METRIC CONVERSION HANDBOOK

by

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Foreword

The United States of America is scheduled to undergo a major conversion from its customary system of measurement to the metric system. Of course metric units have been in use in our country for many years in many fields of endeavor. However, in a very few years metric units are to replace completely all of the customary units.

There will be problems. It will be quite expensive for all of us to make this complete conversion to the metric system. It will take a major effort to learn to understand the metric system and to use it properly. Of great help to us will be the present International System of Units because it greatly reduces the number of units we have to learn in the metric system, and because it links the many categories of measurement together into one sensible, coherent system. This book stresses the importance of the International System of Units.

The purpose of this book is to make the conversion easier for all of us.

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An Acknowledgement

In my opinion the National Bureau of Standards is the "last word" when it comes to measurement. This book is based primarily upon publications of the Bureau.

The Bureau joins similar governmental organizations throughout the world in making final decisions in the field of metrology, the science of measurement. A truly major accomplishment was the creation of the International System of Units (SI) with its precise definitions of critical units. The Bureau has also played a vital part in the development of many other definitions of units and concepts that have been adopted internationally. Examples include the acceptance of the standard acceleration of gravity, the definitions of the standard atmosphere, thermochemical calorie, inch, pound, etc.

A special thanks is extended to Louis E. Barbrow, Coordinator of Metric Activities for the National Bureau of Standards. He supplied me with several very valuable references including some of his own articles. He taught me about the survey units of length and area. It was his suggestion to identify the ambiguous mass-related units of force by labeling them as units of force. He advised me to emphasize the use of SI units for many categories of measurement. He further advised me in a private conversation in 1976 that it was his opinion that three non-SI metric units would gain strong acceptance: the liter, hectare, and the metric ton. The liter will likely have the symbol L in the United States and other English-speaking countries.

In 1977, the liter and metric ton were listed as units acceptable for use with SI, and the liter was given the symbol L for use in the United States. Furthermore, the hectare was recommended for use with SI in the United States.

Mr. Barbrow answered my many requests for help rapidly and completely. He even reviewed the whole book.

For the section on units of pressure, Mr. Barbrow provided me with the densities of water and mercury. The following is taken from his letter to me dated April 19, 1976:

"For the maximum density of water, my colleagues at NBS tell me that the PTB (Germany) 1971 value is the best available: 999.9720 kilograms per cubic meter at 3.98°C. Similarly, the NPL (England) 1961 determination of the density of mercury at 0°C is recognized as the best available: 13 595.080 kilograms per cubic meter."

If there are any errors in computations, they are mine. No one else checked my computations. However, I have made every effort and will continue my efforts to proofread and check the entire book to the best of my ability.

The choice of units included in the 17 categories of measurement is mine, although I did draw heavily on Mr. Barbrow's 1975 revision of an article on units of length, mass, area, and volume, published by the Bureau. Most of the other categories consist of units compounded from the basic units of length and mass and the familiar time units.

If this book helps people to make the conversion to the metric system, particularly to SI, it will have served its purpose. And eventually it will serve no other purpose than as a historical record of how complicated the field of measurement was before the metric era.

Marvin H. Green

Introduction and Guide

The primary purpose of this book is to provide accurate, detailed easy-access factors for converting to and from the United States customary and metric systems of measurement. The International System of Units is discussed in detail. It is basically a metric system that links the many categories of measurement together in one sensible, coherent system of units. It is properly abbreviated SI after the French Systéme International d'Unités, an abbreviation that will become familiar to everyone. Suggestions are made for easing the conversion from the customary system to SI, and most, but not quite all, of the units recommended for practical and scientific use are part of SI. In fact, a great many non-SI metric units should be replaced by SI units.

Conversion factors are provided for the following 17 categories of measurement:

1. Angular Measure
2. Area
3. Atomic Energy Units
4. Density and Concentration
5. Electricity and Magnetism
6. Energy
7. Flow
8. Force
9. Length
10. Light
11. Mass
12. Power
13. Pressure
14. Temperature
15. Time
16. Velocity
17. Volume

Pocket calculators are now relatively inexpensive and available in many stores. Most handle 8- or 10-digit numbers, and therefore the majority of the conversion factors in this book are presented with 10 significant figures. All calculations were made to at least 16-digit accuracy. Of course, in most cases and for most people, such accuracy will not be needed. However, it is easy to round off a 10-digit number to the desired number of digits. It requires a great deal of work to expand the number of digits from a few to many.

