FUNDAMENTALS OF THERMOMETRY

PART I

by Henry E. Sostmann

1: THE ABSOLUTE, OR THERMODYNAMIC KELVIN, TEMPERATURE SCALE

Temperature is a measure of the hotness of something. For a measure to be rational (and useful between people), there must be agreement on a scale of numerical values (the most familiar of which is the Celsius or Centigrade Scale), and on devices for interpolating between the defining values.

The only temperature scale with a real basis in nature is the Thermodynamic Kelvin Temperature Scale (TKTS), which can be deduced from the First and Second laws of Thermodynamics. The low limit of the TKTS is absolute zero, or zero Kelvin, or 0K (without the ˚ mark), and since it is linear by definition, only one nonzero reference point is needed to establish its slope. That reference point was chosen, in the original TKTS, as 273.15K, or 0˚C.

0˚C is a temperature with which we all have a common experience. It is the temperature at which water freezes, or, coming from the other side, ice melts; at which water exists under ideal conditions as both a liquid and a solid under atmospheric pressure. In 1954 the reference point was changed to a much more precisely reproducible point, 0.01˚C. This is known as the triple point of water, and is the temperature at which water exists simultaneously as a liquid and a solid under its own vapor pressure. The triple point of water will be the subject of extended discussion in a later article in this series of articles. It is the most important reference point in thermometry.

The unit of temperature of the TKTS is the kelvin, abbreviated "K". The temperature interval ˚C is identically equal to the temperature interval K, and ˚C or K (the latter without the ˚ symbol) may be used also to indicate a temperature interval. The difference between 1˚C and 2˚C is 1K or 1˚C, but the temperature 1˚C = the temperature 274.15K.

Measurements of temperature employing the TKTS directly are hardly suitable for practicable thermometry. Most easily used thermometers are not based on functions of the First and Second Laws. The practicable thermometers that will be discussed later in this series of articles depend upon some function that is a repeatable and single-valued analog

of, or consequence of, temperature, and they are used as interpolation devices of utilitarian temperature scales (such as the International Temperature Scale) which are themselves artifacts. The main purpose for the realization of the TKTS is to establish relationships between the Thermodynamic Scale of nature and the practical scales and thermometers of the laboratory or of industry, so that measurements made by non-thermodynamic means can be translated into terms of the TKTS, and rational temperature scales can be constructed on a basis related to realizable physical phenomena.

There exist in nature a number of what are called thermometric fixed points. These are physical states in which some pure material exists in two or three of the three possible phases simultaneously, and temperature is constant.

A two-phase equilibrium is represented by the earlier example of the freezing point of water, or, more properly, the coexistence of liquid and solid water. For this equilibrium to represent a constant temperature, $0°C$, pressure must be specified, and the specification is a pressure of 1 standard atmosphere, 10 1325 Pascal. (A two-phase fixed point at 1 standard atmosphere is called the "normal" point). The variation due to pressure from the defined temperature of a liquid-solid equilibrium is not large (which is not to say that it may not be significant). The freezing point of water is reduced approximately 0.01K for an increase of pressure of 1 atmosphere. The variation due to pressure for a liquid-vapor equilibrium is relatively very large.

A three-phase equilibrium is represented by the triple point of water, the coexistence of liquid and solid water under its own vapor pressure, at $0.01°C$. Because all three possible phases are determined by the physical state, it is generally possible to realize a triple point more accurately than a two-phase point.

This may be seen from the Phase Rule of Gibbs:

$$P - C - 2 = F \qquad \qquad \text{Eq.1}$$

where P is an integer equal to the number of phases present, C is the number of kinds of molecule present (for an ideally pure material, C = 1) and F is an integer giving the number of degrees of freedom. Obviously, for the two-phase equilibrium there is one degree of freedom, pressure, and for the three-phase equilibrium F = 0; that is, the temperature is independent of any other factor. Fig.1 illustrates one, two and three-phase equilibria.

