A REPORT ON THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968

F. D. ROSSINI

University of Notre Dame, Notre Dame, Indiana, U.S.A.

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University of Notre Dame, Notre Dame, Indiana, U.S.A.

ABSTRACT

This report summarizes the essential parts of the International Practical Temperature Scale of 1968, indicates the differences from the International Practical Temperature Scale of 1948, as amended in 1960, and discusses the problem of conversion of temperatures and certain calorimetric data obtained under the previous scale.

CONTENTS

1. INTRODUCTION

The purpose of this paper is to present in a simple way, for the benefit of practising thermodynamicists and thermochemists, the essential features

of the new International Practical Temperature Scale of 1968, how the changes may affect their work and measurements, and the manner of correcting to the new scale temperatures and data produced under the International Practical Temperature Scale of 1948. This paper has been prepared at the request, made in July 1969, of the Commission on Thermodynamics and Thermochemistry of the International Union of Pure and Applied Chemistry. For additional details, readers are referred to references 1 to 5 inclusive. References 1, 4 and 5 include manuscripts made available to the present author prior to their publication, by Dr T. B. Douglas, Dr R. P. Hudson and Dr C. W. Beckett, of the National Bureau of Standards, Washington, D.C., U.S.A., and by Dr S. Angus, of the Imperial College of Science and Technology, London, U.K.

At its meeting in October 1968, the International Committee on Weights and Measures, on the recommendation of its International Committee on Thermometry, set up the International Practical Temperature Scale of 1968 (IPTS-1968). Effective 1 January 1969, IPTS-1968 replaces the International Practical Temperature Scale of 1948, as amended in 1960 (IPTS-1948).

The basic temperature is the thermodynamic temperature, to which is given the symbol T, and the unit for which is the kelvin, to which is given the symbol K. The kelvin is the fraction, $1/273 \cdot 16$, of the thermodynamic temperature of the triple point of water.

Temperatures on the Celsius scale are denoted by the symbol t, the unit for which is the degree Celsius, to which is given the symbol °C. The unit on the Celsius scale is exactly equal to the unit on the thermodynamic scale. That is, one kelvin is exactly equal to one degree Celsius. Any difference in temperatures may be expressed either in kelvins or in degrees Celsius.

Temperatures on the Celsius scale are related to those on the Kelvin scale by the relation:

$$t = T - 273 \cdot 15 \text{ (exactly)} \tag{1}$$

2. BASIS OF THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968

IPTS-1968 differs from IPTS-1948 in a number of ways: several new fixed points have replaced some old ones ; some new fixed points have been included ; significant changes have been made in the values assigned to a number of the fixed points ; the lower end of the scale has been extended down from the boiling point of oxygen (~ 90 K) to the triple point of hydrogen (~ 14 K) ; a new value for the constant c_2 in the Planck radiation formula results in significant changes (about $0 \cdot 1$ to $0 \cdot 2$ per cent) in the values calculated with the radiation formula for temperatures above the gold point ; new equations are provided for calculating temperatures with the platinum resistance thermometer ; the range of use of the platinum resistance thermometer is extended down from the boiling point of oxygen (~ 90 K) to the triple point of hydrogen (~ 14 K). In addition, new specifications for materials of construction of thermometers and new procedures for calibrating thermometers are given.

IPTS-1968 distinguishes temperatures on the International Practical Kelvin

Scale with the symbol T_{68} and temperatures on the International Practical Celsius Scale with the symbol t_{68}. The relation between T_{68} and t_{68} is

$$t_{68} = T_{68} - 273 \cdot 15 \text{ (exactly)} \tag{2}$$

IPTS-1968 has been set up in such a way that the temperatures measured on it are very close to thermodynamic temperatures, the difference between the two being within the limits of accuracy of present day measurements. IPTS-1968 is constructed by assigning an exact value of temperature to the defining point and selected best experimentally determined values of temperature to a number of reproducible primary fixed points. These points involve thermodynamic equilibrium between two phases (solid–liquid or liquid–gas) or three phases (solid–liquid–gas) of a pure substance, with standard instruments calibrated at these temperatures. Interpolation between adjacent primary fixed points is done by means of formulas relating readings with the standard instruments and thermometers to values of temperature on IPTS-1968.

3. DEFINING POINT: TRIPLE POINT OF WATER

The defining point for IPTS-1968 is the triple point of water (equilibrium of water in three phases, solid, liquid and gas, in the absence of air or other substance). The value of temperature assigned to this point is 273·16 K (exactly). This definition determines the size of the degree kelvin, as previously stated, and hence also the size of the degree Celsius.

The triple point of water replaced the freezing point of water (equilibrium between the solid and liquid phases of water, in the presence of air at a pressure of one atmosphere) because the former is much more reproducible and stable than the latter.