For those who require and demand great accuracy, this book provides the necessary factors. With so many excellent calculators available, there may develop a desire to expend the little extra effort required to handle 10-digit numbers.

The tables of conversion factors comprise the major portion of the book. Major features of the tables and a guide to their use are listed below:

1. The tables are separated from the text so that the reader may get to the conversion factors as easily and rapidly as possible.
2. The 17 categories are presented in alphabetical order.
3. Within each category (except temperature) units are listed in ascending order, and under each unit the conversion factors are also presented in ascending order.
4. To avoid any ambiguity, each table is headed by a statement like the following:

One KILOGRAM-FORCE PER SQUARE CENTIMETER is equal to:

5. All computations were made to at least 16-digit accuracy, and many were calculated beyond this point to make sure that factors were or were not exact.
6. All exact relationships are presented with only the number of digits required; unnecessary zeroes are not added. For example, one calorie is equal to exactly 4.184 joules and is presented as such.
7. All exact relationships are followed by an asterisk (*) and are presented without using the powers of 10.
8. Almost all inexact relationships are presented with 10 significant figures. Exceptions are factors for temperature, and for atomic energy units and pressure, which are based on measured values with less than 10-digit accuracy.
9. If more than 10 digits are required to show that a conversion factor is exact, the factor is presented with the required number of digits. For example, the bushel is shown to equal exactly 35.239 070 166 88 liters.
10. Numbers on either side of the decimal point are printed with a space separating each group of 3 digits. Commas are not used to separate numbers to the left of the decimal point. Commas were designated to be eliminated as far back as 1948 by international agreement. In some countries the comma is used instead of the decimal point.
11. All inexact factors between 0.1 and 0.000 001 are given in decimal form. Smaller factors use exponents of 10. Those inexact factors with more than 9 digits to the left of the decimal point are also presented using the powers of 10.
12. Abbreviations are used only to save space.

13. Each section except temperature concludes with a list of additional units that are generally not used as often as those in the tables. Electricity and magnetism, and light list additional categories as well as units.

14. The section on temperature differs in style from the other sections. It consists of equations, tables, and examples designed to provide the easiest means of converting from one scale to another.

The chapter titled "The International System of Units (SI)" is necessarily very technical. It presents the precise definitions of SI base, derived, and supplementary units written by international experts. This chapter discusses SI in general and lists many non-SI units that are accepted for use with SI and others that are not accepted. A table is included that lists the SI units and their symbols, and expressions in terms of other SI units. A second table presents the SI prefixes.

We must recognize SI as a truly great accomplishment by experts from many countries, one that has far-reaching importance for both the general public and the scientific community.

The chapter titled "Categories and Units of Measurement" is also technical. Each category is presented with the list of units included in the tables. Generally units are divided into metric and customary groups. Dimensions are presented and SI units listed and discussed.

Basic or definitive conversion factors are those like 1 mile is equal to 5 280 feet, 1 square yard equals 9 square feet, etc. This chapter provides such factors for the units in the following categories:

1. Angular Measure
2. Area
3. Length
4. Light
5. Mass
6. Time
7. Volume

In order to emphasize the importance of SI, this chapter presents only the relationships to the SI unit for all units, metric and customary, for the following categories:

1. Atomic Energy Units
2. Electricity and Magnetism
3. Energy
4. Force
5. Power
6. Pressure
7. Velocity

In two categories each unit is related to a unit that is not part of SI. For density and concentration the basic unit used is the gram per liter; the SI unit is the kilogram per cubic meter, which equals the gram per liter but is not used as frequently. For flow the basic unit used is the liter per second; the SI unit is the cubic meter per second and it is too large for practical purposes. The liter is not an SI unit, but it is used very widely and is acceptable for use with SI.

In "Categories and Units of Measurement" the conversion factors are presented following the rules used in the tables: numbers in ascending order in the metric and customary groups, mostly 10-digit numbers unless fewer or more digits are required to make the relationship exact, each exact relationship followed by an asterisk, etc.

The chapter titled "Suggestions for Easing the Conversion to SI" is the least technical chapter. Its primary purpose is to serve as a practical guide to the use of few units to replace many. Most of the units recommended for use are a part of SI, but there are exceptions.