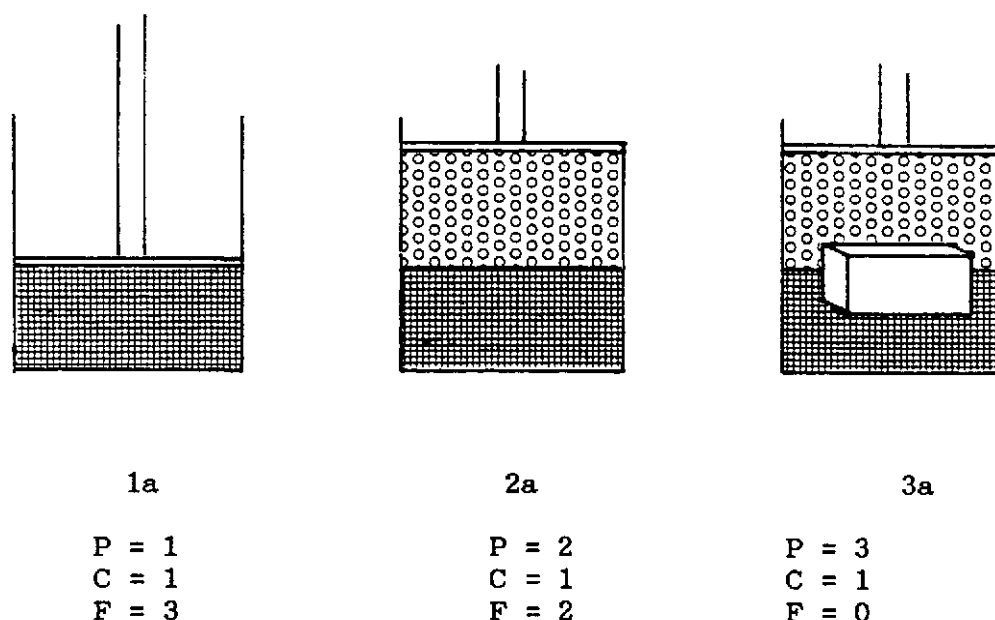| 1a	2a	3a
P = 1	P = 2	P = 3
C = 1	C = 1	C = 1
F = 3	F = 2	F = 0

Fig. 1: The Phase Rule of Gibbs. P = the number of phases present; C = the number of components (1 for a pure material); F = the degrees of freedom. 1a is uncontrolled. 1b is a melt or freeze point. 1c is a triple point.

A typical device for realizing the TKTS is the helium gas thermometer, since the vapor pressure of an ideal gas is a thermodynamic function (or rather a statistical mechanical function, which for the purpose is the same thing). The transfer function of a gas thermometer may be chosen to be the change in pressure of a gas kept at constant volume, or the change in volume of a gas kept at constant pressure. Since it is easier to measure accurately change in pressure than it is to measure change in volume, constant-volume gas thermometers are more common in use than constant-pressure gas thermometers.

A rudimentary gas thermometer is shown in Fig 2. Its operation will be illustrated by using it to show that the zero of the TKTS is 273.15K below the temperature of the normal freezing point of water, 0° on the Celsius Scale.

Fig. 2 shows a cylindrical bulb of constant volume, connected by tubing defined as constant-volume, to a U-tube manometer. A second connection to the manometer leads to a reservoir of mercury, which contains a plunger, P, by means of which the column height of the manometer may be varied. The constant-volume bulb and tubing contain an ideal gas.

The bulb is first surrounded by an equilibrium mixture of ice and water (C, in Fig 2a). When the gas is in thermal equilibrium with the slurry in the bath, the pressure of the gas is adjusted by moving the plunger so that both columns of mercury in the U-tube are at the same height, corresponding to an index mark 1.

