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# The International Temperature Scale of 1990 (ITS-90)

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**Introductory Note.**

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## The International Temperature Scale of 1990

The International Temperature Scale of 1990 was adopted by the International Committee of Weights and Measures at its meeting in 1989, in accordance with the request embodied in Resolution 7 of the 18th General Conference of Weights and Measures of 1987. This scale supersedes the International Practical Temperature Scale of 1968 (amended edition of 1975) and the 1976 Provisional 0,5 K to 30 K Temperature Scale.

### 1. Units of Temperature

The unit of the fundamental physical quantity known as thermodynamic temperature, symbol $T$, is the kelvin, symbol K, defined as the fraction 1/273,16 of the thermodynamic temperature of the triple point of water[1].

Because of the way earlier temperature scales were defined, it remains common practice to express a temperature in terms of its difference from 273,15 K, the ice point. A thermodynamic temperature, $T$, expressed in this way is known as a Celsius temperature, symbol $t$, defined by:

$$t/°\mathrm{C} = T/\mathrm{K} - 273{,}15\,. \tag{1}$$

[1] Comptes Rendus des Séances de la Treizième Conférence Générale des Poids es Mesures (1967–1968), Resolutions 3 and 4, p. 104

The unit of Celsius temperature is the degree Celsius, symbol °C, which is by definition equal in magnitude to the kelvin. A difference of temperature may be expressed in kelvins or degrees Celsius.

The International Temperature Scale of 1990 (ITS-90) defines both International Kelvin Temperatures, symbol $T_{90}$, and International Celsius Temperatures, symbol $t_{90}$. The relation between $T_{90}$ and $t_{90}$ is the same as that between $T$ and $t$, i.e.:

$$t_{90}/°\mathrm{C} = T_{90}/\mathrm{K} - 273{,}15\,. \tag{2}$$

The unit of the physical quantity $T_{90}$ is the kelvin, symbol K, and the unit of the physical quantity $t_{90}$ is the degree Celsius, symbol °C, as is the case for the thermodynamic temperature $T$ and the Celsius temperature $t$.

### 2. Principles of the International Temperature Scale of 1990 (ITS-90)

The ITS-90 extends upwards from 0,65 K to the highest temperature practicably measurable in terms of the Planck radiation law using monochromatic radiation. The ITS-90 comprises a number of ranges and sub-ranges throughout each of which temperatures $T_{90}$ are defined. Several of these ranges or sub-ranges overlap, and where such overlapping occurs, differing definitions of $T_{90}$ exist: these differing definitions have equal status. For measurements of the very highest precision there may be detectable numerical differences between measurements made at the same temperature but in accordance with differing definitions. Similarly, even using one definition, at a temperature between defining fixed points two acceptable interpolating instruments (e.g. resistance thermometers) may give detectably differing numerical values of $T_{90}$. In virtually all cases these differences are of negligible practical importance and are at the minimum level consistent with a scale of no more than reasonable complexity: for further information on this point, see "Supplementary Information for the ITS-90" (BIPM-1990).

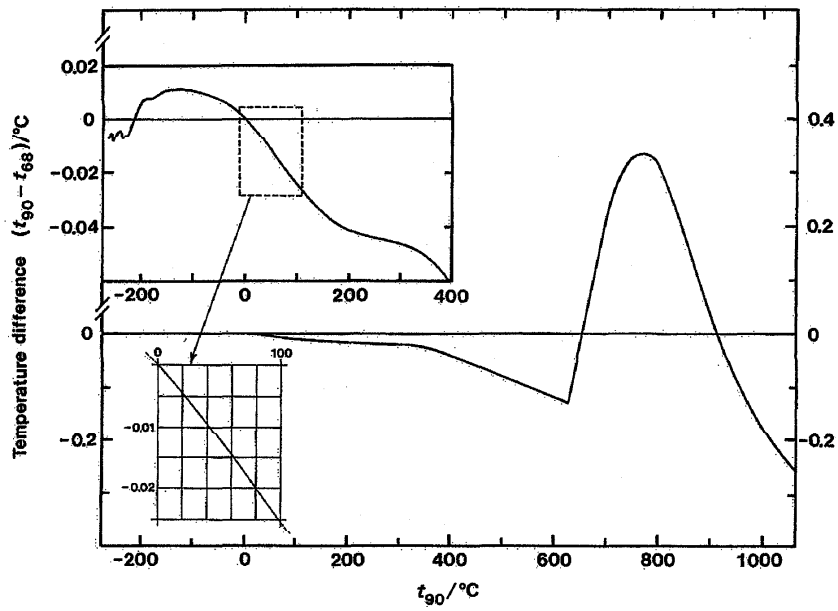


**Fig. 1.** The differences $(t_{90}-t_{68})$ as a function of Celsius temperature

The ITS-90 has been constructed in such a way that, throughout its range, for any given temperature the numerical value of $T_{90}$ is a close approximation to the numerical value of $T$ according to best estimates at the time the scale was adopted. By comparison with direct measurements of thermodynamic temperatures, measurements of $T_{90}$ are more easily made, are more precise and are highly reproducible.

There are significant numerical differences between the values of $T_{90}$ and the corresponding values of $T_{68}$ measured on the International Practical Temperature Scale of 1968 (IPTS-68), see Fig. 1 and Table 6. Similarly there were differences between the IPTS-68 and the International Practical Temperature Scale of 1948 (IPTS-48), and between the International Temperature Scale of 1948 (ITS-48) and the International Temperature Scale of 1927 (ITS-27). See the Appendix and, for more detailed information, "Supplementary Information for the ITS-90".

## 3. Definition of the International Temperature Scale of 1990

Between 0,65 K and 5,0 K $T_{90}$ is defined in terms of the vapour-pressure temperature relations of $^3$He and $^4$He.

