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THE METRICATION OF THERMAL ANALYSIS OR CONVERSION TO SI UNITS*

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Countries in many parts of the world are requiring the use of the International System of Units (abbreviated SI) in commerce. These requirements are already in effect in Australia, New Zealand and some other countries. The European Community members put their requirements into force by 21 April 1978. Since that date, all items of commerce sold within these countries have been required by law to be labeled in SI units as their primary labeling. All trade literature, operator's manuals, and applications briefs must also be written in SI units. Since the passage of the Metric Conversion Act of 1975, metrication activity has also accelerated in the U.S. This is only the latest step, however, of nearly 400 years of activity directed at a worldwide uniform system of measurements.

The decimal system of measurements was conceived in the 16th century by the Flemish mathematician Simon Stevins to try to put into order the great confusion of units of weights and measures then in use Fig. 1. It was not, however, until over 200 years later that the French National Assembly requested the Paris Academy of Science to work out a system of units suitable for adoption by the entire world. The result of their study was a system based on the meter as a unit of length and the gram as a unit of mass. Their system was adopted in France as a practical measure to benefit industry and commerce. The advantages of the system were soon recognized by the scientific community and was almost universally adopted for scientific use.

Although the need for a uniform system of weights and measures was recognized by the founding fathers of the United States, it was not until 1866 that the metric system was legalized in the U.S. In 1893, the international meter and kilogram became the primary standards of weights and measures in the United States.

After evolving for nearly four centuries, a particular metric system, called the International System of Units, was adopted by the 11th General Conference of Weights and Measures in 1960. Since that date, SI has become almost universal in use. The United States is one of the last of the world's major nations to be committed to using this metric system.

The International System of Units is a modernized, rationalized version of the metric system. It is a consistent system with seven base units for which names, symbols,

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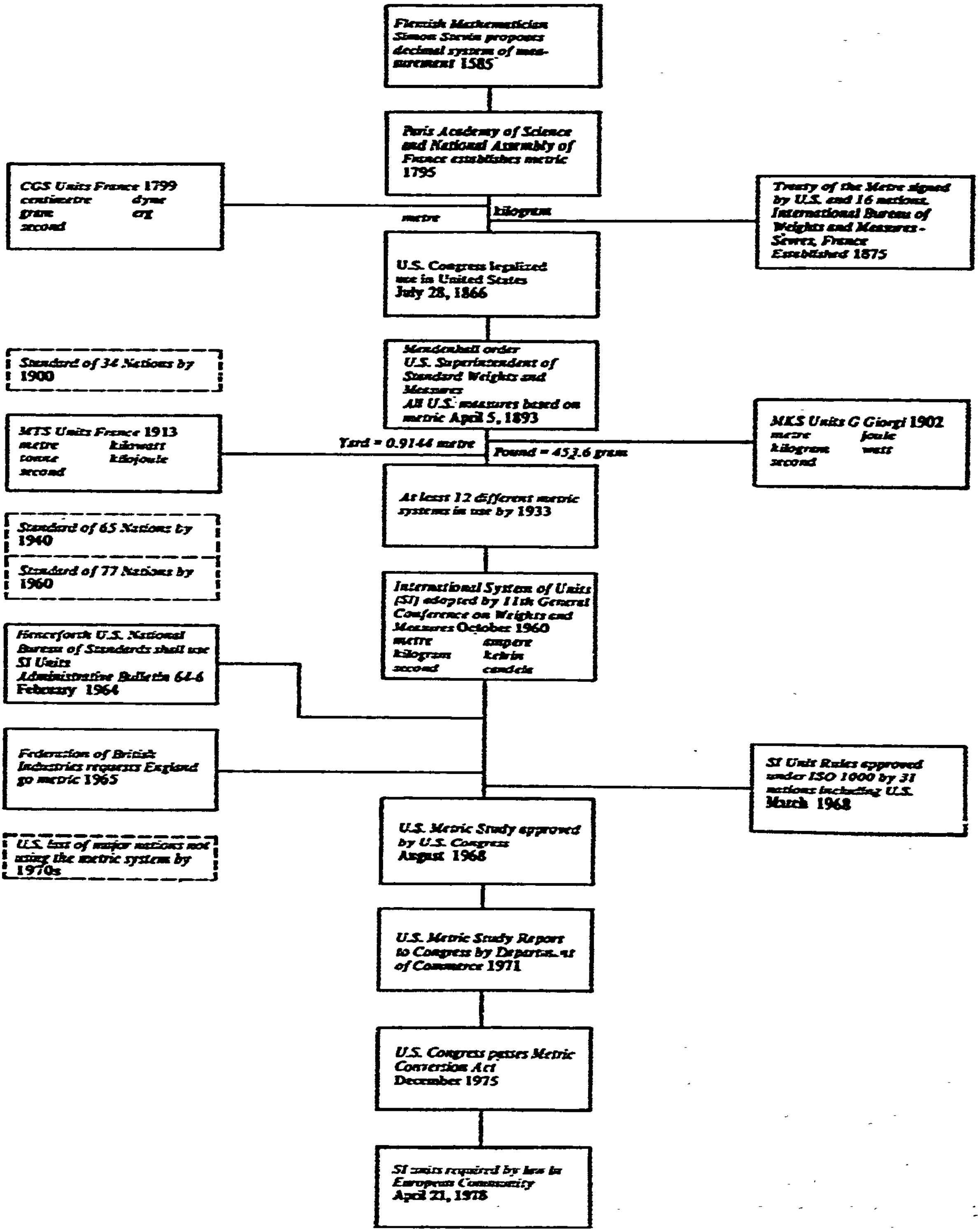