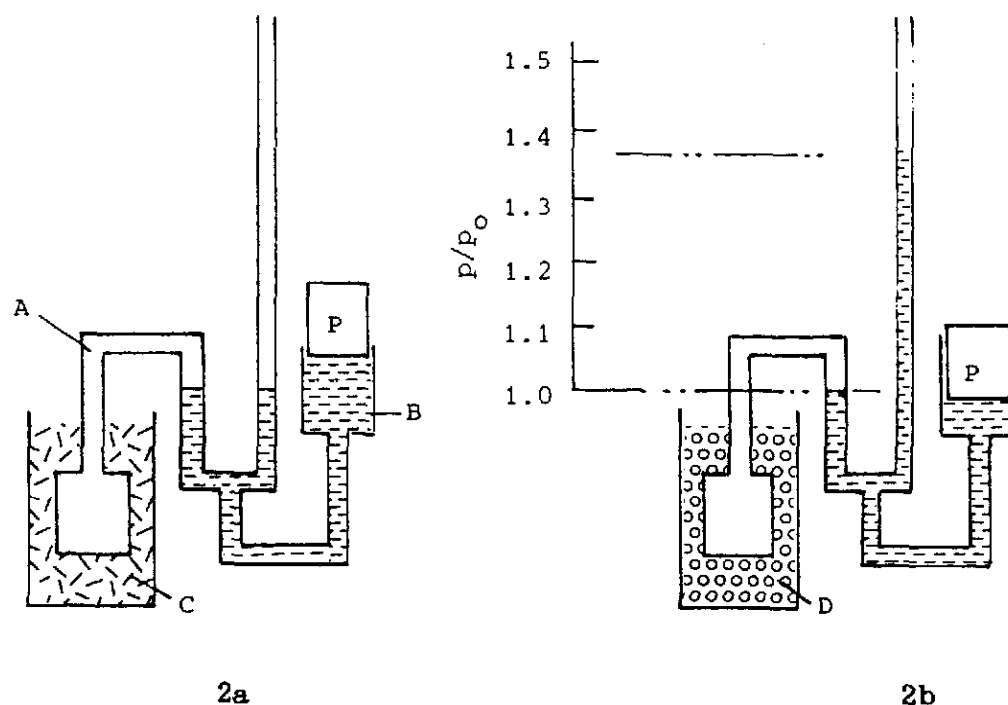2a   2b

Fig.2: A rudimentary gas thermometer. A = helium gas.
B = mercury, C = water + ice (0°C), D = water + steam
(100°C), P = a plunger for adjusting mercury level.

Next, the ice bath is removed and replaced with a bath containing boiling water, or more correctly, an equilibrium mixture of liquid and vapor water at a pressure of 1 standard atmosphere, (D, in Fig 2b). As the manometric gas is heated by the boiling water it expands, and the mercury in the manometer is displaced. The plunger is actuated to reposition the surface of the mercury in the left leg at the index mark 1, restoring the criterion of constant volume in the closed gas system, a condition shown in Fig 2b. However the mercury in the right, open leg is not now at the index mark 1, but measurably higher. In fact, the difference in heights indicates that the pressure of the enclosed gas at the boiling point is 1.366099 times the pressure at the freezing point. We can then calculate:

$$(100°C - 0°C)/(1.366099 - 1) = 273.15 \qquad \text{Eq.2}$$

and from this we can understand the Celsius degree as 1/273.15 of the pressure ratio change between 0°C and 100°C. Thus if temperature is reduced by 273.15 Celsius or kelvin intervals below 0°C, an absolute zero is reached which is the zero of the TKTS. The zero of the Celsius Scale is therefore 273.15K, and

$$T = t + 273.15 \qquad\qquad Eq.3$$

where T is temperature on the TKTS and t is temperature on the Celsius Scale. Note that the temperature interval and the zero of the TKTS have been defined without reference to the properties of any specific substance.

All constant volume gas thermometer measurements can be expressed in terms of the equation

$$P_1 / P_2 = (T_1 - T_0) / (T_2 - T_0) \qquad\qquad Eq.4$$

where the Ts are temperatures on the TKTS, the natural temperature Scale, and the T_0s are the zero of that Scale.

This relationship assumes an ideal gas. The reader will have observed that the gas thermometer reflects Charles' or Boyle's law, if the pressure or the volume of the gas, respectively, be held constant. An ideal gas is a gas whose behavior can be predicted exactly from Boyle's or Charles' Law, which obeys it through all ranges of temperature or pressure, and where the relationship between concentration (n/V), absolute temperature and absolute pressure is

$$(n/V)(T/P) = 1/R = a \text{ constant} \qquad\qquad Eq.5$$

more commonly written as

$$PV = nRT \qquad\qquad Eq.6$$

where R is the gas constant, identical for all ideal gases. R = 0.082053, and is known to about 30ppm. A second condition is that there be no intermolecular forces acting, thus the internal energy, V, does not depend on the molecular distances, and

$$(\delta E / \delta V)_T = 0 \qquad\qquad Eq.7$$

Unfortunately there is no real ideal gas, and the uncertainty of 30ppm is a large number. Helium comes closest, carbon dioxide varies most

widely from ideality. However real gases approach ideality as their pres-
sures are reduced, reflecting a reduction in density. Since it is not
possible to measure the change in pressure of a gas at zero pressure
(or the change in volume of a gas at zero volume) the requirement for
an ideal gas is approached by making a number of measurements at a
number of pressures and extrapolating to zero pressure. Such a system
of measurements is shown in Fig. 3. Regardless of the nature of the gas,
all gas thermometers at the same temperature approach the same reading
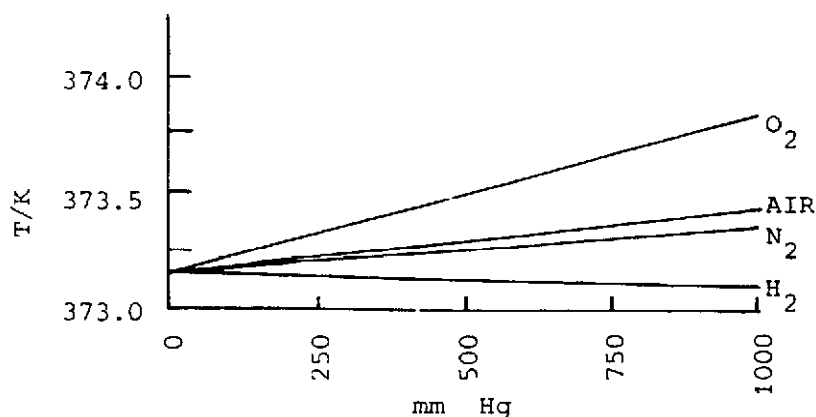as the pressure of the gas approaches zero.