Between 3,0 K and the triple point of neon (24,5561 K) $T_{90}$ is defined by means of a helium gas thermometer calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.

Between the triple point of equilibrium hydrogen (13,8033 K) and the freezing point of silver (961,78 °C) $T_{90}$ is defined by means of platinum resistance thermometers calibrated at specified sets of defining fixed points and using specified interpolation procedures.

Above the freezing point of silver (961,78 °C) $T_{90}$ is defined in terms of a defining fixed point and the Planck radiation law.

The defining fixed points of the ITS-90 are listed in Table 1. The effects of pressure, arising from significant depths of immersion of the sensor or from other causes, on the temperature of most of these points are given in Table 2.

### *3.1. From 0,65 K to 5,0 K: Helium Vapour-Pressure Temperature Equations*

In this range $T_{90}$ is defined in terms of the vapour pressure $p$ of $^3$He and $^4$He using equations of the form:

$$T_{90}/\mathrm{K} = A_0 + \sum_{i=1}^{9} A_i\,[(\ln(p/\mathrm{Pa}) - B)/C]^i\,. \qquad (3)$$

The values of the constants $A_0$, $A_i$, $B$ and $C$ are given in Table 3 for $^3$He in the range of 0,65 K to 3,2 K, and for $^4$He in the ranges 1,25 K to 2,1768 K (the $\lambda$ point) and 2,1768 K to 5,0 K.

### *3.2. From 3,0 K to the Triple Point of Neon (24,5561 K): Gas Thermometer*

In this range $T_{90}$ is defined in terms of a $^3$He or a $^4$He gas thermometer of the constant-volume type that has been calibrated at three temperatures. These are the triple point of neon (24,5561 K), the triple point of equilibrium hydrogen (13,8033 K), and a temperature between 3,0 K and 5,0 K. This last temperature is determined using a $^3$He or a $^4$He vapour pressure thermometer as specified in Sect. 3,1.

**Table 1.** Defining fixed points of the ITS-90

| Number | Temperature $T_{90}$/K | Temperature $t_{90}$/°C | Substance[a] | State[b] | $W_r(T_{90})$ |
|---|---|---|---|---|---|
| 1 | 3 to 5 | −270,15 to −268,15 | He | V | |
| 2 | 13,8033 | −259,3467 | e-$H_2$ | T | 0,001 190 07 |
| 3 | ≈17 | ≈−256,15 | e-$H_2$ (or He) | V (or G) | |
| 4 | ≈20,3 | ≈−252,85 | e-$H_2$ (or He) | V (or G) | |
| 5 | 24,5561 | −248,5939 | Ne | T | 0,008 449 74 |
| 6 | 54,3584 | −218,7916 | $O_2$ | T | 0,091 718 04 |
| 7 | 83,8058 | −189,3442 | Ar | T | 0,215 859 75 |
| 8 | 234,3156 | −38,8344 | Hg | T | 0,844 142 11 |
| 9 | 273,16 | 0,01 | $H_2O$ | T | 1,000 000 00 |
| 10 | 302,9146 | 29,7646 | Ga | M | 1,118 138 89 |
| 11 | 429,7485 | 156,5985 | In | F | 1,609 801 85 |
| 12 | 505,078 | 231,928 | Sn | F | 1,892 797 68 |
| 13 | 692,677 | 419,527 | Zn | F | 2,568 917 30 |
| 14 | 933,473 | 660,323 | Al | F | 3,376 008 60 |
| 15 | 1234,93 | 961,78 | Ag | F | 4,286 420 53 |
| 16 | 1337,33 | 1064,18 | Au | F | |
| 17 | 1357,77 | 1084,62 | Cu | F | |

[a] All substances except $^3$He are of natural isotopic composition, e-$H_2$ is hydrogen at the equilibrium concentration of the ortho- and para-molecular forms

[b] For complete definitions and advice on the realization of these various states, see "Supplementary Information for the ITS-90". The symbols have the following meanings: V: vapour pressure point; T: triple point (temperature at which the solid, liquid and vapour phases are in equilibrium); G: gas thermometer point; M, F: melting point, freezing point (temperature, at a pressure of 101 325 Pa, at which the solid and liquid phases are in equilibrium)

**Table 2.** Effect of pressure on the temperatures of some defining fixed points [+]

| Substance | Assigned value of equilibrium temperature $T_{90}$/K | Temperature with pressure, $p$ $(dT/dp)$/ $(10^8\,K\cdot Pa^{-1})$* | Variation with depth, $l$ $(dT/dl)$/ $(10^{-3}\,K\cdot m^{-1})$** |
|---|---|---|---|
| e-Hydrogen (T) | 13,8033 | 34 | 0,25 |
| Neon (T) | 24,5561 | 16 | 1,9 |
| Oxygen (T) | 54,3584 | 12 | 1,5 |
| Argon (T) | 83,8058 | 25 | 3,3 |
| Mercury (T) | 234,3156 | 5,4 | 7,1 |
| Water (T) | 273,16 | −7,5 | −0,73 |
| Gallium | 302,9146 | −2,0 | −1,2 |
| Indium | 429,7485 | 4,9 | 3,3 |
| Tin | 505,078 | 3,3 | 2,2 |
| Zinc | 692,677 | 4,3 | 2,7 |
| Aluminium | 933,473 | 7,0 | 1,6 |
| Silver | 1234,93 | 6,0 | 5,4 |
| Gold | 1337,33 | 6,1 | 10 |
| Copper | 1357,77 | 3,3 | 2,6 |

* Equivalent to millikelvins per standard atmosphere

** Equivalent to millikelvins per metre of liquid

[+] The Reference pressure for melting and freezing points is the standard atmosphere ($p_0$=101 325 Pa). For triple points (T) the pressure effect is a consequence only of the hydrostatic head of liquid in the cell