Fig. 1. Metric milestones.

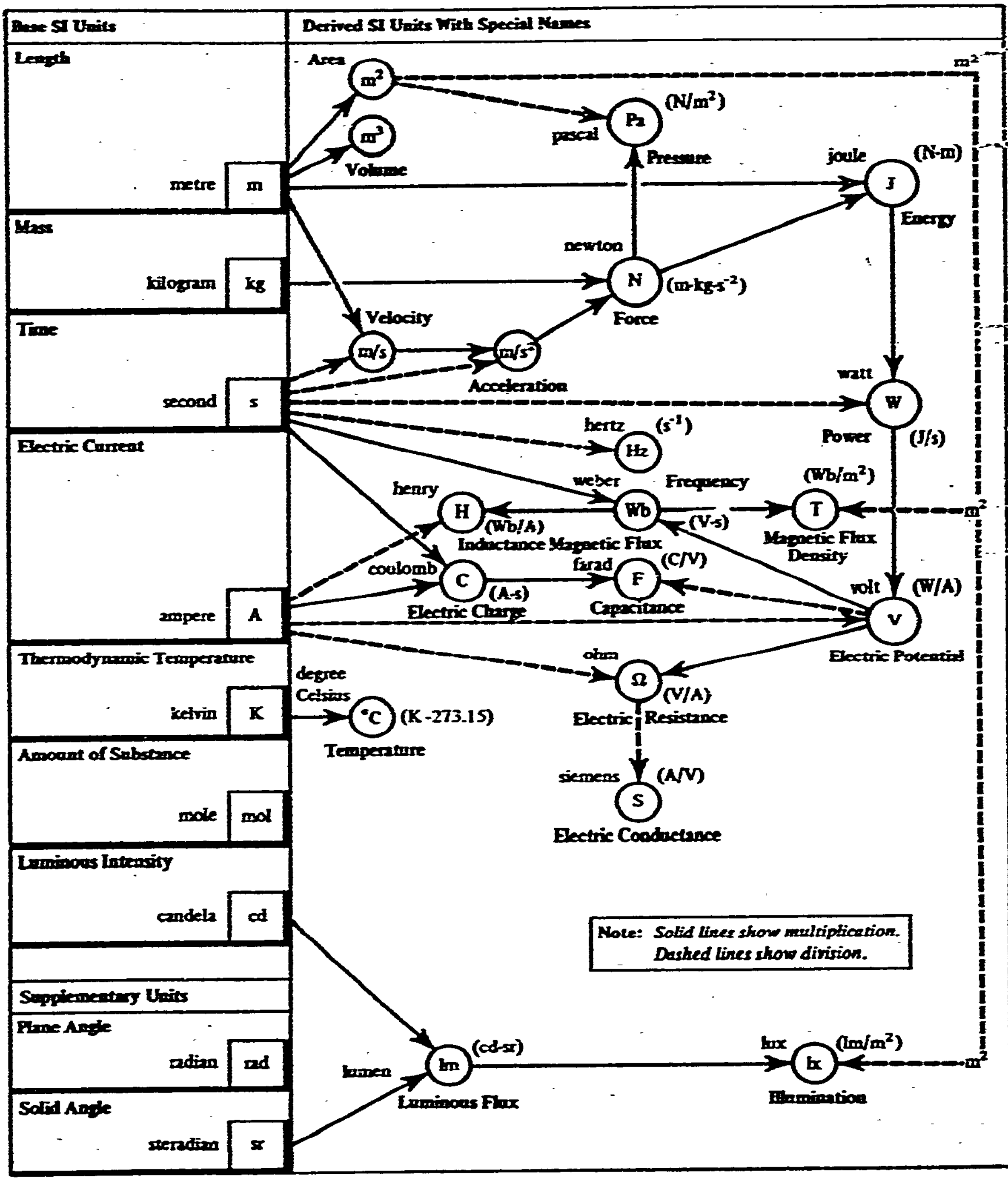

Fig. 2. Basic and derived SI units. Reproduced from Eng. Dig. (Toronto), September, 1972).

and precise definitions have been established. The great advantage of SI is that there is one and only one unit for each physical quantity measure.

While SI is a metric system, it uses a very specific set of metric measurements. For this reason, the scientist, who has used metric units for all of his professional career, should not assume that the metric units with which he is familiar, are consistent with SI usage. Workers in thermal analysis have, by tradition, used a number of units not permitted in SI. While the milligrams measured by a thermogravimetric analyzer are SI units, they may be displayed on a recorder calibrated in inches. Other techniques, such as differential scanning calorimetry and thermomechanical analysis have used less metric notation. Thus the thermal analyst should be preparing himself to give up the millicalorie and to think in terms of millijoules and similar SI units.

There are seven basic SI units: the meter (length), kilogram (mass), second (time), ampere (electric current), kelvin (thermodynamic temperature), mole (amount of substance), and candela (luminous intensity). Two additional supplementary units are added to measure plane and solid angles. From these nine basic quantities, all other acceptable derived units are created by algebraic combination. Figure 2 illustrates the lines of derivation for some of the more important derived units. Solid lines represent term multiplication, and broken lines show divisions. For example, the SI unit of force is the newton. It is derived from the product of mass (kilogram) and acceleration. Acceleration itself is a derived unit equal to length (meter) per square time (second). Thus the newton is the force which, when applied to a body having a mass of one kilogram, gives it an acceleration of one meter per second squared (kgm/s^2).

technique	name	symbol
DSC	milliwatt	mW
TGA	milligram	mg
TMA	micrometer	μm
DTA	kelvin	°C or K
DMA	hertz	Hz
	decibel	dB
TEA	nanogram/second	ng/s
MEA	microgram	μg