Simplified conversion factors are presented with few significant figures, and asterisks are not used to indicate exact relationships because some of these relationships require many figures to become exact. Multiples of the primary SI units are recommended in many cases because they are more compatible numerically with the other unit in the relationship. For example, the kilometer is recommended as the replacement for the mile because it is numerically closer to the mile than is the meter, which is the primary SI unit.

This chapter concludes with a table of recommended units for each category except atomic energy units. The chapter demonstrates very clearly that in many categories a few SI units may and should be used to replace the many non-SI metric and customary units listed in the tables. For the categories listed below, the number of recommended units is presented together with the number of other units in the tables that they should replace:

1. Area: 4 replace 12
2. Density and Concentration: 1 replaces 17
3. Energy: 4 replace 13
4. Flow: 2 replace 14
5. Force: 2 replace 7
6. Length: 4 replace 12
7. Mass: 4 replace 11
8. Power: 4 replace 13
9. Pressure: 2 replace 16
10. Velocity: 2 replace 9
11. Volume: 2 replace 16

The chapter titled "Lists of Additional Units" provides details on the selection of units for the lists and the methods of presentation.

The International System of Units (SI)

The International System of Units, abbreviated SI after the French Systême International d'Unités, is the name given to a single, practical, worldwide system of units for international relations, teaching, and scientific work. It was adopted by the General Conference on Weights and Measures, which governs the International Committee for Weights and Measures, which in turn supervises the International Bureau of Weights and Measures. The National Bureau of Standards represents the United States in the activities and meetings of the General Conference.

A great advantage of SI is that there is a rationalized and coherent system consisting of base units, derived units, and supplementary units. The meter, kilogram, and second are three of the base units and are called the MKS group. A previously popular group, the centimeter, gram, and second, called the CGS group, is preferably not to be used with SI except in special circumstances.

BASE UNITS OF SI

There are seven well-defined base units in SI that by convention are regarded as dimensionally independent. The following definitions are copied from SI (ref 5).

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 KILOGRAM is the unit of mass equal to the mass of the international prototype of the kilogram.
3. 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.
4. 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.
5. The KELVIN, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

6. 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.

7. 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.

The only liberties taken with the definitions as presented in SI (ref 5) are that units have been capitalized, the reference uses the spelling metre (English) instead of meter (American), either of which is acceptable, and the reference presents the definitions in italics.

It is important to note that these base units are regarded as dimensionally independent *by convention*. This certainly simplifies the derivation of dimensions of units related to the base units. Obviously the ampere and candela could be considered dependent upon other units of measurement as noted in their definitions.

DERIVED UNITS OF SI

There are of course a great number of units that may be derived from the seven base units of SI. At this point the derived units that are important in this book are dealt with in brief; more detailed treatment is provided in the chapter "Categories and Units of Measurement."

One great advantage of SI is that the various categories of measurement and their SI units are linked together in a coherent, easily understood system.

The meter is the base unit for length, the kilogram is the base unit for mass, and the second is the base unit for time. These three base units and their fundamental categories of measurement serve as the bases for nine other categories of measurement in this book.

1. Area has the dimensions: length squared (l^2). Thus the SI unit is the square meter (m^2).

2. Volume has the dimensions: length cubed (l^3). Thus the SI unit is the cubic meter (m^3).

3. Velocity has the dimensions: length per time (l/t). The SI unit is the meter per second (m/s).

4. Flow has the dimensions: volume per time (l^3/t). In this case the SI unit is the cubic meter per second (m^3/s).

5. Density and concentration are really two categories of measurement treated in combination in this book, and they have the same dimensions:

mass per volume (m/l^3). The SI unit is the kilogram per cubic meter (kg/m^3).

6. Force has the dimensions: mass times acceleration (ma) and acceleration has the dimensions: length per time squared (l/t^2) thus force equals (ml/t^2). The SI unit is the kilogram-meter per second squared ($kg \cdot m/s^2$) which is called the newton (N).

7. Pressure has the dimensions: force per area (m/lt^2). The SI unit is the newton per square meter (N/m^2) which has recently been named the pascal (P).

8. Energy has the dimensions: force times length (ml^2/t^2). The SI unit is the newton-meter, called the joule (J).

9. Power has the dimensions: energy per time (ml^2/t^3). In this case the SI unit is the joule per second, which is called the watt (W).

The kelvin is the base unit for temperature although the Celsius scale is accepted as part of SI and is the commonly used metric scale.

