

**Notice:** This text is the draft of the *Mise en Pratique* of the definition of the kelvin, as envisaged and approved by the CCT in 2013. It is to be implemented after that the new definition of the kelvin has been decided by the Conférence Générale des Poids et Mesures (CGPM), expected to take place in 2018. However, as the value of the Boltzmann constant and the date of the new definition are not yet fixed, figures marked as **X** (high-lighted in yellow) are still to be determined. Further, the technical annexe and appendices are not listed here. For more information, the interested reader may consult published documents under the titles “[Temperature scales and the kelvin](#)” and “[Guide to the realization of the ITS-90](#)”, on the CCT web pages at [www.bipm.org](http://www.bipm.org).

## MISE EN PRATIQUE OF THE DEFINITION OF THE KELVIN

Adopted by the Consultative Committee for Thermometry (CCT) in XXX

### 1. Scope

Historically, the best guide for the realisation of the kelvin has been the text and corresponding supplementary information for the International Temperature Scales. Recent developments in thermometry and the change in the definition of the kelvin have motivated the creation of a broader and flexible document that incorporates the temperature scales in current use and primary methods: the *Mise en Pratique* of the definition of the kelvin (*MeP-K*).

As envisaged by the CCT [Recommendation T3 (2005)] and in accordance with the report of the 97<sup>th</sup> meeting of the International Committee for Weights and Measures (CIPM) in 2008, the *MeP-K* provides or makes reference to the information needed to perform a practical measurement of temperature, in accordance with the International System of Units (SI), at the highest level of accuracy.

The *MeP-K* is presented here and consists of:

- Section 2: Introduction, giving the new definition of the base unit kelvin, the rationale for the change, and the effect of the new definition on the realisation of the kelvin,
- Section 3: Nomenclature, defining fundamental terms of thermometry to support an unambiguous taxonomy of methods in the *MeP-K*,
- Section 4: Primary thermometry, describing the realisation of the kelvin based on fundamental laws of thermodynamics and statistical mechanics,
- Section 5: Defined temperature scales, providing the text and supporting information for the International Temperature Scales ITS-90 and PLTS-2000.

## 2. Introduction

The unit of the SI base quantity thermodynamic temperature, symbol  $T$ , is the kelvin, symbol K. The explicit-constant definition of the kelvin, adopted at the 26<sup>th</sup> meeting of the General Conference on Weights and Measures (CGPM) in 2019, Resolution X, is as follows:

**The kelvin, symbol K, is the SI unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the Boltzmann constant to be equal to exactly  $1.380\,658 \times 10^{-23}$  when it is expressed in the SI base unit  $\text{s}^{-2} \text{m}^2 \text{kg K}^{-1}$ , which is equal to  $\text{J K}^{-1}$ .**

Thus one has the exact relation  $k = 1.380\,658 \times 10^{-23} \text{ J/K}$ . The effect of this definition is that the kelvin is equal to the change of thermodynamic temperature  $T$  that results in a change of thermal energy  $kT$  by  $1.380\,658 \times 10^{-23} \text{ J}$ .

Prior to 2019 the kelvin was defined as the fraction  $1/273.16$  of the thermodynamic temperature  $T_{\text{TPW}}$  of the triple point of water [13<sup>th</sup> CGPM meeting in 1967, Resolutions 3 and 4]. The kelvin is now defined in terms of the SI derived unit of energy, the joule, by fixing the value of the Boltzmann constant  $k$ , which is the proportionality constant between thermodynamic temperature and the associated thermal energy  $kT$ . The new definition has its origin in statistical mechanics where thermodynamic temperature is defined through the relation between the entropy and energy of a physical system. The natural unit of thermodynamic temperature in this relation is energy (joules in the SI). While, in principle, a separate base unit for temperature is not required, it is nevertheless a quantity of a distinctly different kind, and for practical and historical reasons the kelvin will continue to be a base unit of the SI. The explicit-constant definition is sufficiently wide to encompass any form of thermometry and leaves the *MeP-K* to spell out the practical details.

It remains common practice to call the difference  $T - 273.15 \text{ K}$  Celsius temperature, symbol  $t$ . The unit of Celsius temperature is the degree Celsius, symbol  $^{\circ}\text{C}$ , which is by definition equal in magnitude to the kelvin.

