ASME PTC 2-2001
[Revision of ASME PTC 2-1980 (R1985)]

DEFINITIONS AND VALUES

PERFORMANCE TEST CODES

An American National Standard

The American Society of Mechanical Engineers

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The next edition of this Code is scheduled for publication in 2006. There will be no addenda issued to this edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Code. Interpretations are published on the ASME Web site under the Committee Pages at http://www.asme.org/codes/ as they are issued.

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FOREWORD

Precise definitions of terms and exact values of constants employed in the various Performance Test Codes of this Society are fundamentally important. This Code is intended to provide standard definitions and values required by each respective Performance Test Code (PTC) and to supplement each of them. The principal purpose of this Code (PTC 2), *Definitions and Values*, is to provide a source for any item used by more than one of the PTC committees reporting to the Board on Performance Test Codes. This Code is an outgrowth of five previous codes concerning definitions and values issued and adopted by the Society, and it supersedes them.

A draft of the first edition was printed in the December 1921 issue of Mechanical Engineering and was presented to the Society during the spring meeting held in Atlanta, Georgia the following May. On January 21, 1926, the first such code was approved and adopted by Council as a standard practice of the Society. The second edition of this code was approved by Council on May 14, 1931.

Beginning in June 1936, a thorough review and a complete rewriting of this code was undertaken, and the fruits of this labor were adopted by Council on June 17, 1945. In June, 1969, Performance Test Code Committee No. 2, acting under instructions from the Standing Committee on Performance Test Codes, proceeded to revise this Code, the draft of which was presented to the Society as a paper during the 1970 Winter Annual Meeting in New York. It was adopted in final form by action of the Policy Board on Codes and Standards on February 26, 1971.

The last major revision of this Code began in 1972 to incorporate metrication and the use of Systeme International (SI) units. The values of many of the physical constants and conversion factors were brought up to date as well. The 1980 Code was approved by the Performance Test Codes Supervisory Committee on February 26, 1979, and it was approved as an American National Standard by the ANSI Board of Standards Review on July 21, 1980.

The Code presented herein was revised by the PTC 2 Project Team and approved by the Board on Performance Test Codes on May 29, 2001. This Performance Test Code was also approved as an American National Standard by the ANSI Board of Standards Review on October 31, 2001.

NOTICE

All Performance Test Codes **MUST** adhere to the requirements of **PTC 1, GENERAL INSTRUCTIONS**. The following information is based on that document and is included here for emphasis and for the convenience of the user of the Code. It is expected that the Code user is fully cognizant of Parts I and III of PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures which yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests. They specify procedures, instrumentation, equipment operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree **before starting the test and preferably before signing the contract** on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

BOARD ON PERFORMANCE TEST CODES

(The following is the roster of the Committee at the time of approval of this Code.)

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SECTION 2
MEASUREMENT OF PERFORMANCE

2.1 INTRODUCTION

The Codes provide test procedures which yield results of the highest level of accuracy consistent with the best engineering knowledge and practice, taking into account the cost of tests and monetary value of efficiency to industry. Performance of equipment is determined in part by measurements of physical quantities. A measurement consists of sensing a physical variable and translating this result into data that is either indicated or recorded. Analog data are indicated by the position of a pointer on a dial or by a point or line on a chart. Digital data are indicated by a visual display of numbers or by a numerical printout. Devices used to make measurements are called instruments but many devices called instruments must be used with additional components to measure certain physical variables and quantities. A millivoltmeter, for example, can measure voltage but a thermocouple must be used in conjunction with the voltmeter to obtain a temperature measurement.

2.2 MEASUREMENT SYSTEM

In order to make a measurement of a physical quantity it must first be sensed, and the information about the energy change due to sensing must be transmitted to a component that communicates the data. The requirements for measurement are met by the system shown in Fig. 2.2.

The primary element is that part of the measurement system that first senses the variable to be measured. The energy change produced by the sensing must be transmitted to an information-communicating unit where it may be used directly or changed (transduced) to some other form to indicate or record data. The measurement system may be very simple or very complex but the three functions appearing in Fig. 2.2 are required to make a physical measurement. The measurement system may be a single component such as a liquid-in-glass thermometer where the sensing is done by the bulb, the transmitting by the liquid column, and the data display by the scale. On the other hand, the measurement system may be multi-component such as flow measurement with orifices where the primary element (the orifice) causes fluid acceleration to produce a pressure differential which is transmitted via tubing to a manometer where the data are displayed on the scale.

2.3 UNCERTAINTY OF MEASURING SYSTEMS

Measurement of a physical quantity never continuously gives a result which is correct in an absolute sense. The numerical value determined nearly always differs by some amount from the true value, and the extent of the deviation (called error) depends upon the type of measurement system used. Code writers and test engineers must demonstrate that the test measurements used will provide results sufficiently accurate to accomplish the purposes of the test.

The accuracy obtainable for a given measurement is dependent upon the following three components:

(a) the characteristics of the measured quantity,

(b) the accuracy of the observation, and

(c) the measurement system used.

(1) The intrinsic accuracy of the measurement system.

(2) The in-situ conditions of its use.

Item (c)(1) is generally well treated by most engineers and data concerning measurement system components is given in the Instruments and Apparatus Supplements. Item (c)(2) is often responsible for gross errors of measurement. Specific analysis is necessary for each application and installation.

ASME PTC 19.1, *Test Uncertainty*, defines *accuracy* as the closeness of agreement between a measured value and the true value; *error* as the difference between the true value and the measured value; and *uncertainty* as a numerical estimate of the error.

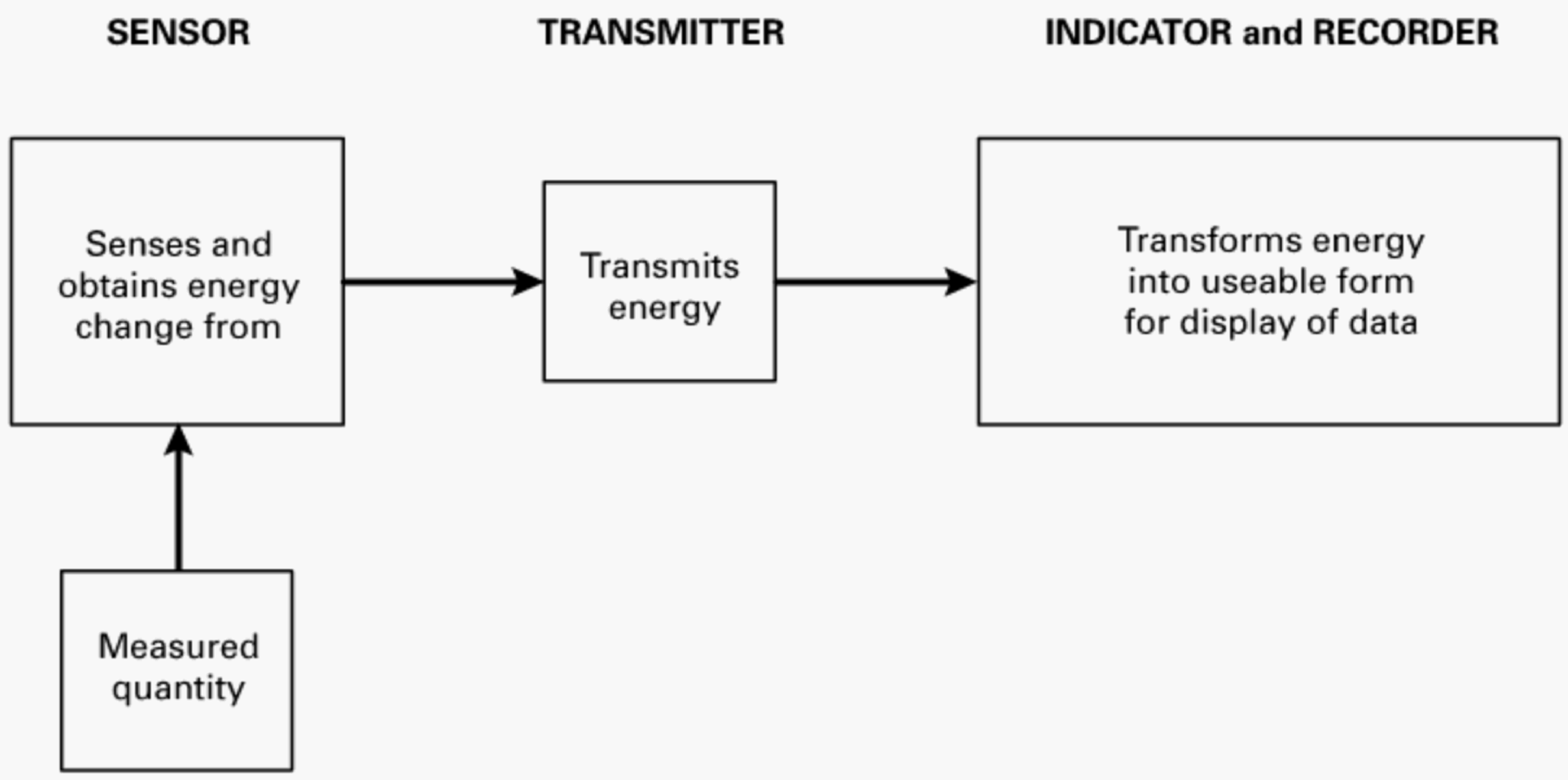

FIG. 2.2 MEASURING SYSTEM

2.4 INTRINSIC ACCURACY

The intrinsic or inherent accuracy of a measurement system depends upon

(a) materials,

(b) construction, and

(c) physical condition at time of use.

While the inherent accuracy of the first two items can be estimated from published data concerning an individual measuring system component, the actual accuracy at the time of use must be determined by calibration. For this reason, all significant and primary measuring system components must be calibrated or checked before and after PTC tests to establish the effect of their physical condition on inherent accuracy, unless there is no cause for their calibration to change.

2.5 IN SITU CONDITIONS

The accuracy of a measurement system as used depends upon its ability to

(a) sense the variable to be measured,

(b) transmit energy change,

(c) apply or transduce energy, and

(d) display data.

The last two items are essentially independent of use unless environmental conditions such as vibration, temperature, humidity, etc., are of such magnitude as to prevent normal operation. If care is taken to ensure proper environmental conditions, then the communication function of accuracy is simply the intrinsic accuracy of the components.

2.6 OBSERVATION ACCURACY

Accuracy of observation depends primarily upon the following two factors:

(a) accidental mistakes, e.g., misreading of scales, parallax, incorrect log entries, failure to perform some required manipulation, etc.; and

(b) personal characteristics, e.g., ability to interpolate between graduations, bias in observation (tendency to read high or low), speed of observation.

These types of errors may be minimized (but never completely eliminated) by selection and training of test personnel, by selection of scales with easily-read graduations, and by other human-factor engineering. Modern technology permits the design of instrument systems that will give digital printout, and the use of these should be encouraged to eliminate observation error when their inherent accuracy and in situ conditions permit. However, digital systems may contain programming mistakes, and these systems must be debugged thoroughly.

2.7 SENSING ACCURACY

The accuracy of sensing depends upon the following factors:

(a) Effect of the Primary Element on the Measured Quantity

For example, a Pitot tube installed in a flow stream to sense a local velocity must be designed so that its presence does not change the original velocity profile.

SECTION 3 DEFINITIONS

3.1 PRIMARY DEFINITIONS AND SYSTEMS OF UNITS

The dimensions of mass, length, and time are related to forces as follows in the various systems of units.

A force of one pound applied to a mass of one slug (also known as the geepound) will accelerate the mass at the rate of one ft/sec^2.

A force of one newton applied to a mass of one kilogram will accelerate the mass at the rate of one m/s^2.

Equations written in these units will appear identical. Converting measured values from the U.S. customary units to the primary pound-slug-second system of units will simplify the expression of test results in Systeme International (SI).

By way of contrast and for clarification, a force of one pound applied to a mass of one pound will accelerate the mass at a rate numerically equal to "g_c" ft/sec^2. This fact is the origin of the appearance of the conversion factor, g_c, in engineering equations expressed in the U.S. customary units. Note that g_c is not the local acceleration of gravity at the test site; it is simply a ratio of masses and a constant.