4. DIFFERENCE BETWEEN THE TRIPLE AND FREEZING POINTS OF WATER

In 1960, when the original International Practical Temperature Scale of 1948 was amended to produce what we now label as IPTS-1948, and the triple point of water became the defining point, it was necessary to know rather well the difference between the triple point of water and the freezing point of water. Fortunately, this difference had been determined experimentally with considerable accuracy and precision[6]:

$$T_{\text{triple pt}} - T_{\text{ice pt}} = 0 \cdot 0100 \pm 0 \cdot 0001 \text{ K} \tag{3}$$

or

$$t_{\text{triple pt}} - t_{\text{ice pt}} = 0 \cdot 0100 \pm 0 \cdot 0001 °\text{C} \tag{4}$$

With the foregoing relations, we can write

$$T_{\text{triple pt}} = 273 \cdot 16 \text{ (exactly) K, by definition} \tag{5}$$

$$T_{\text{ice pt}} = 273 \cdot 1500 \pm 0 \cdot 0001 \text{ K} \tag{6}$$

$$t_{\text{triple pt}} = 0.01 \text{ (exactly) } °C \tag{7}$$

$$t_{\text{ice pt}} = 0.0000 \pm 0.0001 °C \tag{8}$$

5. PRIMARY FIXED POINTS

The primary fixed points on IPTS-1968, and the values assigned to them, are given in *Table 1*. The values actually selected are underlined—on the Kelvin scale below the freezing point of water and on the Celsius scale above the triple point of water. The defining point, the triple point of water, is set in bold type. The value for the freezing point of water (now a secondary fixed point) is included in this table simply for convenience. The values for the same temperature on the Kelvin and the Celsius scales differ by 273.15 (exactly).

Table 1. Values of the temperatures of the primary fixed points on the International Practical Temperature Scale of 1968, and their estimated uncertainties in terms of thermodynamic temperatures[a]

Substance	Equilibrium	T^g K	t^g °C	Estimated uncertainty K
Hydrogen[b]	solid–liquid–gas	13.810	−259.340	+0.010
Hydrogen[b]	liquid–gas, at $\frac{25}{76}$ atm	17.042	−256.108	+0.010
Hydrogen[b]	liquid–gas, at 1 atm	20.280	−252.870	+0.010
Neon[c]	liquid–gas, at 1 atm	27.102	−246.048	+0.010
Oxygen	solid–liquid–gas	54.361	−218.789	+0.010
Oxygen	liquid–gas, at 1 atm	90.188	−182.962	+0.010
(Water)[d]	(solid–liquid, in air at 1 atm)	(273.1500)	(0.0000)	(+0.0001)
Water[e]	solid–liquid–gas	**273.16**	**0.01**	**exact**
Water	liquid–gas, at 1 atm	373.150	100.000	+0.005
(Tin)[f]	solid–liquid, at 1 atm	505.118	231.968	+0.015
Zinc	solid–liquid, at 1 atm	692.73	419.58	+0.03
Silver	solid–liquid, at 1 atm	1235.08	961.93	+0.20
Gold	solid–liquid, at 1 atm	1337.58	1064.43	+0.20

[a] In interpreting the facts given in this table the following points are to be noted. The abbreviation 'atm' means the standard atmosphere defined as 1013250 dynes cm^{-2} or 101325 Newtons m^{-2}. The numbers 25/76 and 1 before atm are atmosphere defined as 1013250 dynes cm^{-2} or 101325 Newtons m^{-2}. The numbers 25/76 and 1 before atm are taken as exact. Near 1 atm. the freezing point of various metals changes in amounts ranging only 0.00001 to 0.0001 degree per 0.01 atm change in pressure. The depth of immersion of the thermometer in the liquid phase of various metals affects the temperature only by amounts ranging from 0.00001 to 0.0001 degree per 1 cm change in depth of immersion.

[b] The hydrogen referred to in this table means 'equilibrium' hydrogen, which, at any given temperature, is in equilibrium with respect to the ortho and para forms of hydrogen. At the normal boiling point, 1 atm, the composition of 'equilibrium' hydrogen is 0.21 per cent ortho and 99.79 per cent para, while at room temperature it is near 75 per cent ortho and 25 per cent para. The latter mixture, retained unchanged in composition, has a normal boiling point, at 1 atm, which is 0.12 degree above that of 'equilibrium' hydrogen. Equilibrium between the ortho and para forms of hydrogen is achieved by use of ferric hydroxide as a catalyst.

[c] Neon, which is largely ^{20}Ne, normally contains 0.0026 mole fraction of ^{21}Ne and 0.088 mole fraction of ^{22}Ne.

[d] The value for the temperature of the ice-point is a secondary reference point, but is included here for the convenience of the reader. (See *Table 2*, following).