Light is a form of energy that has its own system of units. There are four major categories of measurement of light included in this book. The candela (cd) is the base unit of luminous intensity. The other categories have derived SI units with the following definitions taken from ASTM (ref 6).

1. The LUMEN is the luminous flux emitted in a solid angle of 1 steradian by a point source having a uniform intensity of 1 candela.

2. The LUX is the illuminance produced by a luminous flux of 1 lumen uniformly distributed over a surface of 1 square meter.

The lumen (lm) is the SI unit of the category called luminous flux and the lux (lx) is the SI unit of the category called illuminance or illumination. The fourth category is luminance and the SI unit is the candela per square meter (cd/m^2).

There are 11 major categories of measurement of electricity and magnetism in this book. The ampere is the base unit of electric current and also of magnetomotive force. The other categories have derived SI units. The following definitions are from ASTM (ref 6).

1. The COULOMB (C) is the quantity of electric charge transported in 1 second by a current of 1 ampere.

2. The VOLT (V) is the difference of electric potential between two points of a conductor carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

3. The OHM (Ω) is the electric resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between these two points, produces in this conductor a current of 1 ampere, this conductor not being the source of any electromotive force.

4. The FARAD (F) is the capacitance of a capacitor between the plates of which there appears a difference of potential of 1 volt when it is charged by a quantity of electricity equal to 1 coulomb.

5. The HENRY (H) 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 a rate of 1 ampere per second.

6. The SIEMENS (S) is the electric conductance of a conductor in which a current of 1 ampere is produced by an electric potential difference of 1 volt.

7. The WEBER (Wb) is the magnetic flux which, linking a circuit of one turn, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second.

8. The TESLA (T) is the magnetic flux density given by a magnetic flux of 1 weber per square meter.

The SI unit of magnetic field strength is the ampere per meter. The eleventh category is magnetomotive force or magnetic potential difference and the SI unit is the ampere; note that the ampere is defined as a current which produces a force.

The SI expressions of the derived units of electricity and magnetism are presented in the table included in this section and are dealt with in detail in the chapter "Categories and Units of Measurement."

SUPPLEMENTARY UNITS OF SI

At this time there are only two supplementary units of SI and they may be regarded either as base units or as derived units. The following definitions are taken from SI (ref 5).

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

2. The STERADIAN (sr) is the solid angle which, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

Angular measure is included in this book, and the SI unit of angular measure is the radian. Although the second, minute, and degree of angular measure are not part of SI, they are important units and are widely used. They are therefore acceptable units for use with SI units.

UNITS OUTSIDE SI

An excellent and basic reference for the International System is SI (ref 5). This reference categorizes several groups of units which are outside

SI. These groups, and the units included in this book that fall into each group, are the following:

1. Units that are not part of SI but which are important and widely used: minute, hour, and day of time; degree, minute, and second of angular measure; liter, symbol L; metric ton (or tonne); and hectare.

2. Units with values expressed in SI units which must be obtained by experiment: electronvolt, unified atomic mass unit, astronomical unit, and parsec.

3. Units accepted temporarily: nautical mile, knot, angstrom, are, barn, bar, and standard atmosphere.

4. CGS units with special names that it is in general preferable not to use with SI: erg, dyne, gauss, oersted, maxwell, stilb, and phot.

5. Other units generally deprecated: metric carat which is also known simply as the carat, torr, kilogram-force, International Steam Table calorie, stere, the gamma which is related to the kilogram, the gamma which is related to the tesla, fermi, and micron.

Of particular interest at this point are the units with values which must be obtained by experiment. The astronomical unit and the parsec are included in this book as additional units of length. The electronvolt and the unified atomic mass unit are included in the category, atomic energy units, although the latter is included in terms of its equivalent energy. The following definitions are taken from SI (ref 5).

1. The ELECTRONVOLT (eV) is the kinetic energy acquired by an electron in passing through a potential difference of 1 volt in vacuum.

2. The UNIFIED ATOMIC MASS UNIT (u) is equal to the fraction 1/12 of the mass of an atom of the nuclide ^{12}C.

The following statement appears only as a footnote on page 16 in SI (ref 5), but it is quoted here because of its clarity of expression:

> "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."

TABLE OF SI UNITS

The categories of measurement listed in the table of SI units presented below include some groups. In some cases the grouping means that the categories have the same dimensions and units, as in the case of density and concentration. Work and quantity of heat are grouped with energy because they are both forms of energy. On the other hand, illuminance and illumination are grouped because they are different names for the same category, although illuminance is preferred.