Fig. 3. Primary thermal analysis units.

Figure 3 illustrates the acceptable SI units expected to be used in thermal analysis. The only variations expected are the choices between temperature in kelvin or degrees Celsius and in the units of time. Of course, the magnitude of quantities can be varied through individual selection of prefixes.

To aid the scientist who is not familiar with the SI system, the remaining portion of this paper will be devoted to the use of, and conversion to the use of SI units, particularly as it applies to thermal analysis. For a more complete guide to SI units, any number of guidelines, practices, handbooks, etc. exist. This author particularly recommends *The Metric Editorial Guide* published by the American National Metric Council (1625 Massachusetts Avenue, N.W., Washington, D.C. 20036) and *Standard for Metric Practice* published by the American Society for Testing and Materials (1916 Race Street, Philadelphia, PA 19103). A number of the examples used here are taken from these works.

Primary SI units, and their symbols, encountered in thermal analysis are tabulated in Fig. 4. Unit names, including prefixes, are not capitalized except at the beginning of a sentence or in titles. The short forms for units are called symbols. They are lower case except that the first letter is upper case when the name of the unit is derived from the name of a person.

The primary SI units are modified in size through the use of prefixes. In general, each prefix modifies the primary unit by steps of three orders of magnitude, although a few double and single order of magnitude prefixes are used near unity. The SI prefixes, their numerical modification values and their symbols are given in Fig. 5. Notice that the symbols for the top five prefixes are upper case and all the rest lower case. It is important to follow the precise use of upper case and lower case letters lest

property	unit name	unit symbol
length	meter	m
weight	kilogram	kg
time	second	s
temperature	kelvin	K
energy	joule	J
force	newton	N
pressure or modulus	pascal	Pa
frequency	hertz	Hz
temperature	degree	deg C, °C
power	watt	W

Fig. 4. Primary SI units and symbols.