[e] The water should have the isotopic composition of ocean water. The extreme differences in temperature of the triple point of water from natural sources, ocean water and continental surface water, has been found to be about 0.00025 degree.

[f] The freezing point of tin may be used in place of the normal boiling point of water as one of the primary fixed points.

[g] The selected values are singly underlined, on the Kelvin scale below the freezing point of water, and on the Celsius scale above the triple point of water. The defining point, the triple-point of water, is in heavy type. The values for the same temperature on the two scales differ by 273.15 (exactly). The number of significant figures given here varies in a few cases from the official report[1].

In the last column of *Table 1* are given the estimated uncertainties of the assigned values of temperature for the primary fixed points, referred to the thermodynamic scale of temperature.

As previosuly noted, all of the fixed points, as well as the defining point, involve thermodynamic equilibrium between two or three phases of a pure substance. In general, the triple point (equilibrium between solid, liquid and gas phases) is the most reproducible and reliable, the freezing point (equilibrium between solid and liquid phases) is next, and the boiling point (equilibrium between liquid and gas phases) is next.

6. SECONDARY REFERENCE POINTS

In addition to the primary fixed points discussed above, the International Committee approved a large number of secondary reference points. The identification of these points, and the values of temperature assigned to them, are given in *Table 2*.

Table 2. Values of the temperatures of the secondary reference points on the International Practical Temperature Scale of 1968[a]

Substance	Equilibrium	T K	t °C
Hydrogen, 'normal'[b]	solid–liquid–gas	13·956	− 259·194
Hydrogen, 'normal'[b]	liquid–gas, 1 atm	20·397	− 252·753
Neon	solid–liquid–gas	24·555	− 248·595
Nitrogen	solid–liquid–gas	63·148	− 210·002
Nitrogen	liquid–gas, 1 atm	77·348	− 195·802
Carbon dioxide	solid–gas, 1 atm	194·674	− 78·476
Mercury	solid–liquid, 1 atm	234·288	− 38·862
Water	solid–liquid, in air, 1 atm	273·1500	0·0000
Phenoxybenzene (Diphenylether)	solid–liquid–gas	300·02	26·87
Benzoic acid	solid–liquid–gas	395·52	122·37
Indium	solid–liquid, 1 atm	429·784	156·634
Bismuth	solid–liquid, 1 atm	544·592	271·442
Cadmium	solid–liquid, 1 atm	594·258	321·108
Lead	solid–liquid, 1 atm	600·652	327·502
Mercury	liquid–gas, 1 atm	629·81	356·66
Sulphur	liquid–gas, 1 atm	717·824	444·674
Cu–Al, Eutectic	solid–liquid, 1 atm	821·38	548·23
Antimony	solid–liquid, 1 atm	903·89	630·74
Aluminium	solid–liquid, 1 atm	933·52	660·37
Copper	solid–liquid, 1 atm	1 357·6	1 084·5
Nickel	solid–liquid, 1 atm	1728	1455
Cobalt	solid–liquid, 1 atm	1767	1494
Palladium	solid–liquid, 1 atm	1827	1554
Platinum	solid–liquid, 1 atm	2045	1772
Rhodium	solid–liquid, 1 atm	2236	1963
Iridium	solid–liquid, 1 atm	2720	2447
Tungsten	solid–liquid, 1 atm	3660	3387

[a] See the footnotes to *Table 1*.

[b] 'Normal' hydrogen is hydrogen having a composition of ortho and para hydrogen corresponding to that of 'equilibrium' hydrogen at room temperature. See Footnote b of *Table 1*.

7. THERMOMETRIC SYSTEMS

Having established the necessary array of fixed points, the next step is to specify the thermometric systems, that is, the thermometric substances to be used, and the properties to be measured, along with the standard measuring instruments, for the several ranges into which the total scale is subdivided.

IPTS-1968 is based on the use of only three thermometric systems:

(i) From 14 to 904 K, the platinum resistance thermometer, with measurement of the electrical resistance of a coil of pure, strain-free, annealed platinum;

(ii) From 904 to 1338 K, the thermocouple, of platinum and an alloy of 90 per cent platinum and 10 per cent rhodium, with measurement of the electromotive force.

(iii) Above 1338 K, the optical pyrometer, using the Planck radiation formula, with measurement of the intensity of radiation.