The symbols are from SI (ref 5).

Expressions in terms of SI base units are presented using exponents although some references prefer using negative exponents in lieu of the solidus (/). A dot should be used to indicate the product of two or more units but may be dispensed with when there is no risk of confusion with another unit sysmbol: N•m or N m means newton times meter, but mN means millinewton.

Category of Measurement	*Name of SI Unit*	*Symbol of SI Unit*	*Expression in Terms of Other SI Units*	*Expression in Terms of SI Base Units*
length	meter	m		m
mass	kilogram	kg		kg
time	second	s		s
area	square meter	m^2		m^2
volume	cubic meter	m^3		m^3
velocity, speed	meter per second	m/s		m/s
flow	cubic meter per second	m^3/s		m^3/s
density, concentration	kilogram per cubic meter	kg/m^3		kg/m^3
force	newton	N		$kg \cdot m/s^2$
pressure, stress	pascal	Pa	N/m^2	$kg/(m \cdot s^2)$
energy, work, quantity of heat	joule	J	N•m	$kg \cdot m^2/s^2$
power, radiant flux	watt	W	J/s	$kg \cdot m^2/s^3$
angular measure, plane angle	radian	rad		rad
thermodynamic temperature	kelvin	K		K

Category of Measurement	*Name of SI Unit*	*Symbol of SI Unit*	*Expression in Terms of Other SI Units*	*Expression in Terms of SI Base Units*
luminous intensity	candela	cd		cd
luminous flux	lumen	lm		cd•sr
luminance	candela per square meter	cd/m^2		cd/m^2
illuminance, illumination	lux	lx	lm/m^2	$cd\cdot sr/m^2$

Category of Measurement	*Name of SI Unit*	*Symbol of SI Unit*	*Expression in Terms of Other SI Units*	*Expression in Terms of SI Base Units*
electric current	ampere	A		A
electric charge, quantity of electricity	coulomb	C		A•s
electric potential, potential difference, electromotive force	volt	V	W/A	$kg\cdot m^2/(s^3\cdot A)$
electric resistance	ohm	Ω	V/A	$kg\cdot m^2/(s^3\cdot A^2)$
electric capacitance	farad	F	C/V	$s^4\cdot A^2/(kg\cdot m^2)$
electric inductance	henry	H	V•s/A	$kg\cdot m^2/(s^2\cdot A^2)$
electric conductance	siemens	S	A/V	$s^3\cdot A^2/(kg\cdot m^2)$
magnetic flux	weber	Wb	V◦s	$kg\cdot m^2/(s^2\cdot A)$
magnetic flux density, magnetic induction	tesla	T	Wb/m^2	$kg/(s^2\cdot A)$
magnetic field strength	ampere per meter	A/m		A/m

Category of Measurement	*Name of SI Unit*	*Symbol of SI Unit*	*Expression in Terms of Other SI Units*	*Expression in Terms of SI Base Units*
magnetomotive force, magnetic potential difference	ampere	A		A
amount of substance	mole	mol		mol
solid angle	steradian	sr		sr

SI PREFIXES

The table below presents the prefixes to be used with units of SI. Barbrow is the source of the prefixes exa and peta, and their symbols, in his 1975 revision of the article written by Judson in 1960: Barbrow and Judson (ref 1).

The names of the numbers are not usually given in official documents. The names in the table are those used in the United States where the billion means 1 000 million. The British billion equals 1 000 000 million, and 1 000 million is the British milliard.

Factor	*Prefix*	*Symbol*		*Name*
10^{18}	exa	E	1 000 000 000 000 000 000	quintillion
10^{15}	peta	P	1 000 000 000 000 000	quadrillion
10^{12}	tera	T	1 000 000 000 000	trillion
10^{9}	giga	G	1 000 000 000	billion
10^{6}	mega	M	1 000 000	million
10^{3}	kilo	k	1 000	thousand
10^{2}	hecto	h	100	hundred
10^{1}	deka	da	10	ten
10^{-1}	deci	d	0.1	tenth
10^{-2}	centi	c	0.01	hundredth
10^{-3}	milli	m	0.001	thousandth
10^{-6}	micro	μ	0.000 001	millionth
10^{-9}	nano	n	0.000 000 001	billionth

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