**Table 3.** Values of the constants for the helium vapour pressure Eqs. (3), and the temperature range for which each equation, identified by its set of constants, is valid

| | $^3$He 0,65 K to 3,2 K | $^4$He 1,25 K to 2,1768 K | $^4$He 2,1768 K to 5,0 K |
|---|---|---|---|
| $A_0$ | 1,053 447 | 1,392 408 | 3,146 631 |
| $A_1$ | 0,980 106 | 0,527 153 | 1,357 655 |
| $A_2$ | 0,676 380 | 0,166 756 | 0,413 923 |
| $A_3$ | 0,372 692 | 0,050 988 | 0,091 159 |
| $A_4$ | 0,151 656 | 0,026 514 | 0,016 349 |
| $A_5$ | −0,002 263 | 0,001 975 | 0,001 826 |
| $A_6$ | 0,006 596 | −0,017 976 | −0,00 4325 |
| $A_7$ | 0,088 966 | 0,005 409 | −0,00 4973 |
| $A_8$ | −0,004 770 | 0,013 259 | 0 |
| $A_9$ | −0,054 943 | 0 | 0 |
| $B$ | 7,3 | 5,6 | 10,3 |
| $C$ | 4,3 | 2,9 | 1,9 |

*3.2.1. From 4,2 K to the Triple Point of Neon (24,5561 K) with $^4$He as the Thermometric Gas.* In this range $T_{90}$ is defined by the relation:

$$T_{90} = a + bp + cp^2\,, \tag{4}$$

where $p$ is the pressure in the gas thermometer and $a$, $b$ and $c$ are coefficients the numerical values of which are obtained from measurements made at the three defining fixed points given in Sect. 3.2, but with the further restriction that the lowest one of these points lies between 4,2 K and 5,0 K.

*3.2.2. From 3,0 K to the Triple Point of Neon (24,5561 K) with $^3$He or $^4$He as the Thermometric Gas.* For a $^3$He gas thermometer, and for a $^4$He gas thermometer used below 4,2 K, the non-ideality of the gas must be accounted for explicitly, using the appropriate second virial coefficient $B_3\,(T_{90})$ or $B_4\,(T_{90})$. In this range $T_{90}$ is defined by the relation:

$$T_{90} = \frac{a + bp + cp^2}{1 + B_x(T_{90})\,N/V}\,, \tag{5}$$

where $p$ is the pressure in the gas thermometer, $a$, $b$ and $c$ are coefficients the numerical values of which are obtained from measurements at three defining temperatures as given in Sect. 3.2, $N/V$ is the gas density with $N$ being the quantity of gas and $V$ the volume of the bulb, x is 3 or 4 according to the isotope used, and the values of the second virial coefficients are given by the relations:

For $^3$He,

$$B\,(T_{90})/\mathrm{m^3\,mol^{-1}} = \{16{,}69 - 336{,}98\,(T_{90}/\mathrm{K})^{-1} + 91{,}04\,(T_{90}/\mathrm{K})^{-2} - 13{,}82\,(T_{90}/\mathrm{K})^{-3}\}\,10^{-6}\,. \tag{6a}$$

For $^4$He,

$$B_4\,(T_{90})/\mathrm{m^3\,mol^{-1}} = \{16{,}708 - 374{,}05\,(T_{90}/\mathrm{K})^{-1} - 383{,}53\,(T_{90}/\mathrm{K})^{-2} + 1799{,}2\,(T_{90}/\mathrm{K})^{-3} - 4033{,}2\,(T_{90}/\mathrm{K})^{-4} + 3252{,}8\,(T_{90}/\mathrm{K})^{-5}\}\,10^{-6}\,. \tag{6b}$$

**Table 4.** The constants $A_0$, $A_i$; $B_0$, $B_i$; $C_0$, $C_i$; $D_0$ and $D_i$ in the reference functions of equations (9a); (9b); (10a); and (10b) respectively

| | | | | | |
|---|---|---|---|---|---|
| $A_0$ | −2,135 347 29 | $B_0$ | −0,183 324 722 | $B_{13}$ | −0,091 173 542 |
| $A_1$ | 3,183 247 20 | $B_1$ | 0,240 975 303 | $B_{14}$ | 0,001 317 696 |
| $A_2$ | −1,801 435 97 | $B_2$ | 0,209 108 771 | $B_{15}$ | 0,026 025 526 |
| $A_3$ | 0,717 272 04 | $B_3$ | 0,190 439 972 | | |
| $A_4$ | 0,503 440 27 | $B_4$ | 0,142 648 498 | | |
| $A_5$ | −0,618 993 95 | $B_5$ | 0,077 993 465 | | |
| $A_6$ | −0,053 323 22 | $B_6$ | 0,012 475 611 | | |
| $A_7$ | 0,280 213 62 | $B_7$ | −0,032 267 127 | | |
| $A_8$ | 0,107 152 24 | $B_8$ | −0,075 291 522 | | |
| $A_9$ | −0,293 028 65 | $B_9$ | −0,056 470 670 | | |
| $A_{10}$ | 0,044 598 72 | $B_{10}$ | 0,076 201 285 | | |
| $A_{11}$ | 0,118 686 32 | $B_{11}$ | 0,123 893 204 | | |
| $A_{12}$ | −0,052 481 34 | $B_{12}$ | −0,029 201 193 | | |
| $C_0$ | 2,781 572 54 | $D_0$ | 439,932 854 | | |
| $C_1$ | 1,646 509 16 | $D_1$ | 472,418 020 | | |
| $C_2$ | −0,137 143 90 | $D_2$ | 37,684 494 | | |
| $C_3$ | −0,006 497 67 | $D_3$ | 7,472 018 | | |
| $C_4$ | −0,002 344 44 | $D_4$ | 2,920 828 | | |
| $C_5$ | 0,005 118 68 | $D_5$ | 0,005 184 | | |
| $C_6$ | 0,001 879 82 | $D_6$ | −0,963 864 | | |
| $C_7$ | −0,002 044 72 | $D_7$ | −0,188 732 | | |
| $C_8$ | −0,000 461 22 | $D_8$ | 0,191 203 | | |
| $C_9$ | 0,000 457 24 | $D_9$ | 0,049 025 | | |

The accuracy with which $T_{90}$ can be realized using Eqs. (4) and (5) depends on the design of the gas thermometer and the gas density used. Design criteria and current good practice required to achieve a selected accuracy are given in "Supplementary Information for the ITS-90".