Table 3. Specifications for the several ranges of the International Practical Temperature Scale of 1968

Range of temperature K	°C	Calibrating points	Measuring instrument
13·810 to 20·280	−259·340 to −252·870	triple pt, H_2 boiling pt, H_2, 25/76 atm boiling pt, H_2, 1 atm triple pt, H_2O	platinum resistance thermometer
20·280 to 54·361	−252·870 to −218·789	boiling pt, H_2, 1 atm boiling pt, Ne, 1 atm triple pt, O_2 triple pt, H_2O	platinum resistance thermometer
54·361 to 90·188	−218·789 to −182·962	triple pt, O_2 boiling pt, O_2, 1 atm triple pt, H_2O	platinum resistance thermometer
90·188 to 273·15	−182·962 to 0·00	boiling pt, O_2, 1 atm triple pt, H_2O boiling pt, H_2O, 1 atm	platinum resistance thermometer
273·15 to 903·89	0·00 to 630·74	triple pt, H_2O boiling pt, H_2O, 1 atm (or freezing pt, Sn) freezing pt, Zn	platinum resistance thermometer
903·89 to 1337·58	630·74 to 1064·43	(freezing pt, Sb)[a] freezing pt, Ag freezing pt, Au	thermocouple: platinum and 10% Rh–90% Pt
1337·58 and above	1064·43 and above	freezing pt, Au, with the Planck radiation equation	optical pyrometer

[a] See text following equation 22.

Table 3 summarizes the specifications for the several ranges of IPTS-1968, showing the temperature covered in each range, the calibrating points for the given range, and the measuring instrument for that range.

8. REALIZATION OF THE SCALE OVER THE RANGE 13·810 TO 903·89 K

For this range, where the platinum resistance thermometer applies, the basic measurement is the resistance ratio W. For the unknown temperature T_x, the resistance ratio is

$$W_{T_x} = R_{T_x}/R_{273·15} \tag{9}$$

Here, R_{T_x} is the resistance at T_x and $R_{273·15}$ is the resistance at 273·15 (exactly) K or 0·00 (exactly) °C, which is 0·01 (exactly) kelvin below the triple point of water. This is also the freezing point of water (within 0·0001°C). One condition applies to W, namely, that its value at 373·15 K (100·00 °C) must not be less than 1·39250.

Below 273·15 K, the relation between temperature and resistance of the thermometer is obtained from a reference function and certain specified deviation equations. For the range 13·81 to 273·15 K, a reference function, W-CCT, has been tabulated as a function of temperature to provide inter-polation with a precision of 0·0001 kelvin[2]. With W-CCT thus defined, T_x is evaluated from the relation,

$$W_{T_x} = R_{T_x}/R_{273·15} = (W\text{-}CCT)_{T_x} + \Delta W_{T_x} \tag{10}$$

Here, ΔW_{T_x} is determined separately for each of four subranges, as follows:

From 13·810 to 20·280 K,

$$\Delta W_{T_x} = A_1 + B_1 T_x + C_1 T_x^2 + D_1 T_x^3 \tag{11}$$

where the constants, A_1, B_1, C_1 and D_1, are evaluated from observations at the four calibrating points specified for this subrange (see *Table 3*): by the measured deviations at the triple point of 'equilibrium' hydrogen (13·810 K), the temperature of 17·042 K (the boiling point of 'equilibrium' hydrogen at 25/76 atmosphere), and the normal boiling point of 'equilibrium' hydrogen* (20·280 K), and by the temperature derivative of ΔW_{T_x} at the normal boiling point of 'equilibrium' hydrogen (20·280 K) as derived from the following equation 12.

From 20·280 to 54·361 K,

$$\Delta W_{T_x} = A_2 + B_2 T_x + C_2 T_x^2 + D_2 T_x^3 \tag{12}$$

where the constants, A_2, B_2, C_2 and D_2, are evaluated from observations at the four calibrating points specified for this subrange (see *Table 3*): by the measured deviations at the normal boiling point of 'equilibrium' hydrogen (20·280 K), the normal boiling point of neon (27·102 K), and the triple point of oxygen (54·361 K), and by the temperature derivative of ΔW_{T_x} at the triple point of oxygen (54·361 K) as derived from the following equation 13.

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* As used here, the terminology 'normal boiling point' means the boiling point (thermo-dynamic equilibrium between the liquid and gas phases) at a pressure of exactly one atmosphere.

From 54·361 to 90·188 K,

$$\Delta W_{T_x} = A_3 + B_3 T_x + C_3 T_x^2 \qquad (13)$$

where the constants, A_3, B_3 and C_3, are evaluated from observations at the three calibrating points specified for this range (see *Table 3*): by the measured deviations at the triple point of oxygen (54·361 K) and the normal boiling point of oxygen (90·188 K), and by the temperature derivative of ΔW_{T_x} at the normal boiling point of oxygen (90·188 K) as derived from the following equation 14.

From 90·188 to 273·15 K,

$$\Delta W_{T_x} = A_4 T_x + C_4 T_x^3 (T_x - 100) \qquad (14)$$

where the constants, A_4 and C_4, are evaluated from observations at the two calibrating points specified for this range (see *Table 3*): by the measured deviations at the normal boiling point of oxygen (90·188 K) and the normal boiling point of water (373·150 K or 100·000°C).