3.2 HISTORICAL DEFINITIONS OF UNITS OF MEASURE

It is often useful to be aware of the historic physical bases for many of the units of performance measurement. The reader is cautioned that the numerical values of these physical definitions have been refined over the years, so that the following historic definitions may be no longer numerically exact. Nonetheless, the embodied physical concepts can improve one's understanding of a measurement or test result. The current values and definitions for use are given starting in para. 3.3.

boiler horsepower: standardized by the ASME in 1889, it was based on an engine steam rate of 30 lbm of steam per horsepower-hour at 70 psig and a feedwater temperature of 100°F. This corresponds to 34.5 lbm/hr evaporated from and at 212°F (33,475 Btu/hr). At the time of standardization, boilers were rated by manufacturers at one horsepower hour per 10 ft^2 of surface heated. Boiler horsepower no longer has much significance in steam generator performance.

British thermal unit (Btu): a unit of energy equal to that needed to raise the temperature of one pound-mass of air-free water from 60°F to 61°F at a constant pressure of one standard atmosphere; the mean Btu is equal to $^1/_{180}$ of the energy needed to raise one pound-mass of air-free water from its freezing point to its boiling point at a constant pressure of one standard atmosphere.

calorie: the amount of energy required to raise the temperature of one gram of pure water from 14.5°C to 15.5°C at a constant pressure of one standard atmosphere.

Celsius scale: invented in 1742 by Anders Celsius, a Swedish astronomer, who graduated the interval between the freezing point and the boiling point of water into one hundred degrees (hence centigrade) at an atmospheric pressure of 760 mm of mercury. The present scale has the freezing point at 0 deg and the boiling point at 100 deg, just the reverse of the numbering by Celsius.

Fahrenheit scale: the temperature scale used by Daniel Gabriel Fahrenheit who invented a thermometer containing alcohol in 1709 and a mercury thermometer in 1714. The zero point on the scale was established by mixing equal quantities by weight of snow and common salt. The freezing point was found to be at 32 deg of graduation and the boiling point very near 212 deg under standard atmospheric pressure.

foot: $^1/_3$ of a yard, originally based on the length of a man's foot.

force: the influence on a body which causes it to accelerate; quantitatively, it is a vector, equal to the body's time rate of change of momentum; units of pound or newton; also see para. 3.1.

For water, two commonly-used bulk moduli are defined corresponding to isothermal and isentropic processes. Empirical equations have been developed and are available to calculate these two numbers for water.

combustion: the process of rapid oxidation of fuel. Unit rate of combustion may be defined as follows.

(a) *All fuels:* heating value of fuel as fired per unit of furnace volume per unit time, Btu/(ft^3-hr) [W/m^3].

(b) *Mass burning of solid fuels:* mass of fuel as fired per unit of grate surface area per unit time, lbm/(ft^2-hr) [kg/(m^2-s)].

(c) *Gaseous fuels:* volume of gas fired per unit of furnace volume per unit time, ft^3/(ft^3-hr) [m^3/(m^3-s)].

condenser, surface: a device which reduces a thermodynamic fluid from its vapor phase to its liquid phase. In the case of steam, the rate of heat transfer is:

$$q = w_c\,(h_2 - h_1) = w_v\,(h_3 - h_4)\ \text{Btu/hr [J/s]}$$

where

w_c = cooling water, lbm/hr [kg/s]
w_v = steam condensed, lbm/hr [kg/s]
h_1 = enthalpy of cooling water entering condenser, Btu/lbm [J/kg]
h_2 = enthalpy of cooling water leaving condenser, Btu/lbm [J/kg]
h_3 = enthalpy of steam entering condenser, Btu/lbm [J/kg]
h_4 = enthalpy of water in hotwell, Btu/lbm [J/kg]

The values of all the enthalpies except h_3 are obtainable from temperature readings and the ASME steam tables (latest edition). The value of h_3 must be determined indirectly because practical procedures for measuring average steam quality exhausting the steam turbine into the condenser have not been developed. Until direct measurement becomes possible, the indirect methods prescribed in ASME PTC 12.2, *Steam Surface Condensers,* shall be used.

density: the mass per unit volume of a material at a specified pressure and temperature.

Water density values are given in the latest ASME steam tables. Dry air density values are tabulated in the latest ASHRAE *Thermodynamic Properties of Refrigerants.*

efficiency, ideal cycle: the ratio of the work of the ideal cycle to the heat supplied. This efficiency is often termed ideal engine efficiency.

efficiency, engine: the actual work of a system divided by the work of a corresponding ideal system. Since indicated, brake, or combined actual work may be involved, three engine efficiency measurement values are possible.

efficiency, thermal: defined as the work done divided by the heat supplied for any engine turbine, entire plant, or power island.

$$\text{indicated thermal efficiency} = \frac{AW_i}{Q}$$

$$\text{brake thermal efficiency} = \frac{AW_b}{Q}$$

$$\text{combined thermal efficiency} = \frac{BW_k}{Q}$$

where

A = 2544.43 Btu/(hp-hr) [1 J/(W–s)]
B = 3412.14 Btu/(kW–hr) [1 J/(W–s)]
Q = heat added, Btu [J]
W_i = indicated net work, hp–hr [J]
W_b = brake net work, hp–hr [J]
W_k = combined net work, kW–hr [J]

The thermal efficiency of a complete plant is expressed similarly to that of a turbine or engine.

efficiency, volumetric (η_v): applies only to positive displacement machinery. The volumetric efficiency of centrifugal or other kinetic machinery cannot be obtained because there is no measurable displacement.

For compressors:

$$\eta_v = \frac{\text{volumetric capacity of compressor}}{\text{displacement}}$$

For pumps:

$$\eta_v = \frac{\text{actual pump delivery}}{\text{displacement}}$$

efficiency, isentropic compression: the ratio of theoretical isentropic power to the fluid power developed.

efficiency, mechanical: the ratio of actual work to internal work for a turbine or engine, and the inverse for a pump or compressor.

efficiency, overall, compressor: the ratio of isentropic power to the actual power supplied.

energy of a substance, internal: a state variable; its change from one state to another is independent of the process which produces the change. Internal energy changes, rather than absolute values, are of importance. Internal energy may be set to any convenient base. For steam this base has been set at the triple point, 32°F and 0.0891 psia (273.15 K and 611.2 Pa). The symbol for internal energy is u and its units are Btu/lbm [J/kg].

enthalpy: the sum of internal energy plus the product of the volume and the pressure. It is also known as the sensible, or total, heat or heat content. It may be expressed as:

$$h = u + pv/J \qquad \text{Btu/lbm [J/kg]}$$

where

h = enthalpy, Btu/lbm [J/kg]
u = internal energy, Btu/lbm (J/kg)
p = pressure of fluid, lbf/ft^2 [Pa]
v = specific volume of fluid, ft^3/lbm [m^3/kg]
J = mechanical equivalent of heat, 778.169 262 (ft–lbf)/Btu, 4.184 J/cal, [1J / J]

entropy: a term first coined by Clausius to mean "transformation." Only changes in entropy can be measured; an overall increase in entropy measures a loss in the ability to do work. S is measured in units of heat/temperature. Unlike energy, entropy is not conserved in nature. The rate of production of entropy serves as the index of irreversibility.

evaporator: a thermodynamic device in which liquid is changed to vapor phase by the addition of heat. The mathematical description of the heat transfer involved is:

$$q = w_e (h_2 - h_1); \text{ or,}$$
$$q = w_s (h_v - h_f) \text{ Btu/hr [W]}$$

where

w_e = mass evaporated per unit time, lbm/hr [kg/s]
w_s = mass of steam condensed per unit time, lbm/hr [kg/s]
h_1 = enthalpy of entering water, Btu/lbm [J/kg]
h_2 = enthalpy of leaving steam, Btu/lbm [J/kg]
h_f = enthalpy of condensed water, Btu/lbm [J/kg]

The first equation is preferred as the second produces higher values if heat is lost during the process.

flow: the rate of passage of a quantity of material through a fixed reference surface per time, measured either in units of mass/time or volume/time.

fuel rate: for solid and liquid fuels, the mass of fuel fired per unit of output. For gaseous fuels it is defined as ft^3 of gas at 59°F and 14.696 psia per unit of output [m^3 at 15°C and 101.325 kPa]. Fuel rates should be qualified by reference to the unit of output.

furnace volume, total: the original scope of the PTC Committee limited the use of furnace volume to steam generators. Since this volume may be used for other equipment, it shall be as defined by the individual code.

grate surface: the horizontal fuel or combustible supporting structure within the walls of a furnace. This would also include fluidized bed support surface.

gravity, standard: international standard gravity is defined at sea level, latitude of 45°32′33″ and equals an acceleration of g_o = 9.806 65 m/s^2 = 32.174 06 ft/sec^2. Sea-level acceleration of gravity at any specified latitude can be calculated from the equation:

$$g_\phi = 999.95 \times 10^{-3} g_o (1 - 2.637\,3 \times 10^{-3} \cos 2\phi + 5.9 \times 10^{-6} \cos^2 2\phi)$$

where

ϕ = latitude, deg
g_ϕ = sea-level acceleration of gravity at latitude ϕ, m/s^2
g_o = international standard gravity, 9.806 65 m/s^2

A tabulation of sea level gravity corrections for selected latitudes is presented in ASME PTC 19.2, *Pressure Measurement.*

Variation of free-air acceleration of gravity with elevation above or below sea level can be calculated from the equation:

$$g_H = g_\phi - 3.086 \times 10^{-6} H$$

where

H = height above or below sea level, m ($H > 0$ above sea level; $H < 0$ below sea level)
g_ϕ = sea-level acceleration of gravity at latitude ϕ, m/s^2
g_H = acceleration of gravity at height H, above or below sea level and latitude ϕ, m/s^2

A tabulation of free-air gravity correction values for selected elevations is presented in ASME PTC 19.2.

ASME PTC 19.2 presents gravitational acceleration values for selected U.S. locations; values for selected international locations are given in the American Institute of Physics Handbook.

heat absorption, rate of: energy absorbed per unit time, Btu/hr [J/s].

heat rate: the classic definition of heat rate is the reciprocal of the thermodynamic efficiency of a prime mover, such as a combustion or steam turbine, or of an entire power plant or power island. It is an indication of how much thermal input is required to produce a unit of power.

heat rate = Q/P, Btu/kWhr [dimensionless]
Q = heat input, Btu/hr [kJ/s]
P = power, kW [kW]

For each type of prime mover or plant, the heat input, Q, is further defined in each applicable Code.

When there are secondary heat inputs or outputs, such as steam for the process generated by a cogeneration power plant, the heat rate is expressed at the specified reference values of those secondary heat flows. Measured heat rate is corrected to the reference values of the secondary heat flows at the test boundary.

Heat rate can be considered from either gross power or net power.

heat transfer coefficient: the energy transmitted per unit area of heating surface per temperature difference per unit time, Btu/(ft^2–°R–hr) [W/(m^2–K–s)]

heat exchanger: a thermodynamic device which transfers heat between two fluids. The rate of heat transfer is

$$q = w_f (h_1 - h_2) \text{ Btu/hr [W]}$$

where

w_f = heat exchanger fluid rate, lbm/hr [kg/s]
h_1 = enthalpy of fluid at inlet, Btu/lbm [J/kg]
h_2 = enthalpy of fluid at outlet, Btu/lbm [J/kg]

heating value: heat released from the rapid oxidation of fuel. Heating value of fuels is determined in accordance with the following codes:
ASME PTC 3.1, *Diesel and Burner Fuels*
ASME PTC 3.2, *Solid Fuels*
ASME PTC 3.3, *Gaseous Fuels*

Each code will specify using either the higher or lower heating value, typically expressed in units of Btu/lbm, [kJ/kg].

Water vapor is one of the products of combustion for all fuels which contain hydrogen. The lower or higher heating value of a fuel depends on whether this water vapor is allowed to remain in the vapor state or is condensed to liquid. In a bomb calorimeter, the products of combustion are cooled to the initial temperature and all of the water vapor formed during combustion is condensed to liquid. This gives the higher, or gross, heating value of the fuel with the heat of vaporization included in the reported value. For the lower, or net heating value, it is assumed that all products of combustion remain in the gaseous state.