### *3.3. The Triple Point of Equilibrium Hydrogen (13,8033 K) to the Freezing Point of Silver (961,78 °C): Platinum Resistance Thermometer*

In this range $T_{90}$ is defined by means of a platinum resistance thermometer calibrated at specified sets of defining fixed points, and using specified reference and deviation functions for interpolation at intervening temperatures.

No single platinum resistance thermometer can provide high accuracy, or is even likely to be usable, over all of the temperature range 13,8033 K to 961,78 °C. The choice of temperature range, or ranges, from among those listed below for which a particular thermometer can be used is normally limited by its construction.

For practical details and current good practice, in particular concerning types of thermometer available, their acceptable operating ranges, probably accuracies, permissible leakage resistance, resistance values, and thermal treatment, see "Supplementary Information for the ITS-90". It is particularly important to take account of the appropriate heat treatments that should be followed each time a platinum resistance thermometer is subjected to a temperature above about 420 °C.

Temperatures are determined in terms of the ratio of the resistance $R(T_{90})$ at a temperature $T_{90}$ and the resistance $R$ (273,16 K) at the triple point of water. This ratio, $W(T_{90})$, is[2]:

$$W(T_{90}) = R(T_{90})/R(273{,}16\ \mathrm{K}). \tag{7}$$

An acceptable platinum resistance thermometer must be made from pure, strain-free platinum, and it must satisfy at least one of the following two relations:

$$W(29{,}7646\ ^\circ\mathrm{C}) \geq 1{,}118\ 07, \tag{8a}$$

$$W(-38{,}8344\ ^\circ\mathrm{C}) \leq 0{,}844\ 235. \tag{8b}$$

An acceptable platinum resistance thermometer that is to be used up to the freezing point of silver must also satisfy the relation:

$$W(961{,}78\ ^\circ\mathrm{C}) \geq 4{,}2844. \tag{8c}$$

In each of the resistance thermometer ranges, $T_{90}$ is obtained from $W_r(T_{90})$ as given by the appropriate reference function {Eqs. (9b) or (10b)}, and the deviation $W(T_{90}) - W_r(T_{90})$. At the defining fixed points this deviation is obtained directly from the calibration of the thermometer: at intermediate temperatures it is obtained by means of the appropriate deviation function {Eqs. (12), (13) and (14)}.

(i) – For the range 13,8033 K 273,16 K the following reference function is defined:

$$\ln[W_r(T_{90})] = A_0 + \sum_{i=1}^{12} A_i \left[\frac{\ln(T_{90}/273{,}16\ \mathrm{K}) + 1{,}5}{1{,}5}\right]^i. \tag{9a}$$

An inverse function, equivalent to Eq. (9a) to within 0.1 mK, is:

$$T_{90}/273{,}16\ \mathrm{K} = B_0 + \sum_{i=1}^{15} B_i \left[\frac{W_r(T_{90})^{1/6} - 0{,}65}{0{,}35}\right]^i. \tag{9b}$$

The values of the constants $A_0$, $A_i$, $B_0$ and $B_i$ are given in Table 4.

A thermometer may be calibrated for use throughout this range or, using progressively fewer calibration points, for ranges with low temperature limits of 24,5561 K, 54,3584 K and 83,8058 K, all having an upper limit of 273,16 K.

(ii) – For the range 0 °C to 961,78 °C the following reference function is defined:

$$W_r(T_{90}) = C_0 + \sum_{i=1}^{9} C_i \left[\frac{T_{90}/\mathrm{K} - 754{,}15}{481}\right]^i \tag{10a}$$

An inverse function, equivalent to equation (10a) to within 0.13 mK is:

$$T_{90}/\mathrm{K} - 273{,}15 = D_0 + \sum_{i=1}^{9} D_i \left[\frac{W_r(T_{90}) - 2{,}64}{1{,}64}\right]^i. \tag{10b}$$

The values of the constants $C_0$, $C_i$, $D_0$ and $D_i$ are given in Table 4.

[2] Note that this definition of $W(T_{90})$ differs from the corresponding definition used in the ITS-27, ITS-48, IPTS-48, and IPTS-68: for all of these earlier scales $W(T)$ was defined in terms of a reference temperature of 0 °C, which since 1954 has itself been defined as 273,15 K

A thermometer may be calibrated for use throughout this range or, using fewer calibration points, for ranges with upper limits of 660,323 °C, 419,527 °C, 231,928 °C, 156,5985 °C or 29,7646 °C, all having a lower limit of 0 °C.

(iii) – A thermometer may be calibrated for use in the range 234,3156 K (−38,8344 °C) to 29,7646 °C, the calibration being made at these temperatures and at the triple point of water. Both reference functions {Eqs. (9) and (10)} are required to cover this range.

The defining fixed points and deviation functions for the various ranges are given below, and in summary form in Table 5.