For the range 273·15 to 903·89 K, the following equations are used:

$$T_x = t_x + 273 \cdot 15 \ (\text{exactly}) \ \text{K} \qquad (15)$$

$$t_x = t' + 0 \cdot 045 \left(\frac{t'}{100}\right)\left(\frac{t'}{100} - 1\right)\left(\frac{t'}{419 \cdot 58} - 1\right)\left(\frac{t'}{630 \cdot 74} - 1\right) \ ^\circ\text{C} \qquad (16)$$

$$t' = \frac{1}{\alpha}(W_{t'} - 1) + \delta\left(\frac{t'}{100}\right)\left(\frac{t'}{100} - 1\right) \qquad (17)$$

In equation 17, the constants, α and δ, are evaluated from measurements of the resistance ratio, $W_{t'}$, at the normal boiling point of water (100·000°C or 373·150 K) or the freezing point of tin (231·968°C or 505·118 K) and the freezing point of zinc (419·58°C or 692·73 K). Here, we have, for the normal boiling point of water,

$$W_{373 \cdot 15} = R_{373 \cdot 15}/R_{273 \cdot 15} \qquad (18)$$

for the freezing point of tin,

$$W_{505 \cdot 118} = R_{505 \cdot 118}/R_{273 \cdot 15} \qquad (19)$$

and for the freezing point of zinc,

$$W_{692 \cdot 73} = R_{692 \cdot 73}/R_{273 \cdot 15} \qquad (20)$$

9. REALIZATION OF THE SCALE OVER THE RANGE 903·89 TO 1377·58 K

For the range 903·89 to 1337·58 K, the following equations are used:

$$T_x = t_x + 273 \cdot 15 \ (\text{exactly}) \qquad (21)$$

$$E_{t_x} = a + bt_x + ct_x^2 \qquad (22)$$

Here, E_{t_x} is the electromotive force of the standard thermocouple, of platinum and an alloy of 90 per cent platinum–10 per cent rhodium, with one junction at 273·15 K, or zero degrees C, and the other at the unknown temperature t_x. The constants, a, b and c, are evaluated from the measured values of the

electromotive force at the freezing point of gold (1337·58 K or 1064·43°C), the freezing point of silver (1235·08 K or 961·93°C), and at 630·74 ± 0·20°C (903·89 K) as determined by the platinum resistance thermometer as specified in the foregoing. (The temperature, 903·89 K or 630·74°C, is a secondary reference point, corresponding to the freezing point of antimony.)

The specifications require that the standard thermocouple shall be annealed and that the purity of the platinum wire shall be such that the resistance ratio $W_{373·15}$, equal to $R_{373·15}/R_{273·15}$, shall be not less than 1·3920. The companion wire shall be an alloy containing 90 per cent platinum and 10 per cent rhodium, by weight.

Further, the thermocouple shall satisfy the following relations:
At the gold point (1337·58 K or 1064·43°C),

$$E_{Au} = 10300 \pm 50 \text{ microvolts} \tag{23}$$

For the difference in electromotive force between the gold point and the silver point (1235·08 K or 961·933°C),

$$E_{Au} - E_{Ag} = 1183 + 0·158\,(E_{Au} - 10300) \pm 4 \text{ microvolts} \tag{24}$$

For the difference in electromotive force between the gold point and 630·74°C (or 903·89 K),

$$E_{Au} - E_{903·89} = 4766 + 0·631\,(E_{Au} - 10300) \pm 8 \text{ microvolts} \tag{25}$$

10. REALIZATION OF THE SCALE ABOVE 1337·58 K

Above the gold point (1337·58 K), the unknown temperature, T_x, is defined by the Planck radiation formula:

$$J_{T_x}/J_{T_{Au}} = [\exp\,(c_2/\lambda T_{Au}) - 1]/[\exp\,(c_2/\lambda T_x) - 1] \tag{26}$$

In this equation: T_x and T_{Au} refer to the unknown temperature and the temperature of the gold point on the Kelvin scale, respectively; J is the spectral concentration, $\partial L/\partial \lambda$, of the radiant energy, L, per unit wavelength interval at the given wavelength, λ, emitted per unit time by unit area of a black body at the given temperature; c_2 is the second radiation constant with the following value:

$$c_2 = 0·014388 \text{ metre kelvin} \tag{27}$$

The measurements involve determination, with an optical pyrometer, of the ratio of the intensity of monochromatic visible radiation of a given wavelength emitted by a black body at the unknown temperature to the intensity of the same radiation of the same wavelength emitted by a black body at the gold point.