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

* seldom used and not recommended

Fig. 5. SI prefixes.

G for giga	g for gram
K for kelvin	k for kilo
M for mega	m for milli
N for newton	n for nano
T for tera	t for metric ton
A for ampere	a for atto
P for peta	p for pico Pa for pascal
h for hecto	h for hour Hz for hertz

Fig. 6. Use of upper case and lower case symbols.

no space following prefix ...

kA	kiloampere
mg	milligram

space between number and symbol ...

22 mg

Fig. 7. Use of spaces.

considerable confusion occur. For example, G is the symbol for giga, and g that for gram. Other sources of confusion are shown in Fig. 6.

When prefixes are used either in symbols or names, no space is left between the prefix and the name or symbol it modifies. A space, however, is used between a number and the symbol to which it refers. Examples are given in Fig. 7.

Prefixes should never be used by themselves. Thus the correct description for 1000 grams is a kilogram not a "kilo". Similarly, use of the symbol gamma (γ) for microgram and lambda (λ) for microliter are not permitted.

More than one modifying prefix should not be used. For example, an electrical capacitor should be rated in picofarads (pF) not micromicrofarads ($\mu\mu$F). Similarly, only one prefix should be used with an expression. Thus, the density of a material is expressed in kilograms per cubic meter (kg/m^3) and not milligrams per cubic centimeter (mg/cm^3) even though their numberical value is equivalent.

One exception which is not "pure" SI, but which is ordinarily acceptable, is the case of potentiometric recorder sensitivities which are ordinarily established in small electromotive force units per unit of chart length. Thus millivolts per centimeter (mV/cm) is ordinarily acceptable for a recorder sensitivity.

The names of units are plural when appropriate. Thus we see 1 meter and 100 meters.

For single values, numbers less than 1 should be avoided and an appropriate prefixed unit used instead. Values less than one are permitted if part of a series (e.g. 0.5, 1.0, and 2.0 mm). Fractions should be avoided and decimal notations used in their place. Values less than 1 take the singular form of the unit name (e.g. 0.5 kilogram).

A period (Fig. 8) is not used after a symbol except at the end of a sentence. In North America, a period or dot on the line is used as a decimal marker, although a comma may be used in some countries for this purpose. In numbers less than unity, a zero should be written before the decimal point to prevent the possibility that a faint decimal point will be overlooked. For example, the oral expression "point seven five" is written 0.75.

For ease in reading, digits may be separated into groups of three, counting from the decimal marker. Commas (,) should not be used. Instead, spaces are left

not used following symbols...

A heat flow of 2 mW is observed...

The sample measured 10 x 15 x 50 mm.

used as decimal markers...

A temperature change of 3.7°C was created.

The oral expression "point seven five" is written 0.75.

Fig. 8. Use of periods and decimal markers.

space at three digital intervals from decimal marker...

for 4,720,525	write 4 720 525
for 0.52875	write 0.528 75
for 6,875	write 6875 or 6 875
for 0.6875	write 0.6875 or 0.687 5

Fig. 9. Grouping of numbers.

correct	incorrect
newton meter	newton·meter
newton–meter	
N m	
N-m	
5.2 x 6	5.2·6

Fig. 10. Compound units, products.

correct	incorrect
meter per second	meter/second
m/s	meter/s
m · s^{-1}	m per s
	m /second
meter per second squared	meter per second per second
m/s^2	m/s/s

Fig. 11. Compound units, quotients.

	preferred		permitted
The slope is	1/100	not	10 mm/m
	0.01		10 m/km
	1%		

Fig. 12. Ratios.

to avoid confusion, since many countries use a comma for the decimal marker. In a four-digit number, the space is not required unless the four-digit number is in a column with numbers of five digits or more. Some examples are shown in Fig. 9.

When writing symbols for units such as square meter or cubic centimeter, write the symbol for the unit, followed by the superscript ^{2} or ^{3}, respectively.

In many cases, the measured quantity will be in compound units, that is more than one unit. An example is that of force moment, shown in Fig. 10, which is the product of force and length. For cases where the compound name (not symbol) is derived as a product, a hyphen is recommended between the individual unit names. A space alone is also permitted here. A "product dot" (a period raised to a centered position) is never used with unit names. The product dot is limited for use with symbols. The product dot should not be used as a multiplier symbol for use in calculations.