*3.3.1. The Triple Point of Equilibrium Hydrogen (13,8033 K) to the Triple Point of Water (273,16 K).* The thermometer is calibrated at the triple points of equilibrium hydrogen (13,8033 K), neon (24,5561 K), oxygen (54,3584 K), argon (83,8058 K), mercury (234,3156 K), and water (273,16 K), and at two additional temperatures close to 17,0 K and 20,3 K. These last two may be determined either: by using a gas thermometer as described in Sect. 3.2, in which case the two temperatures must lie within the ranges 16,9 K to 17,1 K and 20,2 K to 20,4 K respectively; or by using the vapour pressure-temperature relation of equilibrium hydrogen, in which case the two temperatures must lie within the ranges 17,025 K to 17,045 K and 20,26 K to 20,28 K respectively, with the precise values being determined from Eqs. (11 a) and (11 b) respectively:

$$T_{90}/\mathrm{K} - 17{,}035 = (p/\mathrm{kPa} - 33{,}3213)/13{,}32 \qquad (11\,\mathrm{a})$$

$$T_{90}/\mathrm{K} - 20{,}27 = (p/\mathrm{kPa} - 101{,}292)/30\,. \qquad (11\,\mathrm{b})$$

The deviation function is[3]:

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90})-1] + b[W(T_{90})-1]^2 + \sum_{i=1}^{5} c_i [\ln W(T_{90})]^{i+n} \qquad (12)$$

with values for the coefficients $a$, $b$ and $c_i$ being obtained from measurements at the defining fixed points and with $n=2$.

For this range and for the sub-ranges 3.3.1.1 to 3.3.1.3 the required values of $W_r(T_{90})$ are obtained from Eq. (9 b) or from Table 1.

*3.3.1.1. The Triple Point of Neon (24,5561 K) to the Triple Point of Water (273,16 K).* The thermometer is calibrated at the triple points of equilibrium hydrogen (13,8033 K), neon (24,5561 K), oxygen (54,3584 K), argon (83,8058 K), mercury (234,3156 K) and water (273,16 K).

The deviation function is given by Eq. (12) with values for the coefficients $a$, $b$, $c_1$, $c_2$ and $c_3$ being obtained from measurements at the defining fixed points and with $c_4=c_5=n=0$.

*3.3.1.2. The Triple Point of Oxygen (54,3584 K) to the Triple Point of Water (273,16 K).* The thermometer is calibrated at the triple points of oxygen (54,3584 K), argon (83,8058 K), mercury (234,3156 K) and water (273,16 K).

The deviation function is given by Eq. (12) with values for the coefficients $a$, $b$ and $c_1$ being obtained from measurements at the defining fixed points, with $c_2=c_3=c_4=c_5=0$ and with $n=1$.

*3.3.1.3. The Triple Point of Argon (83,8058 K) to the Triple Point of Water (273,16 K).* The thermometer is calibrated at the triple points of argon (83,8058 K), mercury (234,3156 K) and water (273,16 K).

The deviation function is:

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90})-1]\ln W(T_{90}) \qquad (13)$$

with the values of $a$ and $b$ being obtained from measurements at the defining fixed points.

*3.3.2. From 0 °C to the Freezing Point of Silver (961,78 °C).* The thermometer is calibrated at the triple

**Table 5.** Deviation functions and calibration points for platinum resistance thermometers in the various ranges in which they define $T_{90}$

*a Ranges with an upper limit of 273,16 K*

| Section | Lower temperature limit $T$/K | Deviation functions | Calibration points (see Table 1) |
|---|---|---|---|
| 3.3.1 | 13,8033 | $a[W(T_{90})-1]+b[W(T_{90})-1]^2 + \sum_{i=1}^{5} c_i[\ln W(T_{90})]^{i+n}$, $n=2$ | 2–9 |
| 3.3.1.1 | 24,5561 | As for 3.3.1 with $c_4=c_5=n=0$ | 2, 5–9 |
| 3.3.1.2 | 54,3584 | As for 3.3.1 with $c_2=c_3=c_4=c_5=0$, $n=1$ | 6–9 |
| 3.3.1.3 | 83,8058 | $a[W(T_{90})-1] + b[W(T_{90})-1]\ln W(T_{90})$ | 7–9 |

*b Ranges with a lower limit of 0 °C*

| Section | Upper temperature limit $t$/°C | Deviation functions | Calibration points (see Table 1) |
|---|---|---|---|
| 3.3.2* | 961,78 | $a[W(T_{90})-1]+b[W(T_{90})-1]^2 + c[W(T_{90})-1]^3+d[W(T_{90}) - W(660{,}323\,°\mathrm{C})]^2$ | 9, 12–15 |
| 3.3.2.1 | 660,323 | As for 3.3.2 with $d=0$ | 9, 12–14 |
| 3.3.2.2 | 419,527 | As for 3.3.2 with $c=d=0$ | 9, 12, 13 |
| 3.3.2.3 | 231,928 | As for 3.3.2 with $c=d=0$ | 9, 11, 12 |
| 3.3.2.4 | 156,5985 | As for 3.3.2 with $b=c=d=0$ | 9, 11 |
| 3.3.2.5 | 29,7646 | As for 3.3.2 with $b=c=d=0$ | 9, 10 |

*c Range from 234,3156 K (−38,8344 °C) to 29,7646 °C*

| | | | |
|---|---|---|---|
| 3.3.3 | | As for 3.3.2 with $c=d=0$ | 8–10 |

* Calibration points 9, 12–14 are used with $d=0$ for $t_{90} \leq 660{,}323$ °C; the values of $a$, $b$ and $c$ thus obtained are retained for $t_{90} > 660{,}323$ °C, with $d$ being determined from calibration point 15

[3] This deviation function {and also those of Eqs. (13) and (14)} may be expressed in terms of $W_r$ rather than $W$; for this procedure see "Supplementary Information for ITS-90"

point of water (0,01 °C), and at the freezing points of tin (231,928 °C), zinc (419,527 °C), aluminium (660,323 °C) and silver (961,78 °C).