Fig3: Pressure ratios of various gases at various
pressures at the condensation point of steam.

Several authors have proposed modifications of the ideal gas law to ac-
count for the non-ideality of real gases. One which is much used, that
of Clausius, is the virial equation, which is a series expansion in terms
of the density of the gas, and is written:

$$PV = nRT(1 + \frac{nB_v}{v} + \frac{n^2C_v}{v^2} + \frac{n^3D_v}{v^3} + ...) \qquad Eq.8$$

where the coefficients B, C, D, etc., are called the second, third, fourth,
etc., volume virial coefficients, and are constants for a given gas at a
given temperature. Over the usual range of gas densities in gas ther-
mometry, it is seldom necessary to go beyond the second virial
coefficient.

The departure of real gases from ideality is only one of the problems of
accurate gas thermometry.

A second is the purely mechanical matter of dead space. There must be a real connection to convey the pressure from the bulb to the manometer. It is inconvenient to locate the bulb and the manometer in the same thermostatted enclosure, and a common practice is to use two separate enclosures, each carefully thermostatted. Fig. 4 is a modification of Fig. 2 to illustrate this configuration.
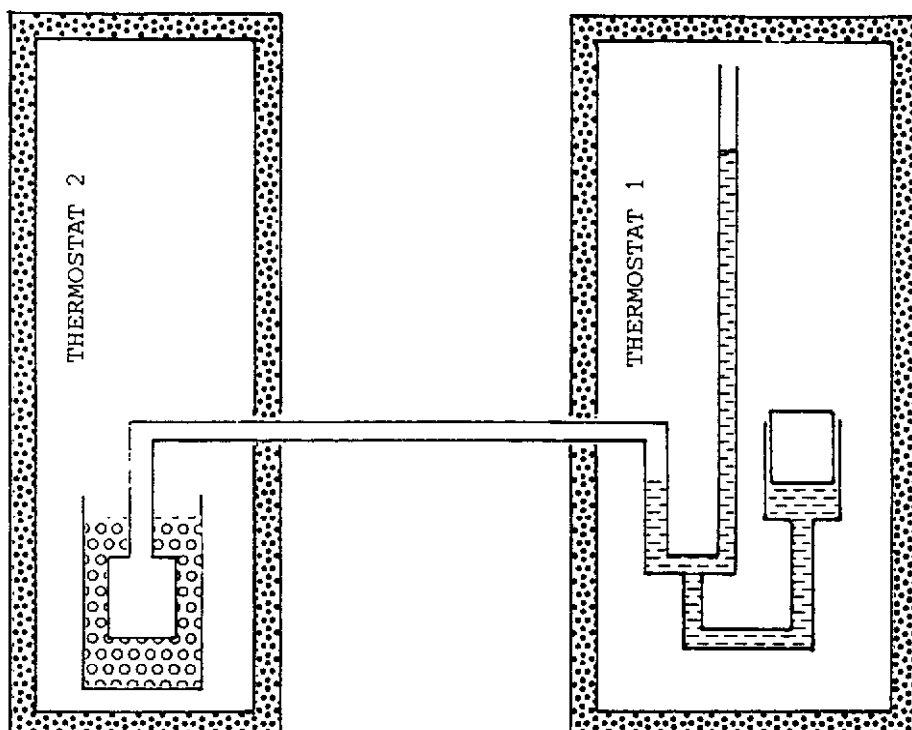

Fig.4: Thermostatted gas thermometer. The U-tube mano-
meter and the gas bulb are separately kept at constant
temperature; the (long, perhaps many meters) capillary
is not.

The price paid is that there is a capillary tube, generally of some length, which goes through the wall of each of the two thermostats and whose temperature is essentially uncontrolled. The solutions are care and compromise. The bulb volume can be made as large as possible relative to the capillary volume. The temperature distribution along the capillary length can be measured at suitable intervals. The capillary volume can be kept small by providing a capillary of small diameter, but not so small as to introduce thermomolecular pressures where the tube passes through a temperature gradient, or, conversely, a correction for thermomolecular pressure can be made.

A third obvious problem is that of the thermal expansion of the materials of construction. An ideal constant-volume gas thermometer assumes that only the contained gas is subject to thermal expansion, while in reality the whole system is subject to temperature changes, which must be known or estimated, and for which correction must be made.