While the higher, or gross, heating value can be accurately determined by established (ASTM) procedures, direct determination of the lower heating value is difficult. Therefore, it is usually calculated.

horsepower: the term was originated by Boulton and Watt to state the power of their steam engines. In a practical test, it was found that the average horse could work constantly at a rate of 22,000 (ft-lb)/min. This was increased arbitrarily by half to define the now universal unit of power: 550 (ft-lb)/sec.

hydrocarbons: any chemical compounds containing only hydrogen and carbon; these are frequently used as fuels. Physical properties in NIST database IDMIX permits the determination of thermodynamic and transport properties of fluid mixtures of various pure gases and heavy hydrocarbons.

ice point: the temperature of an equilibrium mixture of liquid and frozen pure water melting under one standard atmospheric pressure absolute (273.15 K).

internal combustion cycles: for internal-combustion engines, several cycles are in common use, e.g., the Otto and Diesel cycles. It is possible to compute an engine efficiency of ideal cycles. For PTC work, all internal-combustion engine thermal efficiencies shall be determined by a measured work output divided by measured heat input. Engine efficiency shall not be calculated as based on any idealized cycle for internal-combustion engines.

mean effective pressure: for an engine, the work divided by its displacement. Combined brake, friction, or indicated mean effective pressures may be calculated by using the applicable definition and values for work.

mercury, density of: density of mercury at 32°F [0°C] is 0.491 154 lbm/in^3 [13 595.1 kg/m^3]. Density at other temperatures may be computed from the equation:

$$\rho_t = 13\,595.1/(1 + 1.184\,56\times10^{-4}t + 9.205\times10^{-9}t^2 + 6.608\times10^{-12}t^3 + 6.732\times10^{-14}t^4)$$

where

t = temperature of mercury, °C

ρ_t = density of mercury at temperature t, kg/m^3

sound: acoustic output of a machine or process is its sound power (W). This is usually expressed as a sound power level in decibels. Sound power cannot be measured directly. Instead, sound pressures are measured and sound powers calculated therefrom. Modern instrumentation has imbedded this computational capability. Sound pressures (p) are usually expressed as sound pressure levels, also in decibels. A decibel is the logarithmic expression of the ratio of a quantity to a particular reference quantity. The reference quantity for sound power levels (W_o) is 1 pW and that for sound pressure levels (p_o) is 20 μPa, hence

sound power level (dB) = 10 $\log_{10}$ (W/W_o)

sound pressure level (dB) = 20 $\log_{10}$ (p/p_o)

output, net: of an engine and generator unit, defined by the formula:

$$\text{Net output (kW)} = \begin{pmatrix}\text{electrical power}\\ \text{output of}\\ \text{generator (kW)}\end{pmatrix} - \begin{pmatrix}\text{auxiliary}\\ \text{power}\\ \text{supplied (kW)}\end{pmatrix}$$

Auxiliary power supplied is that external power necessary for the unit's operation and includes, but is not limited to, excitation power, power for separately driven lube oil pumps, hydraulic oil pumps, generator cooling water pumps, fans for generator ventilation, and seal evacuators.

power, air or gas: the equations for air power invoke a compressibility factor K_p in this fashion

$$P = \left\{(p_2 - p_1)\, Q_1\, K_p + m\left[(\alpha_2\, V_2^2 - \alpha_1\, V_1^2)/2g_c + g\,(Z_2 - Z_1)/g_c\right]\right\}/A$$

where

P = power, hp [W]

$$K_p = \ell n\, \frac{p_2/p_1}{\frac{p_2}{p_1} - 1}$$

(for a reversible isothermal process)

$$K_p = \frac{\gamma}{\gamma - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right] \Big/ \left[\frac{p_2}{p_1} - 1\right]$$

(for an isentropic process)

$$K_p = \frac{n}{n - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n - 1}{n}} - 1\right] \Big/ \left[\frac{p_2}{p_1} - 1\right]$$

(for a reversible polytropic process)

K_p = 1 [for a reversible isochoric process (constant density)]

γ = ratio of specific heats

n = polytropic exponent

p_1 = inlet pressure, lb/ft^2 [Pa]

p_2 = outlet pressure, lb/ft^2 [Pa]

Q_1 = volumetric flow rate, ft^3/sec [m^3/s]

α_1 = kinetic energy factor at inlet

α_2 = kinetic energy factor at outlet

V_1 = average velocity at inlet, ft/sec [m/s]

V_2 = average velocity at outlet, ft/sec [m/s]

Z_1 = elevation at inlet, ft [m]

Z_2 = elevation at outlet, ft [m]

g = acceleration due to gravity, ft/sec^2 [m/s^2]

g_c = conversion factor, 32.174(ft–lbm)/(lb–sec^2) [1(m–kg)/(N–s^2)]

A = conversion factor, 550 (ft–lb)/(hp–sec) [1(N–m)/(W–s)]

power, water: the energy flux contained in flowing water. Water power is to be computed from the equation

$$P_w = g\rho Q\,(H_1 - H_2)\,/A = Q\,(p_1 - p_2)\,/A$$

where

P_w = water power, hp [W]

ρ = density of water, slug /ft^3 [kg /m^3]

Q = volumetric flow, ft^3/sec [m^3/s]

H_1 = higher head, ft [m]

H_2 = lower head, ft [m]

p_1 = higher pressure, lbf/ft^2 [Pa]

p_2 = lower pressure, lbf/ft^2 [Pa]

A = 550 (ft–lbf) /(hp–sec) [1 W/W]

g = local acceleration of gravity, ft/sec^2 [m /s^2]

All heads and pressures shall be measured at, or corrected to, stagnation conditions.

pressure: a force distributed over an area in units of force/area.

pumps: internal energy added to the fluid by the pump is manifested as an increase in enthalpy, some of which is mechanical energy, and the remainder is heating.

$$E_p = (h_2 - h_1) \quad \text{Btu/lbm [J/kg]}$$

where

h_1 = measured enthalpy at pump inlet, Btu/lbm [J/kg]

h_2 = measured enthalpy at pump discharge, Btu/lbm [J/kg]

Numerical values for all water enthalpies shall be taken from the latest ASME steam tables[1] including the work of isentropic compression of water (Δh_s).

$$\Delta h_s = (h_{s2} - h_1) \text{ Btu/lbm [J/kg]}$$

in which h_{s2} is derived from the pressure of the pump discharge, and the entropy at the pump inlet.

The internal losses and the internal efficiency of a pump may be deduced from the following:

Internal losses = $(h_2 - h_1)-(h_{s2} - h_1)$ Btu/lbm [J/kg]

Internal efficiency = $100(h_{s2} - h_1)/(h_2 - h_1)$ percent

Any compression (except isothermal) will raise the water temperature. Higher pressures produce higher temperature rises.

specific heat: c, of a substance is the amount of energy required to effect a temperature increase in a unit mass of the substance, which is path- or process-dependent.

For gases, two process paths are used. One is the specific heat at constant pressure, c_p; the other is the specific heat at constant volume, c_v. For a unit mass, these are defined

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

and

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

where

h = enthalpy, Btu/lbm [J/kg]

u = internal energy, Btu/lbm [J/kg]

T = temperature, °R [K]

c = specific heat, Btu/(lbm–°R) [J/(kg–K)]

NBS circular 565 (1955), *Tables of Thermal Properties of Gases*, provides specific heat data for air, argon, carbon dioxide, carbon monoxide, hydrogen, nitrogen, oxygen, and steam.

standards, primary: by statute authority, the following exact conversion factors between the SI units and the U.S. Customary units have been adopted and published by the National Institute of Standards and Technology:

1 ft = 0.304 8 m

1 in. = 0.025 4 m = 25.4 mm

1 lbm = 0.453 592 37 kg

1 ft^3 = 0.028 316 85 m^3

Standard atmospheric pressure
= 14.695 95 lbf/in.^{2}
= 101.325 N/m^2

Standard acceleration of gravity
= 32.17 406 ft/sec^2
= 9.806 65 m/s^2

These data were taken from NBS Miscellaneous Publication 286, May 1967.

steam cycle, Rankine: the Rankine steam cycle consists of:

(a) Isentropic expansion of steam from the initial state to the exhaust pressure.

(b) Condensation at constant pressure and temperature to saturated liquid.

(c) Isentropic compression of the liquid to the initial pressure.

(d) Heating, evaporating, and superheating (if any) at constant pressure to the original steam conditions.

steam cycle efficiency, Rankine: this equation expresses the ideal cycle efficiency, defined in *efficiency, ideal cycle,* of the Rankine steam cycle defined previously.

$$\eta = \frac{(h_1 - h_s) - (\text{ideal pump work})}{h_1 - (h_f + \text{ideal pump work})}$$

where

h_1 = initial enthalpy of steam, Btu/lbm [J/kg]

h_s = enthalpy after isentropic expansion, Btu/lbm [J/kg]

h_f = enthalpy of saturated liquid at exhaust pressure, Btu/lbm [J/kg]

[1] For fluids other than water use an appropriate mutually agreed standard of reference (see Appendix A).

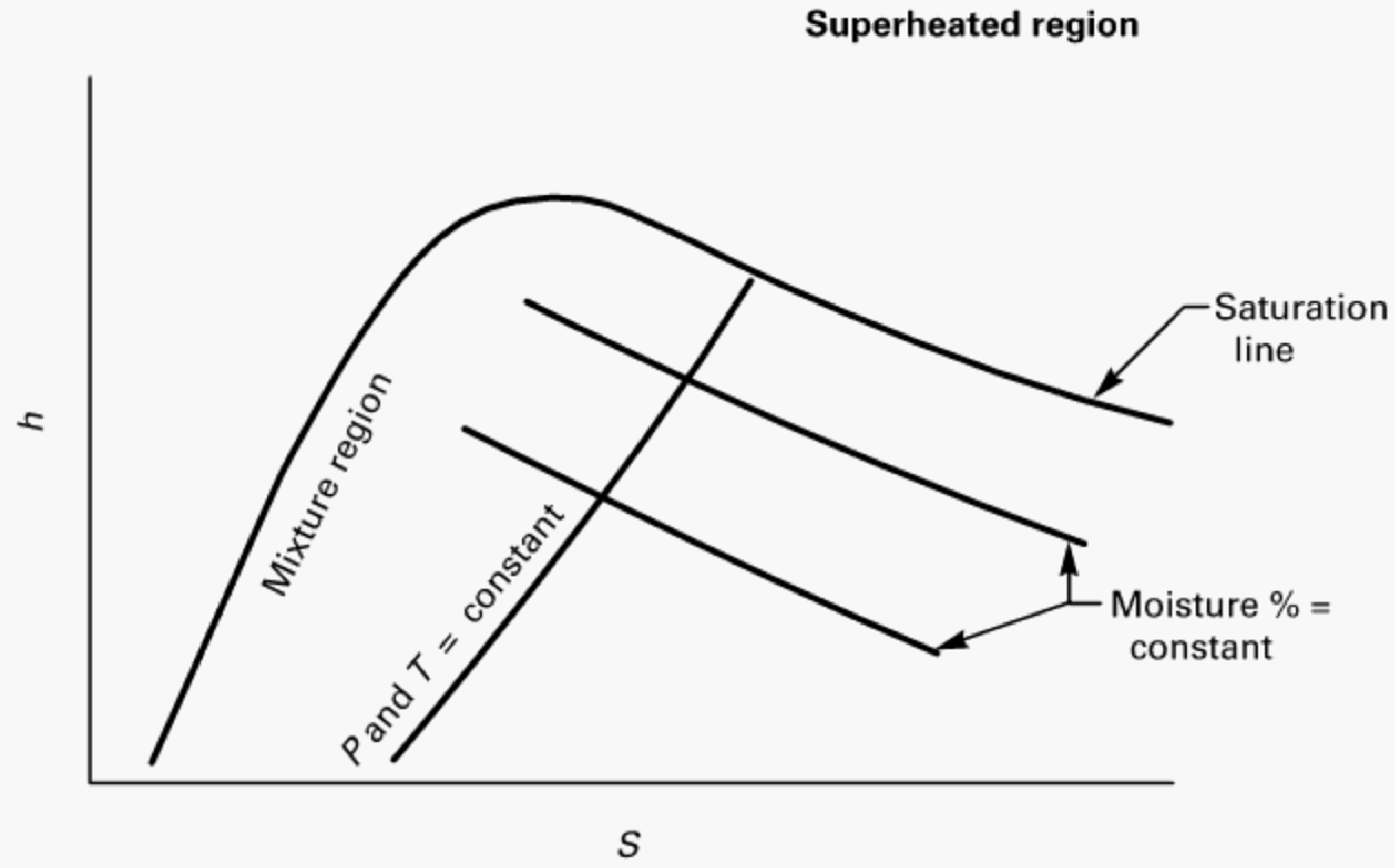

FIG. 3.3 ENTHALPY-ENTROPY DIAGRAM FOR WATER

For ideal pump work, refer to the definition of *pumps* where internal losses are negligible.

steam point: is defined as the temperature of an equilibrium mixture of liquid and condensing water vapor at one standard atmospheric pressure (373.15 K).

steam quality: inside the liquid-vapor-mixture region, quality x is defined as the fraction of the mass which is in the vapor state relative to the total mass of the two-phase mixture:

$$x = m_g/(m_g + m_f)$$

For example, if a mixture at saturated pressure and temperature contains 2.5% moisture, its quality is 97.5%. "Wet" steam means its state is in the mixture region wherein its state is defined by either its pressure or temperature and the portion of water substance which is the vapor phase.