The deviation function is:

$$W(T_{90})-W_r(T_{90})=a[W(T_{90})-1]+b[W(T_{90})-1]^2 + c[W(T_{90})-1]^3+d[W(T_{90})-W(660{,}323\,°C)]^2 . \quad (14)$$

For temperatures below the freezing point of aluminium $d=0$, with the values of $a$, $b$ and $c$ being determined from the measured deviations from $W_r(T_{90})$ at the freezing points of tin, zinc and aluminium. From the freezing point of aluminium to the freezing point of silver the above values of $a$, $b$ and $c$ are retained and the value of $d$ is determined from the measured deviation from $W_r(T_{90})$ at the freezing point of silver.

For this range and for the sub-ranges 3.3.2.1 to 3.3.2.5 the required values for $W_r(T_{90})$ are obtained from Eq. (10b) or from Table 1.

*3.3.2.1. From 0 °C to the Freezing Point of Aluminium (660,323 °C).* The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing points of tin (231,928 °C), zinc (419,527 °C) and aluminium (660,323 °C).

The deviation function is given by Eq. (14), with the values of $a$, $b$ and $c$ being determined from measurements at the defining fixed points and with $d=0$.

*3.3.2.2. From 0 °C to the Freezing Point of Zinc (419,527 °C).* The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing points of tin (231,928 °C) and zinc (419,527 °C).

The deviation function is given by Eq. (14) with the values of $a$ and $b$ being obtained from measurements at the defining fixed points and with $c=d=0$.

*3.3.2.3. From 0 °C to the Freezing Point of Tin (231,928 °C).* The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing points of indium (156,5985 °C) and tin (231,928 °C).

The deviation function is given by Eq. (14) with the values of $a$ and $b$ being obtained from measurements at the defining fixed points and with $c=d=0$.

*3.3.2.4. From 0 °C to the Freezing Point of Indium (156,5985 °C).* The thermometer is calibrated at the triple point of water (0,01 °C), and at the freezing point of indium (156,5985 °C).

The deviation function is given by Eq. (14) with the value of $a$ being obtained from measurements at the defining fixed points and with $b=c=d=0$.

*3.3.2.5. From 0 °C to the Melting Point of Gallium (29,7646 °C).* The thermometer is calibrated at the triple point of water (0,01 °C), and at the melting point of gallium (29,7646 °C).

The deviation function is given by Eq. (14) with the value of $a$ being obtained from measurements at the defining fixed points and with $b=c=d=0$.

*3.3.3. The Triple Point of Mercury (−38,8344 °C) to the Melting Point of Gallium (29,7646 °C).* The thermometer is calibrated at the triple points of mercury (−38,8344 °C), and water (0,01 °C), and at the melting point of gallium (29,7646 °C).

The deviation function is given by Eq. (14) with the values of $a$ and $b$ being obtained from measurements at the defining fixed points and with $c=d=0$.

The required values of $W_r(T_{90})$ are obtained from Eqs. (9b) and (10b) for measurements below and above 273,16 K respectively, or from Table 1.

### *3.4. The Range Above the Freezing Point of Silver (961,78 °C): Planck Radiation Law*

Above the freezing point of silver the temperature $T_{90}$ is defined by the equation:

$$\frac{L_\lambda(T_{90})}{L_\lambda\ [T_{90}(X)]}=\frac{\exp(c_2[\lambda\, T_{90}(X)]^{-1})-1}{\exp(c_2[\lambda\, T_{90}]^{-1})-1} . \quad (15)$$

where $T_{90}(X)$ refers to any one of the silver $\{T_{90}(Ag) = 1234{,}93\ K\}$, the gold $\{T_{90}(Au)=1337{,}33\ K\}$ or the copper $\{T_{90}(Cu)=1357{,}77\ K\}$ freezing points[4] and in which $L_\lambda(T_{90})$ and $L_\lambda(T_{90})(X)]$ are the spectral concentrations of the radiance of a blackbody at the wavelength (in vacuo) $\lambda$ at $T_{90}$ and at $T_{90}(X)$ respectively, and $c_2=0{,}014388\ m \cdot K$.

For practical details and current good practice for optical pyrometry, see "Supplementary Information for the ITS-90" (BIPM-1990).

## 4. Supplementary Information and Differences from Earlier Scales

The apparatus, methods and procedures that will serve to realize the ITS-90 are given in "Supplementary Information for the ITS-90". This document also gives an account of the earlier International Temperature Scales and the numerical differences between successive scales that include, where practicable, mathematical functions for the differences $T_{90}-T_{68}$. A number of useful approximations to the ITS-90 are given in "Techniques for Approximating the ITS-90".

These two documents have been prepared by the Comité Consultatif de Thermométrie and are published by the BIPM; they are revised and updated periodically.

The differences $T_{90}-T_{68}$ are shown in Fig. 1 and Table 6. The number of significant figures given in Table 6 allows smooth interpolations to be made. However, the reproducibility of the IPTS-68 is, in many areas, substantially worse than is implied by this number.

[4] The $T_{90}$ values of the freezing points of silver, gold and copper are believed to be self consistent to such a degree that the substitution of any one of them in place of one of the other two as the reference temperature $T_{90}(X)$ will not result in significant differences in the measured values of $T_{90}$.