For cases where the compound name (not symbol) is derived as a quotient, such as the case of velocity shown in Fig. 11, it is preferable not to use a solidus (/) as a substitute for "per". Use only one "per" in any combination of units unless parentheses are used to avoid ambiguity. Avoid mixing of words and symbols.

The solidus is reserved for use with symbols as an indicator of quotient. The negative exponent may also be used to indicate a division. The use of more than one solidus is not permitted unless parentheses are used to avoid any ambiguity.

Ratios, in which the numerator and denominator contain like quantities, are a special case (Fig. 12). To eliminate the problem of what units and multiples to use, such quantities should be expressed as either a common or decimal fraction or as a percentage. Parts per million (ppm), and similarly derived English expressions, are not permitted.

A few problems of pronunciation may be encountered. Several common mispronunciations are presented in Fig. 13.

One last work of caution should be noted. When converting from one unit of measurement to another, care should be taken not to extend the number of significant figures. Thus the often admired hourglass 36–24–36 inch figure is converted in SI to 91–61–91 centimeters not to 914.4–609.6–914.4 millimeters.

Let us now look at some specific measurements and their units.

joule	rhymes with <u>pool</u>.
pascal	rhymes with <u>rascal</u>.
kilometer	pronounced as <u>kill'</u> oh meter
mu	pronounced as <u>mew</u> not moo
giga	pronounced as <u>jig</u> a

Fig. 13. Pronunciation.

Length

The use of meters (m) and/or millimeters (mm) is the generally preferred unit of length in "pure" SI writing. Although centi- is an SI prefix, the use of centimeters (cm) is usually restricted to non-technical writing but may be encountered in thermal analysis work. The meter is the primary SI unit of length.

Common conversions are

inch	equals	25.40 mm
		2.54 cm
mil	equals	25.40 μm

Area

The primary unit of area is the square meter (m^2). Other acceptable units include square centimeter (cm^2) and square millimeter (mm^2).

Volume

The cubic meter (m^3) is the primary SI unit of volume. Cubic centimeter (cm^3), cubic millimeter (mm^3), and similar units are also acceptable.

Because of their widespread use, the liter (l) and milliliter (ml) are acceptable units for use with fluids (both gases and liquids). No prefix other than milli should be used with liter.

Mass (Weight)

The primary unit of mass is the kilogram (kg). This unit is too large for most applications in thermal analysis and gram (g) and milligram (mg) will be most often encountered.

A common conversions is

lb equals 0.4536 kg

Temperature

When expressing temperature in SI units, use degrees Celsius (deg C). Every degree Celsius corresponds to 1.8 degrees Fahrenheit (deg F). Since this is approximately a two-to-one ratio, for equivalent resolution, each Fahrenheit degree would correspond to approximately 0.5 degrees Celsius. Therefore, in converting from Fahrenheit to Celsius, whole numbers of degrees Fahrenheit are normally converted to the nearest 0.5 degree Celsius. When the Fahrenheit temperature is approximate, convert to the nearest whole number on the Celsius scale.

The kelvin (K) is the primary SI unit for temperature. The magnitude of the degree Celsius is the same as the kelvin, and either may be used to express a temperature interval.

Common conversions are

$$\text{deg C} \quad \text{equals} \quad \frac{5}{9}(\text{deg F} - 32)$$

$$\text{K} - 273.16$$

Time

Conventional time units, while not "pure" SI, are used in the system. Seconds (s), minutes (min), hours (h), days (d), and years (a for annum) are all used. The second, however, is the primary SI unit and is the unit most often encountered in thermal analysis usage.

Common conversions are

s equals 1.667×10^{-2} min

2.778×10^{-4} h

Frequency

The unit for frequency in the SI system is the same as the conventional system. 1 hertz (Hz) is equivalent to a reciprocal second (s^{-1}).

Date

The international standard for calender dates in all numerical format is to list the numbers in descending order of unit size. Thus, the order is year–month–day–hour–second, i.e. the date of 2:30 on September 26, 1977, is written

1977	– 09	– 26	– 14	– 30
year	month	date	hour	minute

Energy (enthalpy, heat, work)

The traditional thermal analysis unit of heat, the millicalorie, is not in SI. The primary SI unit of heat is the joule (J). A small unit, the millijoule (mJ), will be most often encountered in thermal analysis work.