Dry and saturated steam exists when all of the mass of water substance is in the vapor phase at saturation pressure and temperature. This condition exists along the "saturation line" which divides the two-phase mixture region from the superheated region (x = 100% and moisture = 0%). See Fig. 3.3.

steam rate: of an engine, turbine, or complete plant, is expressed as the actual mass of steam per unit of time per unit of output, often expressed in units of lbm/kW.

temperature, absolute: the approximate value of the thermodynamic temperature as defined by the International Practical Temperature Scale. In the U.S. customary system, the absolute temperature is expressed in degrees Rankine, and in the SI (metric) system, in kelvin. For relations between these scales, see Section 5.

temperature, reference: the datum for the steam tables is the triple point of water. The 1968 International Practical Temperature Scale establishes this at 0.01°C or 32.018°F.

For gases, the preferred standard temperature for PTC work is 59°F (15°C). Various industries use different reference conditions; caution is advised.

thermal conductivity: the coefficient of proportionality in the equation of heat transfer by steady unidirectional conduction proposed by Fourier in 1882: $q = -k\ A\ dT/dx$ where q is the rate of heat conduction along the x-axis, A is the cross-sectional area of the path normal to the x-axis, and $-dT/dx$ is the temperature gradient along the path. See Table 5.8. The units of k are Btu/(hr-ft-°F) [W/(m-°C)]

thermal unit conversions: using the identities as defined in the latest edition of ASME steam tables (Appendix 4B) and tables of conversion factors, the following conversions are derived:
Identities:

$$\left(0.453\ 592\ 37\ \frac{\text{kg}}{\text{lbm}}\right) = 1$$

$$\left(778.169\ 262\ \frac{\text{ft–lbf}}{\text{Btu}}\right) = 1$$

$$\left(0.3048\ \frac{\text{m}}{\text{ft}}\right) = 1$$

$$\left(2.326\ \frac{\text{k J–lbm}}{\text{kg–Btu}}\right) = 1$$

$$\text{(mechanical equivalent of heat)}\left(\frac{4.184\ \text{J}}{\text{cal}}\right) = 1$$

$$1 = \frac{\text{kg–m}}{\text{N–sec}^2} = g_c$$

$$= \frac{1}{0.453\ 592}\ \ \frac{\text{lbm}}{\text{kg}} \times \frac{N(4.448\ 222)}{\text{lbf}} \times \frac{\text{ft}}{0.3048}$$

$$g_c = 32.174\ 056\ \frac{\text{ft–lbm}}{\text{s}^2\ \text{–lb}}$$

Conversions:

$$\left(0.4535\ 9237\ \frac{\text{kg}}{\text{lbm}}\right)\left(2.326\ \ \frac{\text{lbm–k J}}{\text{Btu–kg}}\right) = 1$$

yields

$$1\ \text{Btu} = 1.055\ 055\ 6\ \text{kJ}$$

Also

$$\left(550\ \ \frac{\text{ft–lbf}}{\text{s–hp}}\right)\left(3600\ \ \frac{\text{s}}{\text{hr}}\right)\left(778.169\ 262\ \ \frac{\text{Btu}}{\text{ft–lbf}}\right) = 1$$

yields

$$1\ \text{hp–hr} = 2544.433\ \text{Btu}$$

Finally,

$$\left(3600\ \frac{\text{s}}{\text{hr}}\right)\left(2.326\ \frac{\text{kg–Btu}}{\text{k J–lbm}}\right)\left(0.453\ 59\ 237\ \frac{\text{lbm}}{\text{kg}}\right) = 1$$

yields

$$\frac{1\ \text{kJ–hr}}{\text{sec}} = 1\ \text{kWhr} = 3412.141\ 63\ \text{Btu}$$

time: the fourth dimension in the space-time continuum; the duration of a phenomenon or the period between two events. The universal unit of time is the second, which is one part in 84,600 of the sidereal, mean solar day on Earth.

tolerance: a specified allowance for error in weighing, measuring etc., or the maximum allowable error in the value of the quantity indicated, such as the test result (PTCs do not address tolerance; they describe how to measure the relevant performance and how to determine the uncertainty of such measurement).

viscosity: the ratio of shearing stress to the rate of shearing strain of a fluid. For further details on viscosity, PTC 19.17, *Determination of the Viscosity of Liquids* should be consulted. The viscosity of steam and water are given in the latest ASME steam tables.

watt: one newton meter per second.

SECTION 4
LETTER SYMBOLS

4.1 INTRODUCTION

In order to render the terminology of ASME PTCs consistent, certain letter symbols in general use have been adopted. These letter symbols, from the American National Standards Institute (ANSI), are published by the ASME, who sponsors this work. ANSI originally was called American Standards Association (ASA) and many of the symbols have the ASA designation. In August 1966, the American Standards Association was reconstituted as the United States of America Standards Institute (USASI) In October 1969, the name was again changed to the current "American National Standards Institute." The various name changes did not involve any numerical standard designation, simply the "overstamping" of ASA to USASI to ANSI.

4.2 PREFERRED LETTER SYMBOLS

The preferred letter symbols for PTC work are those listed in para. 4.4.

4.2.1 Three General Requirements for Published Symbols and Signs. A letter symbol for a physical quantity is a single letter, specified as to general form and typeface. It is available for use within a mathematical expression. This primary symbol may be modified by subscript or superscript. In a published work, the same primary letter symbol should appear throughout for the same generic physical quantity, regardless of the units employed or special values assigned. As is generally recognized, each published symbol or sign, of whatever kind, should be

(a) standard, where possible. In the use of published symbols, authors of technical works (including textbooks) are urged to adopt the symbols in this and other current standard lists, and to conform to the principles stated here. An author should give a table of the symbols used and their respective interpretations, or else refer to a standard list. For work in a specialized or developing field, the author may need symbols in addition to those already contained in standard lists. In such a case, one should be careful to select simple suggestive symbols which avoid conflict in the given field and in other closely-related fields. Except in this situation, one should not use new symbols or depart from current notation.

(b) clear in reference. One should not assign to a given symbol different meanings, thereby causing ambiguous interpretation in a given context. Conflicts must be avoided. Often a listed alternative symbol or a modifying subscript is available and should be adopted. Except in brief reports, any symbol not familiar to the reading public should be defined in the text. The units should be indicated whenever necessary.

(c) easily identified. Because of the many numerals, letters, and signs which are similar in appearance, a writer should not use separate symbols which, in published form, might be confused by the reader. For example, many letters in the Greek alphabet (lower case and capital) are practically indistinguishable from English letters; the zero is easily mistaken for a capital O.

4.3 SPECIAL PRINCIPLES OF LETTER SYMBOL STANDARDIZATION

(a) The time rate of change of any quantity may be designated by a dot over the symbol.

(b) Quantities suitable for designation as vectors may be so indicated in print by making the symbol boldface. In manuscript or typescript, this may be indicated by underscoring with a single wavy line.

(c) Components of vector and tensor quantities are to be indicated by suitable subscripts or superscripts.

(d) Subscripts and superscripts as independent symbols are not listed as part of this Standard, since practice in various applications is so diverse. In general, subscripts should be in the nature of abbreviations, such as critical temperature T_c or reduced pressure p_r.

(e) Components as occurring in mixtures of chem-

ical reactions may be designated by adding suitable subscripts or parenthetical identification. The latter is preferred if the identification is by chemical species. For example, the chemical potential of an ith component would be μ_i; *or the enthalpy of carbon dioxide,* $h(CO_2)$. Thermodynamic properties so designated are to be understood, in relation to mixtures, as either partial molar or partial specific quantities.

(f) Extensive thermodynamic properties are designated by italic capitals. Specific properties (per unit mass) are designated by the corresponding lowercase italics. Partial molar properties (per mole) are designated by barred capitals, or by plain capitals, if no ambiguity exists with respect to extensive properties. Components may be designated in addition, as above.

(g) Differences in values of thermodynamic quantities as occurring in chemical reactions or phase changes are normally indicated by prefixing the symbol Δ to the symbol for particular quantity and identifying the change by suitable subscripts. If a particular difference occurs repeatedly and if no ambiguity will result, the prefix may be omitted.

(h) Dimensionless groups may be designated by two-letter symbols in most of the well-established cases.

(i) In general, subscripts should either be selected from the standard symbols or be an abbreviation.

(j) Certain symbols, enclosed by parentheses, have been included in the list for information. These represent generally accepted usage. In each case, an alternate standard is indicated.

4.4 DESCRIPTION OF TERMS

a = acceleration
a = acoustic velocity
a = activity
a = Helmholtz function, specific
a = sound velocity
A = affinity
A = free energy, Helmholtz function
A = Helmholtz function
A, S = area
B = virial coefficient, second
c = concentration, mass
c_p = specific heat capacity, constant pressure
c_v = specific heat capacity, constant volume
c = specific heat capacity, general
c = velocity of light
C = heat capacity, general
C = concentration, mole
C_p = heat capacity, constant pressure
C_v = heat capacity, constant volume
d, D = diameter
D = diffusivity, mass
D = mass diffusion coefficient
D_T = thermal diffusion coefficient
E = energy
f = friction factor
f = fugacity
F = force
F, G = free energy Gibbs function
g = Gibbs function, specific
g = gravitational acceleration
g = specific Gibbs function
g_c = inertia proportionality factor
G = mass current density
G = mass velocity
h = enthalpy, specific
h = heat transfer coefficient, surface
h = Planck constant
H = enthalpy
H = irradiance
j = heat transfer factor
J = mechanical equivalent of heat
J = radiant intensity
k = Boltzmann's constant
K = equilibrium constant, chemical
l, L = length
m = mass
m = molality
M = Mach number
M = molar mass
M = molecular weight
n = angular velocity, revolutions per unit time
n = mole quantity
n = number of moles
n = polytropic exponent
N = dimensionless number
N = number of molecules
N = radiance
(Nu) = Nusselt number
N_o = Avogadro's number
p = pressure
P, W = power
(Pr), σ = Prandtl number
q = flow, volumetric
q, Q = heat rate
q_m = flow, mass
Q = heat

Q = quantity, usually volume
r = radius
r = transmissivity
r = transmittance
R = gas constant
R = thermal resistance
(Re), R = Reynolds number
s = arc length
s = path length
S = entropy
t, r = time
t, θ = temperature
T = temperature, absolute or thermodynamic
u = internal energy, specific
u = specific internal energy
U = heat transfer coefficient, overall
U = internal energy
U = radiant energy
v = specific volume
v, V = velocity
V = volume
w, m, q_m = mass flow
w = mass fraction
W = radiant flux density
W = weight
W = work
x = mole fraction
x = quality
y = mole fraction, gas phase
y, σ = surface tension
Z = compressibility factor
α = absorptance
α = absorptivity
α = degree of reaction
α = diffusivity, thermal
α = linear thermal expansion coefficient
α = thermal diffusivity
α = thermal expansion coefficient, linear
β = thermal expansion coefficient, volumetric
β = volumetric thermal expansion coefficient
γ = activity coefficient, stoichiometric
γ, k = heat capacity ratio
ϵ = emissivity
ϵ = emittance
ϵ = turbulence exchange coefficient
η = efficiency
η, μ = viscosity, absolute or dynamic
θ = normal angle
κ = viscosity, volume
κ, λ = temperature conductivity
(k), κ = compressibility coefficient
k_T = thermal diffusion ratio
λ = radiation wavelength
μ = chemical potential
μ = Gibbs function, molar
μ = Joule-Thompson coefficient
ν = kinematic viscosity
ν = radiation frequency
ν = stoichiometric number of molecules in a chemical reaction
ν = viscosity, kinematic
ξ = extent of chemical reaction
ρ = density
ρ = reflectance
ρ = reflectivity
σ = entropy production rate
σ = specific entropy
σ = Stefan-Boltzmann constant
Φ = radiant flux
ω = angular velocity, radians per unit time
ω, Ω = solid angle
Δh = latent heat, specific
ΔH = latent heat

SECTION 5
COMMON CONVERSION FACTORS

Please refer to Tables 5.1 through 5.8 for conversion factors.