**Table 6.** Differences between ITS-90 and EPT-76, and between ITS-90 and IPTS-68 for specified values of $T_{90}$ and $t_{90}$

| | | | | | $(T_{90}-T_{76})$/mK | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $T_{90}$/K | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 0 | | | | | | −0,1 | −0,2 | −0,3 | −0,4 | −0,5 |
| 10 | −0,6 | −0,7 | −0,8 | −1,0 | −1,1 | −1,3 | −1,4 | −1,6 | −1,8 | −2,0 |
| 20 | −2,2 | −2,5 | −2,7 | −3,0 | −3,2 | −3,5 | −3,8 | −4,1 | | |
| | | | | | $(T_{90}-T_{68})$/K | | | | | |
| $T_{90}$/K | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 10 | | | | | −0,006 | −0,003 | −0,004 | −0,006 | −0,008 | −0,009 |
| 20 | −0,009 | −0,008 | −0,007 | −0,007 | −0,006 | −0,005 | −0,004 | −0,004 | −0,005 | −0,006 |
| 30 | −0,006 | −0,007 | −0,008 | −0,008 | −0,008 | −0,007 | −0,007 | −0,007 | −0,006 | −0,006 |
| 40 | −0,006 | −0,006 | −0,006 | −0,006 | −0,006 | −0,007 | −0,007 | −0,007 | −0,006 | −0,006 |
| 50 | −0,006 | −0,005 | −0,005 | −0,004 | −0,003 | −0,002 | −0,001 | 0,000 | 0,001 | 0,002 |
| 60 | 0,003 | 0,003 | 0,004 | 0,004 | 0,005 | 0,005 | 0,006 | 0,006 | 0,007 | 0,007 |
| 70 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 |
| 80 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 |
| 90 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,008 | 0,009 | 0,009 | 0,009 |
| $T_{90}$/K | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| 100 | 0,009 | 0,011 | 0,013 | 0,014 | 0,014 | 0,014 | 0,014 | 0,013 | 0,012 | 0,012 |
| 200 | 0,011 | 0,010 | 0,009 | 0,008 | 0,007 | 0,005 | 0,003 | 0,001 | | |
| | | | | | $(t_{90}-t_{68})$/°C | | | | | |
| $t_{90}$/°C | 0 | −10 | −20 | −30 | −40 | −50 | −60 | −70 | −80 | −90 |
| −100 | 0,013 | 0,013 | 0,014 | 0,014 | 0,014 | 0,013 | 0,012 | 0,010 | 0,008 | 0,008 |
| 0 | 0,000 | 0,002 | 0,004 | 0,006 | 0,008 | 0,009 | 0,010 | 0,011 | 0,012 | 0,012 |
| $t_{90}$/°C | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| 0 | 0,000 | −0,002 | −0,005 | −0,007 | −0,010 | −0,013 | −0,016 | −0,018 | −0,021 | −0,024 |
| 100 | −0,026 | −0,028 | −0,030 | −0,032 | −0,034 | −0,036 | −0,037 | −0,038 | −0,039 | −0,039 |
| 200 | −0,040 | −0,040 | −0,040 | −0,040 | −0,040 | −0,040 | −0,040 | −0,039 | −0,039 | −0,039 |
| 300 | −0,039 | −0,039 | −0,039 | −0,040 | −0,040 | −0,041 | −0,042 | −0,043 | −0,045 | −0,046 |
| 400 | −0,048 | −0,051 | −0,053 | −0,056 | −0,059 | −0,062 | −0,065 | −0,068 | −0,072 | −0,075 |
| 500 | −0,079 | −0,083 | −0,087 | −0,090 | −0,094 | −0,098 | −0,101 | −0,105 | −0,108 | −0,112 |
| 600 | −0,115 | −0,118 | −0,122 | −0,125* | −0,08 | −0,03 | 0,02 | 0,06 | 0,11 | 0,16 |
| 700 | 0,20 | 0,24 | 0,28 | 0,31 | 0,33 | 0,35 | 0,36 | 0,36 | 0,36 | 0,35 |
| 800 | 0,34 | 0,32 | 0,29 | 0,25 | 0,22 | 0,18 | 0,14 | 0,10 | 0,06 | 0,03 |
| 900 | −0,01 | −0,03 | −0,06 | −0,08 | −0,10 | −0,12 | −0,14 | −0,16 | −0,17 | −0,18 |
| 1000 | −0,19 | −0,20 | −0,21 | −0,22 | −0,23 | −0,24 | −0,25 | −0,25 | −0,26 | −0,26 |
| $t_{90}$/°C | 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 |
| 1000 | | −0,26 | −0,30 | −0,035 | −0,039 | −0,044 | −0,49 | −0,54 | −0,60 | −0,66 |
| 2000 | −0,72 | −0,79 | −0,85 | −0,93 | −1,00 | −1,07 | −1,15 | −1,24 | −1,32 | −1,41 |
| 3000 | −1,50 | −1,59 | −1,69 | −1,78 | −1,89 | −1,99 | −2,10 | −2,21 | −2,32 | −2,43 |

* A discontinuity in the first derivative of $(t_{90}-t_{68})$ occurs at a temperature of $t_{90}=630{,}6\,°C$, at which $(t_{90}-t_{68})=-0{,}125\,°C$

## Appendix

### *The International Temperature Scale of 1927 (ITS-27)*

The International Temperature Scale of 1927 was adopted by the seventh General Conference of Weights and Measures to overcome the practical difficulties of the direct realization of thermodynamic temperatures by gas thermometry, and as a universally acceptable replacement for the differing existing national temperature scales. The ITS-27 was formulated so as to allow measurements of temperature to be made precisely and reproducibly, with as close an approximation to thermodynamic temperatures as could be determined at that time. Between the oxygen boiling point and the gold freezing point it was based upon a number of reproducible temperatures, or fixed points, to which numerical values were assigned, and two standard interpolating instruments. Each of these interpolating instruments was calibrated at several of the fixed points, this giving the constants for the interpolating formula in the appropriate temperature range. A platinum resistance thermometer was used for the lower part and a platinum rhodium/platinum thermocouple for temperatures above 660 °C. For the region above the gold freezing point, temperatures were defined in terms of the Wien radiation law: in practice, this invariably resulted in the selection of an optical pyrometer as the realizing instrument.