11. RECOMMENDATIONS REGARDING APPARATUS, METHODS AND PROCEDURES

The official publication[1] on the International Practical Temperature Scale of 1968 gives some detailed recommendations on apparatus, methods and procedures, covering the following items:

Standard resistance thermometer

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Standard thermocouple
Triple point and the normal boiling point of 'equilibrium' hydrogen
Normal boiling point of neon
Triple point and normal boiling point of oxygen
Normal boiling point of water
Freezing point of tin
Freezing point of zinc
Freezing point of silver
Freezing point of gold

12. NUMERICAL DIFFERENCES BETWEEN THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968 AND THAT OF 1948

Values of the numerical differences between IPTS-1968 and IPTS-1948, $T_{68} - T_{48}$, for the range 90 to 10000 K, are given in *Tables 4* and *5**. These values are taken from the paper of Douglas[4], which values are equivalent, to the same number of significant figures, with the values of $T_{68} - T_{48}$ given

Table 4. Differences in the values of temperature, over the range 90 K to the gold point, 1337·58 K, given by IPTS-1968 and IPTS-1948, reported as $T_{68} - T_{48} = \Delta$. (The values in this table are rounded from the tabulation of Douglas[4])

Units: T_{68} in degrees on the Kelvin scale of IPTS-1968; Δ in millikelvins

T_{68}	Δ	T_{68}	Δ	T_{68}	Δ	T_{68}	Δ	T_{68}	Δ
90	+ 8	140	− 9	280	− 3	480	45	860	134
92	11	145	− 5	290	− 7	490	49	880	160
94	13	150	0	300	− 9	500	53	900	194
96	13	155	+ 5	310	− 10	520	60	920	245
98	12	160	10	320	− 10	540	66	940	300
100	11	165	15	330	− 10	560	70	960	354
102	9	170	20	340	− 9	580	74	980	409
104	6	175	24	350	− 7	600	76	1000	464
106	4	180	27	360	− 4	620	77	1020	519
108	1	185	30	370	− 1	640	77	1040	575
110	− 1	190	32	380	+ 2	660	76	1060	631
112	− 4	195	33	390	6	680	76	1080	687
114	− 6	200	34	400	10	700	75	1100	743
116	− 8	210	33	410	15	720	74	1150	886
118	− 10	220	30	420	19	740	75	1200	1029
120	− 11	230	25	430	24	760	77	1250	1173
124	− 13	240	20	440	28	780	81	1300	1319
128	− 14	250	14	450	32	800	88	1337·58	1430
132	− 13	260	7	460	37	820	98		
136	− 11	270	2	470	41	840	113		

in the official report[1] of the International Committee, for the range (up to 4000°C) covered in the latter report.

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* For detailed information on the several scales of temperature in the range 14 to 90 K in use before 1968, and their relation to IPTS-1968, see ref. 3.

Table 5. Differences in the values of temperature, from the gold point, 1337·58 K, to 10000 K, given by IPTS-1968 and IPTS-1948, reported as $T_{68} - T_{48} = \Delta$. (The values in this table are from the tabulation of Douglas[4])

Units: T_{68} in degrees on the Kelvin scale of IPTS-1968; Δ in kelvins

T_{68}	Δ	T_{68}	Δ	T_{68}	Δ	T_{68}	Δ	T_{68}	Δ
1337·58	1·43	1850	2·34	2800	4·6	3900	8·0	5000	12·3
1350	1·45	1900	2·44	2900	4·8	4000	8·3	5500	14
1400	1·53	1950	2·54	3000	5·1	4100	8·7	6000	17
1450	1·61	2000	2·65	3100	5·4	4200	9·1	6500	19
1500	1·70	2100	2·86	3200	5·7	4300	9·4	7000	22
1550	1·78	2200	3·08	3300	6·0	4400	9·8	7500	25
1600	1·87	2300	3·31	3400	6·3	4500	10·2	8000	27
1650	1·96	2400	3·55	3500	6·6	4600	10·6	8500	30
1700	2·05	2500	3·79	3600	7·0	4700	11·0	9000	33
1750	2·15	2600	4·0	3700	7·3	4800	11·4	9500	37
1800	2·24	2700	4·3	3800	7·6	4900	11·8	10000	40

Douglas[4] also provides values of $\mathrm{d}(T_{68} - T_{48})/\mathrm{d}T$, the change of $T_{68} - T_{48}$ with temperature, up to 10000 K. His values are given in *Tables 6* and *7*.