TABLE 5.1
CONVERSIONS TO SI (METRIC) UNITS

Quantity	Conversion From	Conversion To	Multiplication Factor	
Acceleration, linear	ft/sec^2	m/s^2	3.048 [Note (1)]	E – 01
	standard gravity	m/s^2	9.806 65 [Note (1)]	E + 00
Area	in.^{2}	m^2	6.451 6	E – 04
	ft^2	m^2	9.290 304 [Note (1)]	E – 02
Coefficient of thermal expansion	°R^{-1}	K^{-1}	1.8 [Note (1)]	E + 00
Density	lbm/ft^3	kg/m^3	1.601 846	E + 01
	slugs/ft^3	kg/m^3	5.153 788	E + 02
Energy, work, heat	Btu (IT)	J	1.055 056	E + 03
	ft - lbf	J	1.355 818	E + 00
Flow rate , mass	lbm/sec	kg/s	4.535 924	E – 01
	lbm/min	kg/s	7.559 873	E – 03
	lbm/hr	kg/s	1.259 979	E – 04
	slugs/sec	kg/s	1.459 390	E + 01
Flow rate, volume	ft^3/min	m^3/s	4.719 474	E – 04
	ft^3/sec	m^3/s	2.831 685	E – 02
	gallons (U.S. liquid)/min	m^3/s	6.309 020	E – 05
Force	lbf (avoirdupois)	N	4.448 222	E + 00
Frequency	sec^{-1}	Hz	1 [Note (1)]	E + 00
Gas constant	Btu/lbm–°R	J/(kg • K)	4.186 8 [Note (1)]	E + 03
	ft-lbf/lbm – °R	J/(kg • K)	5.380 320	E + 00
Heat rate	Btu/kWh	kJ/kWh	1.055 056	E + 00
Heat transfer coefficient	Btu/hr-ft^2-°R	W/(m^2 • K)	5.678 263	E + 00
Length	in.	m	2.54 [Note (1)]	E – 02
	ft	m	3.048 [Note (1)]	E – 01
	mile (U.S.)	m	1.609 344 [Note (1)]	E + 03
Mass	lbm (avoirdupois)	kg	4.535 924	E – 01
	slug	kg	1.459 390	E + 01
Plane angle	deg	rad	1.745 329	E – 02
Power	Btu(IT)/hr	W	2.930 711	E – 01
	ft-lbf/sec	W	1.355 818	E + 00
	hp (550 ft-lbf/sec)	W	7.456 999	E + 02
Pressure	standard atmosphere	Pa	1.013 25 [Note (1)]	E + 05
	bar	Pa	1 [Note (1)]	E + 05
	lbf/ft^2	Pa	4.788 026	E + 01
	lbf/in.^{2}	Pa	6.894 757	E + 03
Rotational frequency	min^{-1}	s^{-1}	1.666 667	E – 02
Specific enthalpy	Btu/lbm	J/kg	2.326	E + 03
Specific entropy	Btu/lbm -°R	J/(kg • K)	4.186 8 [Note (1)]	E + 03
Specific heat	Btu/lbm -°R	J/(kg • K)	4.186 8	E + 03
Specific internal energy	Btu/lbm	J/kg	2.326	E + 03
Specific volume	ft^3/lbm	m^3/kg	6.242 797	E – 02
Specific weight (force)	lbf/ft^3	N/m^3	1.570 875	E + 02
Surface tension	lbf/ft	N/m	1.459 390	E + 01
Temperature interval	°F	°C	5.555 556	E – 01
Temperature, measured	°F	°C	$t_C = (t_F - 32)/1.8$	
Temperature, thermodynamic	°C	K	$T_K = t_C + 273.15$	
	°F	K	$T_K = t_F + 459.67)/1.8$	
	°R	K	$T_K = T_R/1.8$	
Thermal conductivity	Btu-ft/hr-ft^2– °R	W/(m • K)	1.730 735	E + 00
Time	hr	s	3.6 [Note (1)]	E + 03
	min	s	6 [Note (1)]	E + 01
Torque	lbf-in.	N • m	1.29 848	E – 01
	lbf-ft	N • m	1.355 818	E + 00

(continued)

TABLE 5.1
CONVERSIONS TO SI (METRIC) UNITS (CONT'D)

Quantity	Conversion From	Conversion To	Multiplication Factor	
Velocity	ft/hr	m/s	8.466 667	E − 05
	ft/min	m/s	5.08 [Note (1)]	E − 03
	ft/sec	m/s	3.048 [Note (1)]	E − 01
	knot (international)	m/s	5.144 444	E − 01
	mile (U.S.)/hr	m/s	4.470 4 [Note (1)]	E − 01
Viscosity, dynamic	centipoise	Pa • s	1 [Note (1)]	E − 03
	poise	Pa • s	1 [Note (1)]	E − 01
	lbm/ft-sec	Pa • s	1.488 164	E + 00
	lbf-sec/ft^2	Pa • s	4.788 026	E + 01
	slug/ft-sec	Pa • s	4.788 026	E + 01
Viscosity, kinematic	centistoke	m^2/s	1 [Note (1)]	E − 06
	stoke	m^2/s	1 [Note (1)]	E − 04
	ft^2/sec	m^2/s	9.290 304	E − 02
Volume	gallon (U.S. liquid)	m^3	3.785 412	E − 03
	ft^3	m^3	2.831 685	E − 02
	in^3	m^3	1.638 706	E − 05
	liter	m^3	1 [Note (1)]	E − 03

GENERAL NOTE: The factors are written as a number greater than one and less than ten with six decimal places. The number is followed by the letter E (for exponent), a plus or minus symbol, and two digits which indicate the power of 10 by which the number must be multiplied to obtain the correct value.

For example:

3.785 412 E − 03 is $3.785\ 412 \times 10^{-3}$ or 0.003 785 412

NOTE:
(1) Exact relationship in terms of the base units.

TABLE 5.2
CONVERSION FACTORS FOR PRESSURE (force/area)

To obtain → Multiply, by ↓	atm	bar	$\frac{lbf}{in.^2}$	in. Hg(0°C)	ft H_2O(20°C)	mm Hg(0°C)	$\frac{kp}{cm^2}$	kPa
atm	1	1.013 25	$\frac{1.013\ 250 \times 2.54^2}{980.665 \times 453.592\ 37}$ = 14.695 948 8	$\frac{1\ 013\ 250/980.665}{13.595\ 088\ 9 \times 2.54}$ = 29.921 280 0	$\frac{1\ 013\ 250/980.665}{0.998\ 278\ 282 \times 30.48}$ = 33.957 002 9	$\frac{10\ 132\ 500/980.665}{13.595\ 088\ 9}$ = 760.000 512	$\frac{1.013\ 25}{0.980\ 665}$ = 1.033 227 45	101.325
bar	$\frac{1.0}{1.013\ 25}$ = 0.986 923 267	1	$\frac{2.54^2 \times 10^6}{980.665 \times 453.592\ 37}$ = 14.503 773 8	$\frac{10^6/980.665}{13.595\ 088\ 9 \times 2.54}$ = 29.530 007 4	$\frac{10^6/980.665}{0.998\ 278\ 282 \times 30.48}$ = 33.512 956 2	$\frac{10^7/980\ 665}{13.595\ 088\ 9}$ = 750.062 188	$\frac{10^3}{980.665}$ = 1.019 716 21	100
$\frac{lbf}{in.^2}$	$\frac{980.665 \times 453.592\ 37}{1\ 013\ 250 \times 2.54^2}$ = 0.068 045 963 9	$\frac{980.665 \times 453.592\ 37}{2.54^2 \times 10^6}$ = 0.068 947 572 9	1	$\frac{453.592\ 37/2.54^3}{13.595\ 088\ 9}$ = 2.036 022 34	$\frac{453.592\ 37/2.54^3}{0.998\ 278\ 282 \times 12}$ = 2.310 636 99	$\frac{453.592\ 37 \times 10}{13.595\ 088\ 9 \times 2.54^2}$ = 51.714 967 4	$\frac{453.592\ 37}{2.54^2 \times 10^3}$ = 0.070 306 958 0	$\frac{980.665 \times 453.592\ 37}{2.54^2 \times 10^4}$ = 6.894 757 29
in. Hg (0°C)	$\frac{13.595\ 088\ 9 \times 2.54}{1\ 013\ 250/980.665}$ = 0.033 421 030 1	$\frac{13.595\ 088\ 9 \times 2.54}{10^6/980.665}$ = 0.033 863 858 8	$\frac{13.595\ 088\ 9 \times 2.54^3}{453.592\ 37}$ = 0.491 153 746	1	$\frac{13.595\ 088\ 9}{0.998\ 278\ 282 \times 12}$ =1.134 878 01	25.4	$\frac{13.595\ 088\ 9 \times 2.54}{10^3}$ = 0.034 531 525 8	$\frac{13.595\ 088\ 9 \times 2.54}{10^4/980.665}$ = 3.386 385 88
ft H_2O (20°C)(1)	$\frac{0.998\ 278\ 282 \times 30.48}{1\ 013\ 250/980.665}$ =0.029 449 006 6	$\frac{0.998\ 278\ 282 \times 30.48}{10^6/980.665}$ = 0.029 839 205 9	$\frac{0.998\ 278\ 282 \times 12}{453.592\ 37/2.54^3}$ = 0.432 781 092	$\frac{0.998\ 278\ 282 \times 12}{13.595\ 088\ 9}$ = 0.881 151 971	1	$\frac{9.982\ 782\ 82 \times 30.48}{13.595\ 088\ 9}$ =22.381 260 1	$\frac{0.0998\ 278\ 282 \times 30.48}{10^3}$ = 0.030 427 522 0	$\frac{0.0998\ 278\ 282 \times 30.48}{10^4/980.665}$ = 2.983 920 59
mm Hg (0°C)	$\frac{13.595\ 088\ 9}{10\ 132\ 500/980.665}$ = 0.001 315 788 59	$\frac{13.595\ 088\ 9}{10^7/980.665}$ = 0.001 333 222 79	$\frac{13.595\ 088\ 9 \times 2.54^2}{453.592\ 37 \times 10}$ = 0.019 336 761 7	$\frac{1.0}{25.4}$ = 0.039 370 078 7	$\frac{13.595\ 088\ 9}{9.982\ 782\ 82 \times 30.48}$ = 0.044 680 236 8	1	$13.595\ 088\ 9 \times 10^{-4}$ = 0.001 359 508 89	$\frac{13.595\ 088\ 9}{10^5/980.665}$ = 0.133 322 279
$\frac{kp}{cm^2}$	$\frac{980.665}{1\ 013.25}$ = 0.967 841 105	0.980 665	$\frac{2.54^2 \times 10^3}{453.592\ 37}$ = 14.223 343 3	$\frac{10^3}{13.595\ 088\ 9 \times 2.54}$ = 28.959 044 7	$\frac{10^3}{0.998\ 278\ 282 \times 30.48}$ = 32.864 983 2	$\frac{10^4}{13.595\ 088\ 9}$ = 735.559 736	1	$\frac{9.806\ 65}{10^{-1}}$ = 98.066 5
kPa	$\frac{1.0}{101.325}$ = 0.009 869 232 67	0.01	$\frac{2.54^2 \times 10^4}{980.665 \times 453.592\ 37}$ = 0.145 037 738	$\frac{10^4/980.665}{13.595\ 0889 \times 2.54}$ = 0.295 300 074	$\frac{10^4/980.665}{0.998\ 278\ 282 \times 30.48}$ = 0.335 129 562	$\frac{10^5/980.665}{13.595\ 088\ 9}$ = 7.500 621 88	$\frac{10^{-1}}{9.806\ 65}$ =0.010 197 162	1

GENERAL NOTE: All values given in the rational fractions are exact and are taken from Appendix 4, except the densities of water and mercury. The density of water (0.998 278 282 g/cm^3 at 68 °F) is computed from the IFC Formulation. The density of mercury (13.595 0889 g/cm^3 at 32 °F) is taken from NBS Monograph 8, pgs. 3-4.