### *The International Temperature Scale of 1948 (ITS-48)*

The International Temperature Scale of 1948 was adopted by the ninth General Conference. Changes from the ITS-27 were: the lower limit of the platinum resistance thermometer range was changed from −190 °C to the defined oxygen boiling point of −182,97 °C, and the junction of the platinum resistance thermometer range and the thermocouple range became the measured antimony freezing point (about 630 °C) in place of 660 °C; the silver freezing point was defined as being 960,8 °C instead of 960,5 °C; the gold freezing point replaced the gold melting point (1063 °C); the Planck radiation law replaced the Wien law; the value assigned to the second radiation constant became $1{,}438\times10^{-2}$ m · K in place of $1{,}432\times10^{-2}$ m · K; the permitted ranges for the constants of the interpola-

tion formulae for the standard resistance thermometer and thermocouple were modified; the limitation on $\lambda T$ for optical pyrometry ($\lambda T < 3 \times 10^{-3}$ m · K) was changed to the requirement that "visible" radiation be used.

### *The International Practical Temperature Scale of 1948 (Amended Edition of 1960) (IPTS-48)*

The International Practical Temperature Scale of 1948, amended edition of 1960, was adopted by the eleventh General Conference: the tenth General Conference had already adopted the triple point of water as the sole point defining the kelvin, the unit of thermodynamic temperature. In addition to the introduction of the word "Practical", the modifications to the ITS-48 were: the triple point of water, defined as being 0,01 °C, replaced the melting point of ice as the calibration point in this region; the freezing point of zinc, defined as being 419,505 °C, became a preferred alternative to the sulphur boiling point (444,6 °C) as a calibration point; the permitted ranges for the constants of the interpolation formulae for the standard resistance thermometer and the thermocouple were further modified; the restriction to "visible" radiation for optical pyrometry was removed.

Inasmuch as the numerical values of temperature on the IPTS-48 were the same as on the ITS-48, the former was not a revision of the scale of 1948 but merely an amended form of it.

### *The International Practical Temperature Scale of 1968 (IPTS-68)*

In 1968 the International Committee of Weights and Measures promulgated the International Practical Temperature Scale of 1968, having been empowered to do so by the thirteenth General Conference of 1967–1968. The IPTS-68 incorporated very extensive changes from the IPTS-48. These included numerical changes, designed to bring it more nearly in accord with thermodynamic temperatures, that were sufficiently large to be apparent to many users. Other changes were as follows: the lower limit of the scale was extended down to 13,81 K; at even lower temperatures (0,5 K to 5,2 K), the use of two helium vapour pressure scales was recommended; six new defining fixed points were introduced – the triple point of equilibrium hydrogen (13,81 K), an intermediate equilibrium hydrogen point (17,042 K), the normal boiling point of equilibrium hydrogen (20,28 K), the boiling point of neon (27,102 K), the triple point of oxygen (54,361 K), and the freezing point of tin (231,9681 °C) which became a permitted alternative to the boiling point of water; the boiling point of sulphur was deleted; the values assigned to four fixed points were changed – the boiling point of oxygen (90,188 K), the freezing point of zinc (419,58 °C), the freezing point of silver (961,93 °C), and the freezing point of gold (1064,43 °C); the interpolating formulae for the resistance thermometer range became much more complex; the value assigned to the second radiation constant $c_2$ became $1{,}4388 \times 10^{-2}$ m · K; the permitted ranges of the constants for the interpolation formulae for the resistance thermometer and thermocouple were again modified.

### *The International Practical Temperature Scale of 1968 (Amended Edition of 1975) (IPTS-68)*

The International Practical Temperature Scale of 1968, amended edition of 1975, was adopted by the fifteenth General Conference in 1975. As was the case for the IPTS-48 with respect to the ITS-48, the IPTS-68(75) introduced no numerical changes. Most of the extensive textural changes were intended only to clarify and simplify its use. More substantive changes were: the oxygen point was defined as the condensation point rather than the boiling point; the triple point of argon (83,798 K) was introduced as a permitted alternative to the condensation point of oxygen; new values of the isotopic composition of naturally occurring neon were adopted; the recommendation to use values of $T$ given by the 1958 $^4$He and 1962 $^3$He vapour-pressure scales was rescinded.

### *The 1976 Provisional 0,5 K to 30 K Temperature Scale (EPT-76)*

The 1976 Provisional 0,5 K to 30 K Temperature Scale was introduced to meet two important requirements: these were to provide means of substantially reducing the errors (with respect to corresponding thermodynamic values) below 27 K that were then known to exist in the IPTS-68 and throughout the temperature ranges of the $^4$He and $^3$He vapour pressure scales of 1958 and 1962 respectively, and to bridge the gap between 5,2 K and 13,81 K in which there had not previously been an international scale. Other objectives in devising the ETP-76 were "that it should be thermodynamically smooth, that it should be continuous with the IPTS-68 at 27,1 K, and that is should agree with thermodynamic temperature $T$ as closely as these two conditions allow". In contrast with the IPTS-68, and to ensure its rapid adoption, several methods of realizing the ETP-76 were approved. These included: using a thermodynamic interpolation instrument and one or more of eleven assigned reference points; taking differences from the IPTS-68 above 13,81 K; taking differences from helium vapour pressure scales below 5 K; and taking differences from certain well-established laboratory scales. Because there was a certain "lack of internal consistency" it was admitted that "slight ambiguities between realizations" might be introduced. However the advantages gained by adopting the EPT-76 as a working scale until such time as the IPTS-68 should be revised and extended were considered to outweigh the disadvantages.