Table 6. Differences in the values of the temperature derivatives, over the range 90 K to the gold point, 1337·58 K, given by IPTS-1968 and IPTS-1948, reported as $\mathrm{d}(T_{68} - T_{48})/\mathrm{d}T = \mathrm{d}\Delta/\mathrm{d}T$. (The values in this table are from the tabulation of Douglas[4])

Units: T_{68} in degrees on the Kelvin scale of IPTS-1968; $\mathrm{d}\Delta/\mathrm{d}T$ in millikelvins per Kelvin

T_{68}	$\mathrm{d}\Delta/\mathrm{d}T$	T_{68}	$\mathrm{d}\Delta/\mathrm{d}T$	T_{68}	$\mathrm{d}\Delta/\mathrm{d}T$	T_{68}	$\mathrm{d}\Delta/\mathrm{d}T$	T_{68}	$\mathrm{d}\Delta/\mathrm{d}T$
90	2·2	140	0·71	280	−0·41	480	0·41	860	1·2
92	1·3	145	0·89	290	−0·29	490	0·39	880	1·5
94	0·5	150	1·00	300	−0·18	500	0·37	900	1·9
96	−0·1	155	1·03	310	−0·08	520	0·3	903·89	2·0[a] / 2·7[b]
98	−0·6	160	1·02	320	+0·01	540	0·3	920	2·7
100	−0·89	165	0·96	330	0·09	560	0·2	940	2·7
102	−1·12	170	0·87	340	0·16	580	0·1	960	2·7
104	−1·24	175	0·75	350	0·23	600	0·1	980	2·7
106	−1·30	180	0·61	360	0·28	620	0·0	1000	2·8
108	−1·30	185	0·47	370	0·33	640	0·0	1020	2·8
110	−1·25	190	0·32	380	0·36	660	0·0	1040	2·8
112	−1·16	195	0·17	390	0·39	680	0·0	1060	2·8
114	−1·06	200	0·05	400	0·42	700	0·0	1080	2·8
116	−0·92	210	−0·20	410	0·44	720	0·0	1100	2·8
118	−0·78	220	−0·38	420	0·45	740	+0·1	1150	2·9
120	−0·63	230	−0·51	430	0·45	760	0·1	1200	2·9
124	−0·30	240	−0·59	440	0·45	780	0·3	1250	2·9
128	0·00	250	−0·62	450	0·45	800	0·4	1300	2·9
132	+0·28	260	−0·61	460	0·44	820	0·6	1337·58	3·0[b] / 1·6[c]
136	0·52	270	−0·54	470	0·43	840	0·9		

[a] From the range of platinum thermometer.
[b] From the range of the thermocouple (Pt and 10%Rh–90%Pt.).
[c] From the range of the radiation scale.

Table 7. Differences in the values of the temperature derivatives, from the gold point, 1 337·58 K, to 10 000 K, reported as d($T_{68} - T_{48}$)/d$T =$ dΔ/dT. (The values in this table are from the tabulation of Douglas[4]).

Units: T_{68} in degrees on the Kelvin scale of IPTS-1968; dΔ/dT in millikelvins per Kelvin									
T_{68}	dΔ/dT	T_{68}	dΔ/dT	T_{68}	dΔ/dT	T_{68}	dΔ/dT	T_{68}	dΔ/dT
1 337·58	3·0[b]	1 700	1·9	2 200	2·2	3 500	3	7 000	5
	1·6[c]	1 800	1·9	2 300	2·3	4 000	4	8 000	6
1 400	1·6	1 900	2·0	2 400	2·4	4 500	4	9 000	6
1 500	1·7	2 000	2·1	2 500	2·5	5 000	4	10 000	6
1 600	1·8	2 100	2·2	3 000	3	6 000	5		

[b, c] See corresponding footnotes to *Table 6.*

13. THE PROBLEM OF CONVERTING EXISTING CALORIMETRICALLY DETERMINED DATA TO THE BASIS OF THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968

With new calorimetric data being determined under the International Practical Temperature Scale of 1968, it becomes necessary to arrange for the conversion of existing calorimetrically determined data, obtained under IPTS-1948, to the basis of IPTS-1968.

Douglas[4] has prepared a report which gives detailed and exact formulas for making such conversions for calorimetric data on enthalpy, heat capacity and entropy. Douglas[4] also gives equations for converting extrapolated data, on the basis of the 'T^3', or the other theoretical or empirical relation, from a lowest temperature of measurement to zero K, for enthalpy, heat capacity and entropy.

The problem is to convert experimentally measured calorimetric data, obtained at a given numerical value of temperature on IPTS-1948, to the same numerical value of temperature on IPTS-1968. Letting the given numerical value of temperature on IPTS-1948 be T'_{48} and the same numerical value of temperature on IPTS-1968 be T''_{68}, one can therefore write

$$T''_{68} = T'_{48} \qquad (28)$$

There is one point on IPTS-1948 which has not only the same numerical value but also exactly the same temperature as on IPTS-1968. This point is the triple point of water, at 273·16K. For convenience, the enthalpy, H, the heat capacity, C_p, and the entropy, S, at the same numerical value of temperature on IPTS-1968 and IPTS-1948, are designated as H'' and H', C''_p and C'_p, and S'' and S', respectively.