A fourth correction required is for the hydrostatic head pressure of the gas in the system, including that of the gas column itself.

A fifth relates to the effects of sorption, in which impurities in the gas, or impurities remaining from a less than ideally clean system, are absorbed on the walls of the bulb and other parts of the thermometer system at the reference temperature, desorbed at a higher temperature, with the effect of elevating the measured gas pressure, and then reabsorbed as the temperature approaches the reference temperature. Attention to the elimination of sorption has resulted in gas thermometry measurement of the normal boiling point of water as 99.975°C!

Gas thermometry has claimed the attention of a number of fine experimenters for some generations, the most recent of whom have been Guildner and Edsinger, followed by Schooley, at the National Bureau of Standards. This work forms much of the thrust to replace the International Practical Temperature Scale of 1968 with the International Temperature Scale of 1990, in an effort to more closely approximate thermodynamic temperatures in a practicable Scale. A concise account of the gas thermometer and gas thermometry at the NBS is given by Schooley, and should be consulted by anyone interested in experimental elegance. Schooley provides an example of the accuracy and precision of this work:

Fixed point °C	Gas therm °C	IPTS-68 °C	Uncertainty
Steam pt	99.975	100.000	±0.005
Tin pt	231.924	231.9681	±0.015
Zinc pt	419.514	419.58	±0.03

With the conclusion of work in preparation for ITS-90, gas thermometry is considered to be a finished matter at the NBS. The gas thermometer itself, which should have been preserved as a national shrine or monument, is now in the process of dismemberment.

As a generality, gas thermometry has led the development of thermodynamic values of the thermometric fixed points, and a variety of other methods have been used largely to check its accuracy and consistency.

These include acoustic thermometry, dielectric-constant gas thermometry, noise thermometry and radiation thermometry, each appropriate to a portion of the range of the temperature Scale.

2: THE INTERNATIONAL SCALE OF 1990 (ITS-90)

On October 5, 1989, the International Committee on Weights and Measures accepted a recommendation of its Consultative Committee on Thermometry for a new "practical" temperature scale, to replace the International Practical Temperature Scale of 1968, which had replaced, in turn, a succession of previous Scales, those of 1948, 1927, etc. The official text of the ITS-90, in English translation from the official French, will be published in Metrologia, probably in the first quarter of 1990. The ITS-90 is officially in place as the international legal Scale as of 1 January, 1990.

As in previous "practical" Scales (although the word "practical" is not used in the title of the new Scale) the relationship to the TKTS is defined as

$$t_{90}/°C = T_{90}/K - 273.15 \hspace{4cm} Eq.9$$

and temperatures are defined in terms of the equilibrium states of pure substances (defining fixed points), interpolating instruments, and equations which relate the measured property to $T(90)$. The defining fixed points and the values assigned to them are listed in Table 1, and the values which were assigned on IPTS(68) are listed also, for comparison. It is to be remembered that, while the Scale values assigned to a fixed point may have been changed, the fixed point has the identical hotness it always had.

Several deep cryogenic ranges are provided. These are:

From 0.65K to 5.0K using a helium vapor pressure interpolation device

From 3.0K to the triple point of neon (24.5561K) using a constant-volume gas thermometer

From 4.2K to the triple point of neon with ^{4}He as the thermometric gas

From 3.0K to the triple point of neon with ^{3}He or ^{4}He as the thermometric gas

These ranges are probably of interest to only a limited number of specialists, and will not be dealt with in detail in this paper. The resistance thermometer portion of the Scale is divided into two major ranges, one from 13.8033K to 0°C and the other from 0°C to 961.68°C, with a number of subranges. There is third short range which embraces temperatures slightly below to slightly above 0°C, specifically -38.8344° to +29.7646°C. The Scale ranges are summarized in Table 2.

The interpolations are expressed as the ratios of the resistance of platinum resistance thermometers (PRTs) at temperatures of T(90) and the resistance at the triple point of water; that is:

$$WT(90) = RT(90)/R(273.16K) \qquad Eq.10$$

a change from the definition of IPTS(68) which used the resistance at 0°C, 273.15K, as denominator. The PRT must be made of pure platinum and be strain free; it is considered a measure of these requirements if one of these two constrains are met:

$$W(302.9146K) \geq 1.11807 \quad (gallium\ melt\ point) \qquad Eq.11$$

$$W(234.3156K) \geq 0.844235 \quad (mercury\ triple\ point) \qquad Eq.12$$

and a PRT acceptable for use to the freezing point of silver must also meet this requirement:

$$W(1234.93K) \geq 4.2844 \quad (silver\ freeze\ point) \qquad Eq.13$$

The temperature T(90) is calculated from the resistance ratio relationship:

$$WT(90) - W_r T(90) = dWT(90) \qquad Eq.14$$

where WT(90) is the observed value, $W_r T(90)$ is the value calculated from the reference function, and dWT(90) is the deviation value of the specific PRT from the reference function at T(90). (The reference functions represent the characteristics of a fictitious "standard" thermometer; the deviation function represents the difference between that thermometer and an individual real thermometer). The deviation function is obtained by calibration at the specified fixed points, and its mathematical form depends upon the temperature range of calibration.