Example: 1 bar = 1 bar × 0.986 923 267 atm/bar = 0.986 923 267 atm = (1/1.013 25) atm.

From definitions: 1 lbf = 0.453 592 37 kp (kilopond) = kgf = 4.448 221 161 N; 1Pa = 1N/m^2.

NOTE:
(1) To convert to inches of water gage (iwg) or inches of water, multiply the values in this row by 12.

TABLE 5.3
CONVERSION FACTORS FOR SPECIFIC VOLUME (volume/mass)

To obtain → Multiply, by ↓ ↘	$\frac{ft^3}{lbm}$	$\frac{in.^3}{lbm}$	$\frac{U.S.\ gal}{lbm}$	$\frac{liter}{kg}$	$\frac{m^3}{kg}$
$\frac{ft^3}{lbm}$	1	1 728	$\frac{1\,728}{231}$ = 7.480 519 48	$\frac{30.48^3}{453.592\,37}$ = 62.427 960 6	$\frac{30.48^3 \times 10^{-6}}{0.453\,592\,37}$ = 0.062 427 960 6
$\frac{in^3}{lbm}$	$\frac{1.0}{1\,728}$ = 0.000 578 703 704	1	$\frac{1.0}{231}$ = 0.004 329 004 33	$\frac{2.54^3}{453.592\,37}$ = 0.036 127 292 0	$\frac{2.54^3 \times 10^{-6}}{0.453\,592\,37}$ =0.000 036 127 292
$\frac{U.S.\ gal}{lbm}$	$\frac{231}{1\,728}$ = 0.133 680 556	231	1	$\frac{231 \times 2.54^3}{453.592\,37}$ = 8.345 404 45	$\frac{231 \times 2.54^3 \times 10^{-6}}{0.453\,592\,37}$ = 0.008 345 404 45
$\frac{liter}{kg}$	$\frac{453.592\,37}{30.48^3}$ = 0.016 018 463 4	$\frac{453.592\,37}{2.54^3}$ = 27.679 904 7	$\frac{453.592\,37}{231 \times 2.54^3}$ = 0.119 826 427	1	0.001
$\frac{m^3}{kg}$	$\frac{0.453\,592\,37}{30.48^3 \times 10^{-6}}$ = 16.018 463 4	$\frac{0.453\,592\,37}{2.54^3 \times 10^{-6}}$ = 27 679.904 7	$\frac{0.453\,592\,37}{231 \times 2.54^3 \times 10^{-6}}$ = 119.826 427	1000	1

GENERAL NOTE:
All values given in the rational fractions are exact except 1 U.S. gal = 231 in.^{3} (NBS Misc. Pub. 233 P5).

Example: 1 U.S. gal/lbm =0.133 680 556 ft^3/lbm

TABLE 5.4
CONVERSION FACTORS FOR SPECIFIC ENTHALPY AND SPECIFIC ENERGY (energy/mass)

To obtain → Multiply, by ↓ ↘	$\frac{Btu}{lbm}$	$\frac{ft \times lbf}{lbm}$	$\frac{hp \times hr}{lbm}$	$\frac{lbf/in.^2}{lbm/ft^3}$	$\frac{kp \times m}{g}$	$\frac{kcal}{g}$	$\frac{kJ}{kg}$
$\frac{Btu}{lbm}$	1	$\frac{2.326 \times 10^7}{980.665 \times 30.48}$ = 778.169 262	$\frac{2.326}{980.665 \times 30.48 \times 0.198}$ = 3.930 147 79 × 10^{-4}	$\frac{2.326 \times 10^7}{980.665 \times 30.48 \times 144}$ = 5.403 953 21	$\frac{2.326}{9.806\ 65}$ = 0.237 185 991	$\frac{2.326}{4\ 186.8}$ = 5.555 555 6 × 10^{-4}	2.326
$\frac{ft \times lbf}{lbm}$	$\frac{980.665 \times 30.48}{2.326 \times 10^7}$ = 0.001 285 067 46	1	$\frac{1.0}{1\ 980\ 000}$ = 5.050 505 05 × 10^{-7}	$\frac{1.0}{144}$ = 0.069 444 444 4	30.48 × 10^{-5} = 0.000 304 8	$\frac{980.665 \times 30.48}{4\ 186.8 \times 10^7}$ = 7.139 263 69 × 10^{-7}	980.665 × 30.48 × 10^{-7} = 0.002 989 066 920
$\frac{hp \times hr}{lbm}$	$\frac{980.665 \times 30.48 \times 0.198}{2.326}$ = 2 544.433 58	1 980 000	1	$\frac{1\ 980\ 000}{144}$ = 13 750	30.48 × 19.8 = 603.504	$\frac{980.665 \times 30.48}{4\ 186.8/0.198}$ = 1.413 574 21	$\frac{980.665 \times 30.48 \times 198}{1000}$ = 5 918.352 50
$\frac{lbf/in^2}{lbm/ft^3}$	$\frac{980.665 \times 30.48 \times 144}{2.326 \times 10^7}$ = 0.185 049 715	144	$\frac{144}{1\ 980\ 000}$ =7.272 727 27 × 10^{-5}	1	30.48 × 144 × 10^{-5} =0.043 891 2	$\frac{980.665 \times 30.48 \times 144}{4\ 186.8 \times 10^7}$ = 1.028 053 97 × 10^{-4}	$\frac{980.665 \times 30.48 \times 144}{10^7}$ = 0.430 425 636
$\frac{kp \times m}{g}$	$\frac{9.806\ 65}{2.326}$ = 4.216 100 60	$\frac{10^5}{30.48}$ = 3 280.839 90	$\frac{1.0}{30.48 \times 19.8}$ = 0.001 656 989 85	$\frac{10^5}{30.48 \times 144}$ =22.783 610 4	1	$\frac{9.806\ 65}{4\ 186.8}$ =0.002 342 278 11	9.806 65
$\frac{kcal}{g}$	$\frac{4\ 186.8}{2.326}$ = 1800	$\frac{4\ 186.8 \times 10^7}{980.665 \times 30.48}$ = 1 400 704 67	$\frac{4\ 186.8 \times 10^3}{980.665 \times 30.48 \times 198}$ = 0.707 426 602	$\frac{4\ 186.8 \times 10^7}{980.665 \times 30.48 \times 144}$ = 9 727.115 78	$\frac{4\ 186.8}{9.806\ 65}$ = 426.934 784	1	4 186.8
$\frac{kJ}{kg}$	$\frac{1.0}{2.326}$ = 0.429 922 614	$\frac{10^7}{980.665 \times 30.48}$ = 334.552 563	$\frac{10^3}{980.665 \times 30.48 \times 198}$ = 1.689 659 41 × 10^{-4}	$\frac{10^7}{980.665 \times 30.48 \times 144}$ = 2.323 281 69	$\frac{1.0}{9.806\ 65}$ = 0.101 971 621	$\frac{1.0}{4\ 186.8}$ = 2.388 458 97 × 10^{-4}	1

GENERAL NOTE:
All values given in the rational fractions are exact except 1HP = 550 ft-lbf/sec = 1,980,000 ft-lbf/hr.

Example: $1\ \frac{Btu}{lbm} = 1kN{\cdot}m\ \frac{1Btu}{lbm} \times 778.169\ 262\ \frac{ft \times lbf/lbm}{Btu/lbm} = 778.169\ 262\ \frac{ft \times lbf}{lbm}$

From definitions: $1\ \frac{Joule}{g} = 1\ \frac{J}{g} = 10^7\ \frac{erg}{g} = 10^7\ \frac{dyne\text{-}cm}{g} = 10^3\ \frac{J}{kg} = 1\ \frac{kw\text{-}sec}{kg} = 10\ \frac{bar\text{-}cm^3}{g}$

$1kJ = 1/(0.45359237 \times 2.326) = 0.947817120$ Btu: $1\ kcal = \frac{1.8}{0.45359237} = 3.96832072$ Btu

TABLE 5.5
CONVERSION FACTORS FOR SPECIFIC ENTROPY, SPECIFIC HEAT, AND GAS CONSTANT
(energy/mass × temperature)

To obtain → Multiply, by ↓	$\frac{Btu}{lbm \times R}$	$\frac{ft \times lbf}{lbm \times R}$	$\frac{kw \times hr}{lbm \times R}$	$\frac{bar \times cm^3}{g \times K}$	$\frac{kcal}{g \times K}$	$\frac{kp \times m}{g \times K}$	$\frac{kJ}{kg \times K}$
$\frac{Btu}{lbm \times R}$	1	$\frac{2.326 \times 10^7}{980.665 \times 30.48}$ = 778.169 262	$\frac{2.326 \times 453.592\ 37}{3\ 600\ 000}$ =0.000 293 071 070	41.868	0.0001	$\frac{4.186\ 8}{9.806\ 65}$ = 0.426 934 784	4.186 8
$\frac{ft \times lbf}{lbm \times R}$	$\frac{980.665 \times 30.48}{2.326 \times 10^7}$ = 0.001 285 067 46	1	$\frac{453.592\ 37 \times 30.48}{3.6 \times 10^{13}/980.665}$ = $3.766\ 160\ 97 \times 10^{-7}$	$\frac{30.48 \times 980.665 \times 9/5}{10^6}$ = 0.053 803 204 6	$\frac{980.665 \times 30.48}{2\ 326 \times 10^7}$ $1.285\ 067\ 46 \times 10^{-6}$	$30.48 \times 10^{-5} \times 9/5$ = 0.000 548 64	$\frac{980.665 \times 30.48 \times 10^{-7}}{5/9}$ = 0.005 380 320 46
$\frac{kw \times hr}{lbm \times R}$	$\frac{3\ 600\ 000}{2.326 \times 453.592\ 37}$ = 3 412.141 63	$\frac{3.6 \times 10^{13} / 980.665}{453.592\ 37 \times 30.48}$ =2 655 223.73	1	$\frac{3.6 \times 10^7 \times 9/5}{453.592\ 37}$ = 142 859.546	$\frac{3\ 600\ 000}{2\ 326 \times 453.592\ 37}$ = 3.412 141 63	$\frac{3.6 \times 10^8 \times 9/5}{980.665 \times 453.592\ 37}$ =1 456 761 95	$\frac{3.6 \times 10^6 \times 9/5}{453.592\ 37}$ = 14 285.954 6
$\frac{bar \times cm^3}{g \times K}$	$\frac{1.0}{41.868}$ = 0.023 884 589 7	$\frac{10^6}{30.48 \times 980.665 \times 9/5}$ = 18.586 253 5	$\frac{453.592\ 37}{3.6 \times 10^7 \times 9/5}$ = $6.999\ 882\ 25 \times 10^{-6}$	1	$\frac{1.0}{41\ 868}$ = $2.388\ 458\ 97 \times 10^{-5}$	$\frac{1.0}{98.066\ 5}$ =0.010 197 1621	0.1
$\frac{kcal}{g \times K}$	1000	$\frac{2\ 326 \times 10^7}{980.665 \times 30.48}$ = 778 169.262	$\frac{2\ 326 \times 453.592\ 37}{3\ 600\ 000}$ = 0.293 071 070	41 868	1	$\frac{4\ 186.8}{9.806\ 65}$ = 426.934 784	4 186.8
$\frac{kp \times m}{g \times K}$	$\frac{9.806\ 65}{4.186\ 8}$ = 2.342 278 11	$\frac{10^5}{30.48 \times 9/5}$ = 1 822.688 83	$\frac{980.665 \times 453.592\ 37}{3.6 \times 10^8 \times 9/5}$ = 0.000 686 453 953	98.066 5	$\frac{9.806\ 65}{4\ 186.8}$ = 0.002 342 278 11	1	9.806 65
$\frac{kJ}{kg \times K}$	$\frac{1.0}{4.186\ 8}$ = 0.238 845 897	$\frac{10^7 \times 5/9}{980.665 \times 30.48}$ = 185.862 535	$\frac{453.592\ 37}{3.6 \times 10^6 \times 9/5}$ = $6.999\ 882\ 25 \times 10^{-5}$	10	$\frac{1.0}{4\ 186.8}$ = 0.000 238 845 897	$\frac{1.0}{9.806\ 65}$ = 0.101 971 621	1

GENERAL NOTE:
All values given in the rational fractions are exact.

