering.

Constant	Symbol	Rounded Value
Elementary charge	e	1.6022×10^{-19} C
Speed of light in vacuum	c	$2.997\,924\,58 \times 10^8$ m/s (defined value)
Electric constant (vacuum permittivity)	ϵ_0	$10^7/4\pi(299\,792\,458)^2$ F/m (defined value) $\approx 8.854\,188 \times 10^{-12}$ F/m
Magnetic constant (vacuum permeability)	μ_0	$4\pi \times 10^{-7}$ H/m (defined value)
Planck constant	h	6.626×10^{-34} J·s
Boltzmann constant	k	1.381×10^{-23} J/K
Faraday constant	F	9.648×10^4 C/mol
Standard acceleration of free fall	g_n	$9.806\,65$ m/s^2 (defined value)
Speed of sound in air	c	345 m/s
Density of air	ρ	1.18 kg/m^3

THE AUTHOR



G. Franklin Montgomery was born in Oakmont, Pennsylvania. After receiving a B.S.E.E. degree at Purdue University, he worked at the Naval Research Laboratory from 1941 to 1944 and then served for two years in the U.S. Army Signal Corps. From 1946 to 1978, he was an electronics engineer at the National Bureau of Standards, specializing in ionospheric research and electronic instrumentation. He is now a part-time consulting engineer and a consulting technical editor for the AES *Journal*. Mr. Montgomery is a member of the AES and a fellow of the IEEE.

Updated References for

“Metric Review” by G. Franklin Montgomery

J. Audio Engineering Society (Features), vol. 32, pp. 890...893 (1984 Nov.)

References Updated by J. McKnight, 2004-10-08

Note: Click on the web addresses below, and your browser should open the documents.

The information in “Metric Review” is still correct, but the referenced documents have been revised and redesignated. The current references are as follows:

[1] B. N. Taylor, Ed., “The International System of Units (SI),” NIST Spec. Publ. 330, 2001 ed. (Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325, USA.) Free download available at http://www.physics.nist.gov/Pubs/SP330/sp330.pdf .

Comment: NIST subtitles this document “Guide to the SI, with a Focus on History.” It is of limited interest to most AES *Journal* authors.

Many other useful papers on SI units are available at the NIST website, at http://www.physics.nist.gov/cuu/Units/index.html .

The entries on that page under the title “Essentials of the SI” give a nice summary of the SI for those having a limited interest in the SI *per se.*

[2] IEEE/ASTM SI 10-2002, “American National Standard for the Use of the International System of Units (SI): The Modern Metric System,” (Institute of Electrical and Electronics Engineers, New York, NY 10016-5997, USA). Available for download for 40 $ to IEEE members, or 50 $ to nonmembers, at http://shop.ieee.org/store/.

Comment: Most of this material is covered in the following free NIST publication:

B. N. Taylor, “Guide for the Use of the International System of Units (SI),” NIST Spec. Publ. 811, 1995 ed. (Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325, USA.) For a free download, it takes two steps (direct access doesn’t work): first go to http://www.physics.nist.gov/cuu/Units/bibliography.html , then under “References,” “Publication 811," click on “View Publication”.

This guide was prepared by the National Institute of Standards and Technology (NIST) to assist members of the NIST staff, as well as others who may have a need of such assistance, in the use of the SI in their work, including the reporting of results of measurements. This document gives rules and style conventions for printing and using units, for expressing the values of quantities, and for spelling unit names. Twenty-eight pages of factors are given for converting values of quantities expressed in various units — predominantly units outside the SI that are unacceptable for use with it — to values expressed either in SI units, or in units that are accepted for use with the SI.

[3] J. G. McKnight, “Quantities, Units, Letter Symbols, and Abbreviations," *J. Audio Eng. Soc., (Features)* , vol. 24, pp. 40...44 (1976 Jan./Feb.).

The information in this paper is still correct, but the referenced documents have been revised and redesignated. These references are being revised, and that revision will be posted on the AES website.