Also, at a given actual temperature, the value on IPTS-1968 will be T_{68} and that on IPTS-1948 will be T_{48}.

(a) Conversion of calorimetric data on enthalpy

Douglas[4] gives an exact equation, of an infinite series type, for calculating the conversion of calorimetric data on enthalpy from a given numerical value of temperature, T'_{48}, on IPTS-1948, to the same numerical value of temperature T''_{68}, on IPTS-1968.

However, it is shown that all of the terms of this equation beyond the first are normally negligible in actual practice[4]. Consequently, one obtains for the correction in enthalpy[4]:

$$\delta H = H'' - H' = -C_p(T_{68} - T_{48}) \tag{29}$$

Here C_p is the measured value of the heat capacity at the given temperature, $T_{68} - T_{48}$ is taken from *Tables 4* and *5*, and $H'' - H'$ is the correction to be added to the value of enthalpy previously reported under IPTS-1948.

(b) Conversion of calorimetric data on heat capacity

Douglas[4] gives an exact equation, also of an infinite series type, for calculating the conversion of calorimetric data on heat capacity from a given numerical value of temperature, T'_{48}, on IPTS-1948, to the same numerical value of temperature, T''_{68}, on IPTS-1968.

However, it is shown that the following approximate equation, adequate for nearly all cases encountered in actual practice, can be derived[4]:

$$\delta C_p = C''_p - C'_p = -C_p \, \mathrm{d}(T_{68} - T_{48})/\mathrm{d}T - (T_{68} - T_{48}) \, \mathrm{d}C_p/\mathrm{d}T \tag{31}$$

Here C_p and $T_{68} - T_{48}$ have the same significance as above for enthalpy: values of $\mathrm{d}(T_{68} - T_{48})/\mathrm{d}T$, the rate of change of $T_{68} - T_{48}$ with temperature are given in *Tables 6* and *7*, $\mathrm{d}C_p/\mathrm{d}T$ is the rate of change of C_p with temperature, and $C''_p - C'_p$ is the correction to be added to the value of heat capacity previously reported under IPTS-1948.

(c) Conversion of calorimetric data on entropy

Douglas[4] gives an exact equation, also of an infinite series type, for calculating the conversion of calorimetric data on entropy from a given numerical value of temperature, T'_{48}, on IPTS-1948, to the same numerical value of temperature, T''_{68}, on IPTS-1968.

However, it is shown that the following approximate equation, adequate for nearly all cases in actual practice, can be derived[4]:

$$\delta S = S'' - S' = -\int_0^T [(T_{68} - T_{48}) C_p/T^2] \, \mathrm{d}T - (T_{68} - T_{48}) C_p/T \tag{32}$$

Here C_p and $T_{68} - T_{48}$ have the same significance as above for enthalpy, the integration is taken from 0 to T, and $S'' - S'$ is the correction to be added to the value of entropy previously reported under IPTS-1948.

14. CONVERSION OF P–V–T DATA TO THE BASIS OF THE INTERNATIONAL PRACTICAL TEMPERATURE SCALE OF 1968

Angus[5] has prepared a report in which he discusses the correction of experimental P–V–T data obtained under IPTS-1948 to the basis of IPTS-1968. In general, the procedure involves the conversion of data labelled for a given numerical value of temperature, T'_{48}, under IPTS-1948, to the same numerical value of temperature, T''_{68}, under IPTS-1968. In setting up the procedure for correcting the existing experimental data on P–V–T

measurements to the new IPTS-1968, one simply traces the effect of shifting the temperature by the amount $T_{68} - T_{48}$ (from *Tables 4* and *5*) at each temperature of measurement, utilizing values of $d(T_{68} - T_{48})/dT$ (from *Tables 6* and *7*) as appropriate. Since this report is mainly concerned with calorimetric data, the reader is referred to the report of Angus[5] for further details.

15. THERMODYNAMIC PROPERTIES CALCULATED STATISTICALLY

In each case of values of thermodynamic properties calculated statistically from spectroscopic and other molecular data, with the proper values of the fundamental physical constants being used, no changes are necessary as a result of the introduction of the new IPTS-1968. Following is the reasoning. (a) The values of thermodynamic properties calculated statistically are specified for temperatures on the thermodynamic scale. (b) The values of temperature on the new IPTS-1968 are as near the corresponding temperatures on the thermodynamic scale as is possible at the present time.

16. CONCLUSION

Utilizing the information given in this report, and the references cited, the bench scientist or engineer should be able to determine readily what effect the shift from IPTS-1948 to IPTS-1968 has on his current experimental measurements involving temperature, what he must do to have his measurements of temperature conform to the new IPTS-1968, and how he should proceed to correct his previous data, obtained under IPTS-1948, to the basis of the new IPTS-1968.

ACKNOWLEDGEMENT

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