A common conversion is

mJ equals 0.2387 mcal

Power (heat flow)

Differential scanning calorimeters measure differential heat flow or power. The traditional thermal analysis unit of measurement has been the millicalorie per second. These units are quite useful since, when integrated over time, they produce the previously desired unit of energy, the millicalorie.

The SI unit of heat flow, however, is the watt (W), and DSC's measure milliwatt (mW) signal levels. A milliwatt is equal to a millijoule per second (mJ/s) and thus integrating the DSC signal over time still produces the desired energy unit (mJ). A millicalorie is about four times the size of the milliwatt.

Common conversions are

mW equals mJ/s
0.2387 mcal/s

Pressure

The SI unit of pressure is the pascal (Pa). Since this is a small unit, the usually encountered values will be in the kilopascal (kPa) range.

correct	incorrect
kPa, absolute,	kPa a
kPa gage	kPa g

...4 kilopascals absolute pressure...

...a gage pressure of 4 kilopascals...

Fig. 14. Pressure.

The bar (b) is also a temporarily acceptable SI unit and is used in some (particularly European) countries. However, North American practice prescribes the use of the pascal and its multiples and "strongly discourages" the use of the bar.

Other units such as the torr, the atmosphere or millimeters of mercury are not permitted.

All pressures are usually measured in the absolute sense in SI (Fig. 14). Occasionally, a "gage" pressure may be encountered. Gage pressure is absolute pressure minus ambient pressure. It is positive or negative (vacuum) according to whether the pressure is higher or lower, respectively, than the ambient pressure. Absolute pressure is specified either by using the phrase "absolute pressure" or by adding the word "absolute" after the unit symbol separating the two by a comma or a space. Do not add to the unit symbol either a "g" for gage or an "a" for absolute.

Common conversions are

Pa	equals	N/m^2
		$10\ dyne/cm^2$
		7.501×10^{-3} mm Hg
		7.501×10^{-3} torr
kPa	equals	0.145 psi
		9.869×10^{-3} atm
		10^{-2} bar

Modulus

Modulus is a force per unit area and thus is a pressure unit. The SI unit of pressure is the pascal (Pa).

Common conversions are

Pa	equals	N/m^2
		$10\ dyne/cm^2$
		1.45×10^{-4} psi

Viscosity

Viscosity is defined as the ratio of the shear stress (a force) to the shear rate (a frequency). The SI unit of force is the pascal and that of frequency is reciprocal seconds. Thus the unit of viscosity is the pascal second (Pa s).

$$\frac{\text{shear stress}}{\text{shear rate}} = \frac{\text{Pa}}{\text{s}^{-1}} = \text{Pa s}$$

The poise, which is equal to 1 dyne second per square centimeter, is not permitted. Fortunately, the centipoise, the commonly used unit for liquid viscosity, is equivalent to the millipascal second.

Common conversions are

Pa s	equals	10 poise
		$10\ dyne\ sec/cm^2$

In conclusion, let me add a word or two about our experience with the human part of converting to the use of SI. Initially, the suggested use of SI met with some modest resistance from the people in our laboratory. It was clear that on their own, they would choose not to convert to the use of SI on its own merits.

When it became policy that SI was to be used exclusively after a specific, near term date, most people quickly converted to its use. Indeed, those who had already made the transition to SI, good naturedly teased those who continued to use traditional units about their use of an "archaic" and "obsolete" system. The result of this good-natured, genial ribbing was that everyone made the transition to SI before the required date.

The key to the transition, however, is the availability of a series of specific statements about the syntax and units of SI. People need to know what SI is before they can use it. The two references mentioned earlier and presentations like this one, meet that need.

Let me offer a few suggestions on how to go about incorporating SI into your laboratory.

(a) Check your organization's policy on conversion to SI. Most companies are aware of SI and are already planning to implement it. Larger companies may even have an SI coordinator who will be glad to help you.

(b) Provide each worker with a specific (readable) statement on the syntax and units of SI. *The Metric Editorial Guide* (published by the American National Metric Council, 1625 Massachusetts Ave., N. W., Washington, DC, 20036) is suggested.

(c) Set a specific, near term date for the exclusive use of SI. This date should be no more than a year away. Our laboratory made the transition easily in six months.

(d) Begin immediately to use SI. All new reports, letters, and papers should use SI. Do not wait until the last minute.

(e) Use SI as the primary system followed by traditional values in parentheses. Those who are not used to SI can thus still operate, but get the concept that SI is preferred.

Our experience with the transition to SI has been a very positive one. I hope that yours is too.