THE RANGE FROM 13.8033k TO 273.16K

The reference function for this range is

$$\ln[W_r T(90)] = A_0 + \sum_{i=1}^{12} A_i \{[\ln(T(90)/273.16K)+1.5]/1.5\}^i \quad \text{Eq.15}$$

where the values of A_0 and A_i are given in the text of the Scale.

If the PRT is to be calibrated over the entire range, down to 13.8033K, it must be calibrated at specified fixed points and also at two temperatures determined by vapor pressure or gas thermometry. Such thermometers will most likely be calibrated only by National Laboratories, and this paper will not include details, but assume that the subranges of general interest to the primary calibration laboratory begin at 83.8058K (-189.3442°C), the triple point of argon.

The subrange from -189.3442° to 273.16°C requires calibration at the triple point of argon (-189.3442°C), the triple point of mercury (-38.8344°C) and the triple point of water to obtain the coefficients a and b. The deviation function is:

$$dW = a[W(T(90)) - 1] + b[W(T(90)) - 1]\ln W(T(90)) \quad \text{Eq.16}$$

THE RANGE FROM 0°C TO 961.78°C

For the range from 0°C to 961.78°C, the freezing point of water to the freezing point of silver, the reference function is:

$$W_r T(90) = C_0 + \sum_{i=1}^{9} C_i \ [(T(90)/K - 754.15)/481]^i \quad \text{Eq.17}$$

and the coefficients C_0 and C_i are specified in the text of the Scale.

The PRT to be used over this entire range must be calibrated at the triple point of water and the freezing points of tin, zinc, aluminum and silver. The coefficients a, b and c are derived from the tin, zinc and aluminum calibrations respectively, and the coefficient d is derived from the deviation of WT(90) from the reference value at the freezing point of silver. For temperature measurements below the freezing point of silver, d = 0. The deviation function is

$$dWT(90) = a[WT(90) - 1] + b[WT(90) - 1]^2 \quad \text{Eq.18}$$

$$+ c[WT(90) - 1]^3 + d[Wt(90) - W(933.473K)]^2$$

PRTs may be calibrated over the whole range or for shorter ranges terminating at the freezing points of aluminum or zinc. For the shorter ranges of Eq. 18, the equation is truncated as follows:

Upper limit	Coefficient
Aluminum	$d = 0$
Zinc	$c = d = 0$

For the still shorter range from the triple point of water to the freezing point of tin, calibrations are required at the water triple point and the freezing points of indium and tin. The deviation function is:

$$dT(90) = a[WT(90) - 1] + b[WT(90) - 1]^2 \qquad \text{Eq.19}$$

For the range from the triple point of water to the freezing point of indium, calibrations are required at the triple point of water and the freezing point of indium. The reference function is:

$$dWT(90) = a[WT(90) - 1] \qquad \text{Eq.20}$$

For the range from the triple point of water to the melting point of gallium, calibrations are required at these points, and the deviation equation is the same as Eq.20 except for the coefficients.

For the range from the triple point of mercury to the melting point of gallium – a most useful range for near-environmental thermometry – calibrations are required at the mercury and water triple points and the gallium melting point, and the deviation equation is

$$dT(90) = a[WT(90) - 1] + b[WT(90) - 1]^2 \qquad \text{Eq.21}$$

However the reference function must be calculated from Eq.15 for the portion of the Scale below 0°C, and from Eq.17 for the portion above 0°C.

For a relatively simple polynomial approximation over the resistance thermometer range from -200° to +600°C, accurate to 1mK above 0°C and 1.5mK below, see the article "Realizing the ITS(90)" in this issue of the Isotech Journal.

The temperature range above the freezing point of silver employs a radiation thermometer as interpolating instrument, and the relationship is:

$$L\lambda(T90)/L\lambda(T90(X)) = (\exp[c_2/\lambda T90(X)] - 1)$$ Eq.22

$$/(\exp[c_2/\lambda T90] - 1)$$

where $L\lambda(T90)$ and $L\lambda(T90(X))$ are the spectral concentrations of radiance of a blackbody at wavelength λ in vacuum at T90 and at T90(X). T90(X) may be the silver point, the gold point or the copper point. C_2 = 0.014388 m·K.