Example:1 Btu / (lbm × R) = 778.169 262 ft × lbf / (lbm × R)

TABLE 5.6
CONVERSION FACTORS FOR VISCOSITY
(force × time/area ~ mass/length × time)

To obtain → Multiply, by ↓ ↘	Pa × s	$\frac{\text{lbf} \times \text{sec}}{\text{ft}^2}$	$\frac{\text{lbm}}{\text{ft} \times \text{sec}}$	$\frac{\text{lbm}}{\text{hr} \times \text{ft}}$	$\frac{\text{g}}{\text{cm} \times \text{sec}}$ (poise)	$\frac{\text{kg}}{\text{m} \times \text{sec}}$
Pa × s [Note (1)]	1	$\frac{(0.3048)^2}{9.80665 \times 0.453\,59237}$ $= 0.020\,885\,4342$	$\frac{0.3048}{0.453\,592\,37}$ $= 0.671\,968\,975$	$\frac{0.3048 \times 3600}{0.453\,592\,37}$ $= 2419.088\,31$	10	1
$\frac{\text{lbf} \times \text{sec}}{\text{ft}^2}$	$\frac{9.806\,65 \times 0.453\,592\,37}{(0.3048)^2}$ $= 47.880\,259\,0$	1	$\frac{980.665}{30.48}$ $= 32.174\,048\,6$	$\frac{980.665 \times 3\,600}{30.48}$ $= 115\,826.575$	$\frac{980.665 \times 453.592\,37}{30.48^2}$ $= 478.802\,590$	$\frac{980.665 \times 453.592\,37}{10 \times 30.48^2}$ $= 47.880\,259\,0$
$\frac{\text{lbm}}{\text{ft} \times \text{sec}}$	$\frac{0.453\,592\,37}{0.3048}$ $= 1.488\,163\,94$	$\frac{30.48}{980.665}$ $= 0.031\,080\,950\,2$	1	3 600	$\frac{453.592\,37}{30.48}$ $= 14.881\,639\,4$	$\frac{453.592\,37}{304.8}$ $= 1.488\,163\,94$
$\frac{\text{lbm}}{\text{hr} \times \text{ft}}$	$\frac{0.453\,592\,37}{0.3048 \times 3600}$ $= 0.413\,378\,873 \times 10^{-3}$	$\frac{30.48}{980.665 \times 3\,600}$ $= 8.633\,597\,27 \times 10^{-6}$	$\frac{1.0}{3\,600}$ $= 0.000\,277\,777\,778$	1	$\frac{453.592\,37}{30.48 \times 3\,600}$ $= 0.004\,133\,788\,73$	$\frac{453.592\,37}{304.8 \times 3\,600}$ $= 0.000\,413\,378\,873$
$\frac{\text{g}}{\text{cm} \times \text{sec}}$ (poise)	0.1	$\frac{30.48^2}{980.665 \times 453.592\,37}$ $= 0.002\,088\,543\,42$	$\frac{30.48}{453.592\,37}$ $= 0.067\,196\,897\,5$	$\frac{3\,600 \times 30.48}{453.592\,37}$ $= 241.908\,831$	1	0.1
$\frac{\text{kg}}{\text{m} \times \text{sec}}$ [Note (1)]	1	$\frac{10 \times 30.48^2}{980.665 \times 453.592\,37}$ $= 0.020\,885\,434\,2$	$\frac{304.8}{453.592\,37}$ $= 0.671\,968\,975$	$\frac{10 \times 3\,600 \times 30.48}{453.592\,37}$ $= 2\,419.088\,31$	10	1

GENERAL NOTE:
All values given in the rational fractions are exact.
Example: 1 lbf × sec/ft^2 = 32.174 048 6 lbm/(ft × sec)
From definitions: 1 poise = 1 P = 1 g/cm × sec = 1 dyne × sec/cm^2 = 0.1 kg/m × sec = 0.1 Newton × sec/m^2 = 0.1 Pascal × sec = 0.1 Pa × sec

NOTE:
(1) SI Units for ASME use.

TABLE 5.7
CONVERSION FACTORS FOR KINEMATIC VISCOSITY (area/time)

To obtain → Multiply, by ↓	$\frac{m^2}{s}$ [Note (1)]	$\frac{ft^2}{sec}$	$\frac{cm^2}{sec}$ (stoke)	$\frac{cm^2}{hr}$	$\frac{m^2}{hr}$
$\frac{m^2}{s}$ [Note (1)]	1	$\frac{1.0}{(0.3048)^2}$ = 10.763 9104	$(100)^2$ = 10 000	$(100)^2 \times 3600 = 36 \times 10^6$	3600
$\frac{ft^2}{sec}$	$(0.3048)^2$ = 0.092 903 04	1	$(30.48)^2$ = 929.030 4	$(30.48)^2 \times 3\,600$ = 3 344 509.440 000	$(0.304\,8)^2 \times 3\,600$ = 334.450 944 000
$\frac{cm^2}{sec}$ (stoke)	$\frac{1.0}{(100)^2}$ = 10^{-4}	$\frac{1.0}{(30.48)^2}$ = 0.001 076 391 04	1	3 600	$\frac{3\,600}{(100)^2}$ = 0.36
$\frac{cm^2}{hr}$	$\frac{1.0}{(100)^2 \times 3\,600}$ = $27.777\,777\,8 \times 10^{-9}$	$\frac{1.0}{(30.48)^2 \times 3\,600}$ = $0.2\,989\,975\,12 \times 10^{-6}$	$\frac{1.0}{3\,600}$ 0.000 277 777 778	1	$\frac{1.0}{(100)^2}$ = 0.000 1
$\frac{m^2}{hr}$	$\frac{1.0}{3\,600}$ = $277.777\,778 \times 10^{-6}$	$\frac{1.0}{(0.3048)^2 \times 3\,600}$ = $2.989\,975\,12 \times 10^{-3}$	$\frac{(100)^2}{3\,600}$ 2.777 777 78	$(100)^2$ = 10 000	1

GENERAL NOTE:
All values given in the rational fractions are exact.
Example: 1 ft^2/sec = 3600 ft^2/hr.

NOTE:
(1) SI Units for ASME use.

TABLE 5.8
CONVERSION FACTORS FOR THERMAL CONDUCTIVITY (energy/time × length × temp. diff. ~ power/length × temp. diff.)

To obtain → / Multiply, by ↓	$\frac{Btu}{hr\times ft\times F}$	$\frac{ft\times lbf}{hr\times ft\times F}=\frac{lbf}{hr\times F}$	$\frac{Watt}{ft\times F}$	$\frac{Watt}{m\times C}$	$\frac{kp\times m}{hr\times m\times C}=\frac{kp}{hr\times C}$	$\frac{cal}{sec\times cm\times C}$	$\frac{kcal}{hr\times m\times C}$
$\frac{Btu}{hr\times ft\times F}$	1	$\frac{2.326\times10^7}{980.665\times30.48}$ = 778.169 262	$\frac{2.326\times453.592\ 37}{3\ 600}$ = 0.293 071 070	$\frac{4.186\ 8\times453.592\ 37}{3\ 600\times0.304\ 8}$ = 1.730 734 67	$\frac{4.186\ 8\times453.592\ 37}{980.665\times30.48\times10^{-4}}$ = 635.348 952	$\frac{453.592\ 37}{3\ 600\times30.48}$ = 0.004 133 788 73	$\frac{453.592\ 37}{10\times30.48}$ = 1.488 163 94
$\frac{ft\times lbf}{hr\times ft\times F}$	$\frac{980.665\times30.48}{2.326\times10^7}$ = 0.001 285 067 46	1	$\frac{980.665\times453.592\ 37}{3\ 600\times10^7/30.48}$ = 0.000 376 616 097	$\frac{980.665\times453.592\ 37}{3\ 600\times10^5\times5/9}$ = 0.002 224 110 81	$\frac{453.592\ 37\times9/5}{1\ 000}$ 0.816 466 266 000	$\frac{980.665\times453.592\ 37}{3\ 600\times2.326\times10^7}$ = $5.312\ 197\ 40\times10^{-6}$	$\frac{980.665\times453.592\ 37}{2.326\times10^8}$ = 0.001 912 391 06
$\frac{Watt}{ft\times F}$	$\frac{3\ 600}{2.326\times453.592\ 37}$ = 3.412141 63	$\frac{3\ 600\times10^7/30.48}{980.665\times453.592\ 37}$ =2 665.223 74	1	$\frac{9/5}{0.304\ 8}$ = 5.905 511 81	$\frac{3\ 600\times10^4\times9/5}{980.665\times30.48}$ = 2 167.900 61	$\frac{1.0}{30.48\times2.326}$ = 0.014 105 072 6	$\frac{360}{30.48\times2.326}$ =5.077 826 15
$\frac{Watt}{m\times C}$	$\frac{3\ 600\times0.304\ 8}{4.186\ 8\times453.592\ 37}$ = 0.577 789 316	$\frac{3\ 600\times10^5\times5/9}{980.665\times453.592\ 37}$ = 449.617 886	0.304 8×5/9 = 0.169 333 333	1	$\frac{3\ 600\times100}{980.665}$ = 367.097 837	$\frac{1.0}{418.68}$ =0.002 388 458 97	$\frac{360}{418.68}$ = 0.859 845 228
$\frac{kp\times m}{hr\times m\times C}$	$\frac{980.665\times30.48\times10^{-4}}{4.186\ 8\times453.592\ 37}$ = 0.001 573 938 22	$\frac{10^3\times5/9}{453.592\ 37}$ = 1.22479 035	$\frac{980.665\times30.48\times5/9}{3\ 600\times10^4}$ = 0.000 461 275 759	$\frac{980.665}{3\ 600\times100}$ = 0.002 724 069 44	1	$\frac{980.665}{3\ 600\times4.186\ 8\times10^4}$ = $6.506\ 328\ 09\times10^{-6}$	$\frac{980.665}{4.186\ 8\times10^5}$ = 0.002 342 278 11
$\frac{cal}{sec\times cm\times C}$	$\frac{3\ 600\times30.48}{453.592\ 37}$ = 241.908 831	$\frac{3\ 600\times2.326\times10^7}{980.665\times453.592\ 37}$ = 188 246.017	2.326×30.48 = 70.896 48	418.68	$\frac{3\ 600\times4.186\ 8\times10^4}{980.665}$ = 153 696.522	1	360
$\frac{kcal}{hr\times m\times C}$	$\frac{10\times30.48}{453.592\ 37}$ = 0.671 968 975	$\frac{2.326\times10^8}{980.665\times453.592\ 37}$ = 522.905 602	$\frac{2.326\times30.48}{360}$ = 0.196 934 667	$\frac{418.68}{360}$ = 1.163	$\frac{4.186\ 8\times10^5}{980.665}$ = 426.934 784	$\frac{1.0}{360}$ = 0.002 777 777 78	1

GENERAL NOTE:
All values given in the rational fractions are exact.

Example: $1\ \frac{Watt}{ft \times F} = 1\ \frac{Watt}{ft \times F} \times 3.412\ 141\ 632\ \frac{Btu / (hr \times ft \times F)}{Watt / (ft \times F)} = 3.412\ 141\ 632\ \frac{Btu}{hr \times ft \times F}$

NONMANDATORY APPENDIX A
SOURCES OF FLUID AND MATERIAL DATA

Brochure in Psychrometry
Thermodynamic Properties of Refrigerants
Publisher: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329

ASME Steam Tables, Thermodynamic and Transport Properties of Steam, 6th ed. 1993.
Fluid Meters, Their Theory and Application 6th ed. 1971.
Publisher: The American Society of Mechanical Engineers (ASME International), Three Park Avenue, New York, NY 10016-5990

Field Test Handbook, Cooling Tower Institute, ATC-105
Publisher: Cooling Technology Institute (CTI), 2611 FM 1960 West, Suite H-200, Houston, TX 77068-3730

Tube Properties, 9th ed., Standards for Steam Surface Condensers. 1995.
Publisher: Heat Exchange Institute, Inc. (HEI), 1300 Sumner Avenue, Cleveland, OH 44115-2815

Aviation Fuel Properties
Publisher: Society of Automotive Engineers (SAE), 400 Commonwealth Drive, Warrendale, PA 15096-0001

Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables. Abramowitz, M. & Stegun, I. U.S. Dept of Commerce, NBS-AMS 55.
Sea Water Properties from Reproduced Charts, Office of Saline Water, U.S. Dept. of Interior, Contract No. 14-30-2639.
Publisher: Federal specifications available from: Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402-9325

Avallone, E. and Baumeister, T. "Mark's Standard Handbook for Mechanical Engineers." New York: McGraw-Hill Book Co.