3: THE 1990 VALUE OF THE OHM

The National representations of the standard ohm also change in 1990. The change was made because the quantum Hall effect, the new international standard of resistance, permits correction of the slight but not insignificant differences in the value assigned to the ohm by the various national laboratories, due to drift over years of the standard resistors which were kept as National standards of resistance. The following adjustments were made by England, the United States and West Germany:

NPL (England) increased the value of their ohm by +1.61 ppm. Thus a perfectly stable 1 ohm resistor calibrated at NPL prior to January 1, 1990, has a new value of 0.99999839 ohm. A 10 ohm resistor has a new value of 9.9999839 ohm.

1Ω (NPL 90) = 1.0000016$1\Omega$ (NPL 89)
1Ω (NPL 89) = 0.9999983$9\Omega$ (NPL 90)

NIST (United States) increased the value of their ohm by +1.69 ppm. A drift-free 1 ohm resistor calibrated at NIST prior to January 1, 1990, has a new value of 0.99999831 ohm. A 10 ohm resistor has a new value of 9.9999831 ohm.

1Ω (NIST 90) = 1.0000016$9\Omega$ (NBS 89)
1Ω (NBS 89) = 0.9999983$1\Omega$ (NIST 90)

PTB (West Germany) increased the value of their ohm by +0.56 ppm. A drift-free 1 ohm resistor calibrated at PTB prior to January 1, 1990, has a new value of 0.99999944 ohm. A 10 ohm resistor has a new value of 9.9999944 ohm.

1Ω (PTB 90) = 1.00000056 Ω (PTB 89)
1Ω (PTB 89) = 0.999999944 Ω (PTB 90)

Other laboratories adjusted the ohm as follows: VNIIM (USSR) -0.15ppm (a decrease); France, +0.71ppm; BIPM, +1.92ppm.

The effects on the calibration of a standard platinum resistance thermometer calibrated by in 1989, with a typical resistance value at 0°C (for example 25.52490Ω) and at 650°C (for example 85.28842Ω) are as follows:

t(89)	NBS 89 Ω	NIST 90 Ω	d(Ω)	d(t)
0°C	25.52490	25.52486	-0.00004	+0.000393
650°C	85.28842	85.28828	-0.00014	+0.001705

where d(Ω) is the decrease in resistance measured for the same hotness and d(t) is the increase in hotness represented by the same resistance.

In addition, practicable resistance standards as maintained in most thermometry laboratories have a small but real resistance dependance upon temperature, written as

$$R_1 = R_o [1 + \alpha(t_1 - t_o) + \beta(t_1 - t_o)^2] \qquad \text{Eq.23}$$

(values of α and β are given in the calibration report for the individual resistor).

The value of resistance is conventionally reported at 25°C, and will continue to be. However

$$25°C \text{ (t68)} = 24.994°C \text{ t(90)} \qquad \text{Eq.24}$$

The change in the value of the ohm may be significant in precision thermometry. It is unlikely that the difference in the value of the reference temperature for the resistor will require consideration. Certainly the β term can be ignored.

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In our next issue, we will discuss in detail the physical embodiment of the fixed points and of the equipment and operations involved in realizing them.

TABLE 1

FIXED POINTS OF THE IPTS-68

AND OF THE ITS(90) AS ADOPTED BY CIPM, OCTOBER 5 1989

SUBSTANCE	STATE	CELSIUS TEMP. IPTS-68	CELSIUS TEMP. ITS-90
e-H_2	Trip	-259.34	-259.3467
O_2	Trip	-218.789	-218.7916
Ar	Trip	-189.352	-189.3442
N_2	Boil	-195.802	-195.794
Hg	Trip	-38.842	-38.8344
H_2O	Trip	0.01	0.01
Ga	Melt	29.772	29.7646
In	Freeze	156.634	156.5985
Sn	Freeze	231.9681	231.928
Zn	Freeze	419.58	419.527
Al	Freeze	660.46	660.323
Ag	Freeze	961.93	961.78
Au	Freeze	1064.43	1064.18
Cu	Freeze	1084.88	1084.62

Notes:

e-H_2 represents hydrogen in equilibrium between the ortho and para molecular forms

Boiling, melt and freeze points are at 1 standard atmosphere = 101 325 Pa.

TABLE 2

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RANGES OF THE ITS-90

THE PURCHASER OF A CALIBRATION MUST STATE
THE RANGE REQUIRED*

LOW LIMIT	HIGH LIMIT	FIXED POINTS REQUIRED
-259.3467	0.01	e-H_2 (TP), e-H_2 (VP), Ne (TP), O_2 (TP), Ar (TP), Hg (TP), H_2O (TP)
-218.7916	0.01	O_2 (TP), Ar (TP), Hg (TP), H_2O (TP)
-189.3442	0.01	Ar (TP), Hg (TP), H_2O (TP)
0.01	29.7646	H_2O (TP), Ga (MP)
0.01	156.5985	H_2O (TP), Ga (MP), In (FP)
0.01	231.928	H_2O (TP), Ga (MP), Sn (FP)
0.01	419.527	H_2O (TP), Sn (FP), Zn (FP)
0.01	660.323	H_2O (TP), Sn (FP), Zn (FP), Al (FP)
0.01	961.78	H_2O (TP), Sn (FP), Zn (FP), Al (FP), Ag (FP)
-38.8344	29.7646	Hg (TP), H_2O (TP), Ga (MP)

(TP) = triple point, (VP) = a vapor pressure determination, (FP) = freezing point at 1 standard atmosphere, (MP) = melting point at 1 standard atmosphere

*The purchaser may choose to specify a combination of several ranges, for example, -189.3442° to +419.527°, or some extrapolation, for example, -200° to +500°.

TABLE 3

THE COEFFICIENTS OF THE REFERENCE FUNCTIONS

The values of the coefficients A_i and C_i of the reference functions of Eq. 15 and 17

Eq.15   Eq.17

CONSTANT OR COEFFICIENT	VALUE	CONSTANT OR COEFFICIENT	VALUE
A_0	-2.135 347 29	C_0	2.781 572 54
A_1	3.183 247 20	C_1	1.646 509 16
A_2	-1.801 435 97	C_2	-0.137 143 90
A_3	0.717 272 04	C_3	-0.006 497 67
A_4	0.503 440 27	C_4	-0.002 344 44
A_5	-0.618 993 95	C_5	0.005 118 68
A_6	-0.053 323 22	C_6	0.001 879 82
A_7	0.280 213 62	C_7	-0.002 044 72
A_8	0.107 152 24	C_8	-0.000 461 22
A_9	-0.293 028 65	C_9	0.000 457 24
A_{10}	0.044 598 72		
A_{11}	0.118 686 32		
A_{12}	-0.052 481 34		

TABLE 4

VALUES OF $W_r(t90)$ AT THE RESISTANCE THERMOMETER FIXED POINTS

FIXED POINT	Wr(T(90))	FIXED POINT	Wr(T90)
$e-H_2$ (TP)	0.001 190 07	Ga (MP)	1.118 138 89
Ne (TP)	0.008 449 74	In (MP)	1.609 801 85
O_2 (TP)	0.091 718 04	Sn (FP)	1.892 797 68
Ar (TP)	0.215 859 75	Zn (FP)	2.568 917 30
Hg (TP)	0.844 142 11	Al (FP)	3.376 008 60
H_2O (TP)	1.000 000 00	Ag (FP)	4.286 420 53

FUNDAMENTALS OF THERMOMETRY, PART 1, REFERENCES

GAS THERMOMETRY AND THE THERMODYNAMIC SCALE

James F. Schooley, *Thermometry*, CRC Press, Boca Raton, Florida (1986) especially on gas thermometry at the NBS

T. J. Quinn, *Temperature*, Academic Press, London and New York (1873)

F. Henning, H. Moser, *Temperaturmeßung*, Springer-Verlag, Berlin and New York, 3rd edition (1977). German text; fine section on vapor-pressure thermometry by W. Thomas

THE INTERNATIONAL TEMPERATURE SCALE

H. Preston-Thomas, *The International Practical Temperature Scale of 1968 (revision of 1975)* Metrologia 12, 1 (1976)

Supplementary Information for the IPTS-68 and the EPT-76, Bureau International des Poids et Mesures, Sevres, France. This publication continues to be valuable, but will be revised at some future date to include ITS-90

R. E. Bedford, G. Bonnier, H. Maas, F. Pavese, *Techniques for approximating the International Temperature Scale of 1990*, BIMP, when published; no projected date is known. Our reading of unofficial copies of a late draft indicate that this will be of great value.

The International Temperature Scale of 1990 is the title of the official text of the new Scale, and it will be published in Metrologia. Metrologia advises that it will be published in Vol. 27 No. 1 (February 1990).

THE 1990 OHM

Changes in the Value of the UK Reference Standards of Electromotive Force and Resistance, National Physical Laboratory, Teddington, England (1989)

N. Belecki at al, NIST Technical Note 1263, *Guidelines for Implementing the New Representations of the Volt and the Ohm*, U.S.Department of Commerce (1989)

V. Kose, H. Bachmair, *Neue Internationale Festlegungen für die Weitergabe elektrischer Einheiten*, Physikalisch-Technische Bundesanstalt PTB-E-35, Braunschweig FRG (1989)