Eshbach O. and Sanders M. "Handbook of Engineering Fundamentals." New York: John Wiley & Sons.

Miller, R. W. "Flow Measurement Engineering Handbook." New York: McGraw-Hill Book Co.

Kutz, M. "Mechanical Engineers' Handbook." New York: John Wiley & Sons.

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NONMANDATORY APPENDIX B
UNITS OF MEASURE FOR ASME PERFORMANCE TEST CODES
by Roger Hecklinger, PE

ABSTRACT

The American Society of Mechanical Engineers has been developing and issuing Performance Test Codes for mechanical equipment and processes for more than 100 years. Most of these codes were developed using customary units of the United States; e.g., inches, pounds, Btu's, degrees F, etc. However, most countries use a metric system of units; e.g., meters, kilograms, joules or calories, degrees Celsius or kelvin, etc. Although the International System of Units (SI), the modern metric system, has been developed and promoted as the system for international use, most if not all countries tend to use variations of SI. Units of time – second, minute, hour, day, etc., and electrical measures – ampere, volt, watt, etc., are essentially in worldwide use. It is generally recognized that Performance Test Codes should be useable with US customary units and with metric units. The intent of this paper is to provide guidance in the use of both US customary units and metric units in a readily assimilable manner for use in developing ASME Performance Test Codes.

INTRODUCTION

Units of measure have been adopted for use by all cultures early in their development. As the various nations and cultures have become interrelated, the desirability of an international system of measures has become apparent. At present, the international system of measures is Le Systeme International d'Unites (abbreviated in all languages as SI). This system is also known as The Modern Metric System. The metric system has been evolving for more than 200 years.

The Beginnings of the Metric System

The metric system was a product of the French Revolution. In 1790, Charles Maurice de Talleyrand-Perigord asked the French National Assembly to develop a coherent system of weights and measures using the decimal system and based on the length of a pendulum with a beat of precisely one second at 45 degrees north latitude which runs through France. Accordingly, a length was established that was called a "meter" which was found to be very close to one 10-millionth of the distance along the earth in an arc from the equator to the North Pole. From this one-second pendulum other measures were developed (Boorstin, 1983).

The unit of mass, the gram, was established as the mass of a cubic centimeter of pure water at its maximum density, at about 4 degrees Centigrade (now called Celsius). Later, a unit of chemical or heat energy, the calorie, was established as one hundredth of the energy required to heat a gram of pure water from 0 to 100 degrees Centigrade at sea level. All of these base units were coherent; i.e., they were all interrelated. Prefixes were selected in multiples of ten (myria – 10000, kilo – 1000, hecto – 100, deka – 10, deci – 1/10, centi – 1/100, and milli – 1/1000).

United States' Involvement

It may come as a surprise that the United States has contributed to the development of the metric system from the beginning. The federal Constitution gives the Congress power "to fix the Standards of Weights and Measures". Thomas Jefferson, in 1790, before he was aware of Talleyrand's proposal, prepared his "Report…on the Subject of Establishing a Uniformity in the Weights, Measures and Coins of the U.S.". He reported, "let the standard of measure then be a uniform cylindrical rod of iron, in latitude 38 degrees, in the level of the ocean, and in a cellar, or other place, the temperature of which does not vary through the year, shall perform its vibration in small and equal arcs, in one second of mean time." (The latitude of 38 degrees is very close to Jefferson's Monticello near Charlottesville, Virginia: but when he learned that Talleyrand proposed 45 degrees of latitude which is halfway between the equator and the North Pole, Jefferson agreed to change from 38 degrees to 45 degrees of latitude) (Boorstin, 1983).

In 1865, Congress passed an act, "To authorize the use of the metric system of Weights and Measures". This Act listed one meter as equivalent to 39.37 inches (Congress, 1865). In 1893, the international meter and kilogram became the fundamental standards of length and mass in the United States. This necessitated a slight adjustment to measures of length used here; the inch was reduced in length by about 2-millionths of an inch to become 25.4 millimeters exactly.

The United States has participated in all meetings of the Conference General des Poids et Mesures (CGPM) since the first conference in 1889. The National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards, represents the United States in these activities. At present, SI is taught in schools and colleges, and is widely used in scientific work. However, US customary units remain in everyday use including specification, design, construction, and operation of the types of mechanical equipment for which ASME Performance Test Codes are developed and maintained.

Present SI Standards

The base units of the metric system have evolved since the days of Talleyrand and Jefferson. The concept of a coherent system of base units has been abandoned for the sake of preciseness. The base SI units are the meter for length, the kilogram for mass, the second for time, the ampere for electric current, the kelvin for temperature, the mole for amount of substance, and the candela for luminous intensity. All but the kilogram have been adopted in their present form since 1948. Each of these base units is discussed below:

Length. The length of the meter has been redefined several times since its origin as the length of the one-second pendulum. In 1901 the meter was defined as the distance between two lines on a platinum-iridium bar at 0 degrees Centigrade. It was deposited at the Bureau International des Poids et Mesures (BIPM) headquartered near Paris, France (Kent 1923). Later the meter was defined as wavelengths of radiation under specific conditions. At present the meter is defined as "the length traveled by light in a vacuum during a time interval of 1/299 792 458 of a second" (adopted by the 17th CGPM in 1983). It is interesting to note that the length of a meter can be agreed upon; but the spelling is in dispute. NIST and ASME spell it "meter" and the American Society for Testing and Materials (ASTM) spells it "metre".

Mass. The base unit of mass was changed from the gram to the kilogram (the only base unit with a prefix). In 1901, a prototype kilogram of platinum-iridium was established as the base unit of mass. It is deposited at the BIPM (ASTM, 1997). This change came after a series of ever more sophisticated tests of the density of pure water resulted in agreement on a prototype mass rather than the mass of a volume of water. Note that the prototype kilogram, if a cube, would be about 36 millimeters (1.4 inches) on a side. (Actually, it is in the form of a stubby column.) A platinum-iridium prototype gram cube would have been about 3.6 millimeters (1/8th inch) on a side, which probably would have been too small to be a practical standard.

Time. The second is no longer related to the beat of the meter pendulum. In 1967, at the 13th CGPM, the second was defined as "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" (adopted by the 13th CGPM in 1967). However, one should not lose sight of the fact that the basic unit of time on earth is the day. The day is recognized in some way by all living things on the face of the earth. The day was divided into 24 hours by the Babylonians and/or Egyptians in antiquity, the hour was divided into 60 minutes in the thirteenth century with the development of the mechanical clock, and the minute divided a second time into 60 seconds as the art of clock making advanced. Note that all of these time measures are based on sexagesimal fractions of Babylonian and Egyptian arithmetic rather than decimal fractions. (Boorstin, 1983) Regardless of the periods of the radiation of cesium-133, there are $24 \cdot 60 \cdot 60$ or 86,400 seconds each and every calendar day on earth.

Electric Current. In order to incorporate electrical measures into the metric system, in 1901, the third CGPM decided to adopt one of the electromagnetic units ampere, coulomb, ohm, or volt as a base unit. Subsequently, the ampere, the unit of electric current was selected as a base unit. The ampere is presently defined as, "that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed one meter apart in vacuum would produce between those conductors a force equal to 2 $\cdot 10^{-7}$ newton per meter of length." (Adopted by the 9th CGPM in 1948.) (Do not try to confirm this at home.) The other electromagnetic measures are derived from these first four base units; e.g., the volt in base units of SI is $m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$.

Temperature. The kelvin is defined as, "the fraction 1/273.16 of the thermodynamic temperature of the triple point of water". (Adopted by the 13th CGPM in 1967.) The Celsius Temperature (previously called Centigrade) is the commonly used scale for temperature measurements except for some scientific work where the thermodynamic scale is used. A difference of one degree on the Celsius scale equals one kelvin. Zero on the thermodynamic scale is 273.15 kelvins below zero degrees Celsius.

Amount of Substance. "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." (Adopted by the 14th CGPM in 1971.)

Luminous Intensity. "The candela is the huminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \cdot 10^{12}$ hertz and that has a radiant intensity in that direction of 1/683 watt per steradian." (Adopted by the 16th CGPM in 1979.)

The Modern Metric System

At the 11th CGPM in 1960, SI was formally adopted as the standard system of measures. It has undergone much refinement since then, and probably will undergo additional refinement as time goes by. In addition to the adoption of unrelated base units, another departure from the early metric system is deprecation of prefixes in multiples of ten and adoption of prefixes in multiples of one thousand (giga – one billion, mega – one million, kilo – 1000, milli – 1/1000, micro – one millionth, and mano – one billionth).

Among the technical societies in the United States with ongoing interest in SI are:

American Society for Testing and Materials.
In 1964, ASTM published a Metric Practice Guide without designation which in 1968 was adopted as E 380-68 Standard for Metric Practice. This standard has been revised several times, most recently as E 380–93 Standard Practice for Use of the International System of Units (SI) (the Modernized Metric System) (ASTM, 1997).

American Society of Mechanical Engineers.
In 1968, a Special Committee on Metric Study was established by the Council of ASME to propose and implement constructive solutions to problems associated with conversion to the metric system. As a result, ASME Guide SI—1 was published as ASME Orientation and Guide for Use of SI (Metric) Units. This guide is in its ninth edition dated March 24, 1982, (ASME, 1982). A tenth edition is in development. ASME maintains a committee to advise its Council on Codes and Standards on matters relating to metrication. The Board on Performance Test Codes also reports to the Council on Codes and Standards.

CONFUSION CAUSED IF SI IS STRICTLY APPLIED

Some form of metric system is in use in all countries of the world. It would appear that strict SI is not in general use except for scientific application. Many examples may be found in engineering papers of continued use of the calorie for energy; bars, atmospheres, height of water or mercury, and even kilograms per square centimeter for pressure; kilometers per hour for velocity; and kilowatthours for electrical energy.

US customary units have been impacted by the development of SI. The desire to differentiate between force and mass has resulted in recommended use of "a gage pressure of pounds force per square inch" rather than "psig" (psig and psia have rarely been spelled out in text). Are there those who are confused by psig and psia with regard to either mass versus force or gage versus absolute?

Time units have also been impacted by the development of SI with the second as the base unit of time. Until recently the hour has been the US customary unit for testing mechanical equipment. Use of the second suggests a "snapshot" of operation rather than a sustained average over the course of a test. Further, to convert from US customary units in hours to SI one must make a two stage adjustment; one for mass, volume, energy, etc., and then divide by 3,600 for time.

SI prescribes one measure for energy: the joule. The loss when SI is strictly followed is the convenience of knowing that foot-pounds and newton meters denote mechanical energy, Btu's and joules denote chemical and heat energy, and kilowatthours denote electrical energy. To further confound, a firing rate or a heat release rate customarily expressed as Btu's per hour would, in strict SI, be expressed as watts (not joules per second), a unit formerly reserved for electric power. Thus, the classic US customary term for power plant energy conversion of Btu/kWhr becomes a dimensionless reciprocal of decimal efficiency.

SUGGESTED ACCOMMODATIONS FOR METRIC WHEN USED IN ASME PERFORMANCE TEST CODES

Time

Permit use of the hour, minute, test duration, etc., as the measure of time if that is the US customary measure.

Energy

Permit use of newtonmeter, joule, and kilowatthour for metric units when foot-pound, Btu, and kilowatthour are used for US customary units.

Pressure

Permit use of pascal, pascal (gage), and millimeters of mercury or water when psia, psig, and inches of mercury or water are used for US customary units.

Conversion Table

Each Performance Test Code that is to accommodate both US customary units and metric units should include a Conversion Table similar to the following for each term to be reported in a code test:

US Customary	multiply by	Metric
lb/hr	0.4536	kg/h
psig	6.895	kPa (gage)
psia	6.895	kPa
in. Hg	25.4	mm (Hg)
Btu/kWhr	1.055	kJ/kWh

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