The value of  $k$  adopted for the new definition is the 2019 CODATA value. This ensures that the best estimate of the value of  $T_{\text{TPW}}$  remains  $273.16 \text{ K}$ . One consequence of the new definition is that the former relative uncertainty in the determination of  $k$ ,  $1.5 \times 10^{-6}$ , is transferred to the temperature of the triple point of water,  $T_{\text{TPW}}$ . The standard uncertainty of the  $T_{\text{TPW}}$  is now  $u(T_{\text{TPW}}) = 0.9 \text{ mK}$ .

The CCT is not aware of any thermometry technology likely to provide a significantly improved uncertainty  $u(T_{\text{TPW}})$ . Consequently, there is unlikely to be any change in the value of  $T_{\text{TPW}}$  in the foreseeable future. On the other hand, the reproducibility of  $T_{\text{TPW}}$ , realised in water triple point cells with isotopic corrections<sup>1</sup> applied, is better than  $50 \mu\text{K}$ . Experiments requiring ultimate accuracy at or close to  $T_{\text{TPW}}$  will continue to rely on the reproducibility of the triple point of water. Although the value  $T_{\text{TPW}}$  is not a fundamental constant, the triple point of water is an invariant of nature with the inherent long-term stability of fundamental constants.

Direct measurements of thermodynamic temperature require a primary thermometer based on a well-understood physical system whose temperature can be derived from measurements of other quantities, as described in the following sections. Unfortunately, primary thermometry can be complicated, time consuming, and hence is rarely used as a practical means of disseminating the kelvin. As a practical alternative, the International Temperature Scales (ITSs) provide internationally accepted procedures for both realising and disseminating temperature in a straightforward and reproducible manner, see Section 5.

<sup>1</sup> Recommendation 2, CI-2005 of the CIPM clarified the definition of the triple point of water by specifying the isotopic composition of the water to be that of Vienna Standard Mean Ocean Water (V-SMOW).

### 3. Nomenclature (Taxonomy of Methods)

The purpose of this section is to clarify what is meant by the terms that will be used in the following sections on 1) primary thermometry and 2) defined temperature scales. Clear, well-defined nomenclature is essential to support an unambiguous taxonomy of methods in the *MeP-K*. Within the context of the *MeP-K* the terms below have the following meanings:

1) *Primary thermometry* is performed using a thermometer based on a well-understood physical system, for which the equation of state describing the relation between thermodynamic temperature  $T$  and other independent quantities, such as the ideal gas law or Planck's equation, can be written down explicitly without unknown or significantly temperature-dependent constants. Thermodynamic temperature can be obtained by measuring the independent quantities. Accurate thermodynamic temperature values require not only accurate measurements of the independent quantities, but also sufficient understanding of the system to enable a quantitative assessment of departures from the ideal model in order to apply appropriate corrections.

*Absolute primary thermometry* measures thermodynamic temperature directly in terms of the definition of the base unit, the kelvin, i.e., from the defined numerical value of the Boltzmann constant. No reference is made to any temperature fixed point ( $n = 0$ ,  $n =$  number of points) and all other parameters specified in the equation of state are measured or otherwise determined.

*Relative primary thermometry* measures thermodynamic temperature indirectly using a specified equation of state, with one or more key-parameter values determined from temperature fixed points ( $n > 0$ ), for which values for the thermodynamic temperature  $T$  and their uncertainties are known *a priori* from previous absolute or relative primary thermometry. Tables containing data for  $T$  of fixed points are given in the *MeP-K* appendices “Relative primary radiometric thermometry”, see Section 4.2.3, and “Estimates of the differences  $T-T_{90}$ ”, see Section 5.1.

2) *Defined temperature scales* assign temperature values, which have been determined by primary thermometry, to a series of naturally occurring and highly reproducible states (e.g., freezing and triple points of pure substances), specify the interpolating or extrapolating instruments for a particular subrange of temperature and define any necessary interpolating or extrapolating equations. The defined scales are highly prescriptive and define new temperature quantities  $T_{XX}$  (scale temperatures) that provide close approximations to the thermodynamic temperature  $T$  and have the same unit as  $T$ , i.e., the kelvin. Temperature values assigned to the fixed points of each scale are considered exact and do not change for the life of the scale, even if subsequent research reveals a bias of the values relative to true thermodynamic temperature. Currently, the only such defined temperature scales recommended by the CCT and approved by the CIPM are the International Temperature Scale of 1990 (ITS-90) from 0.65 K and above and the Provisional Low Temperature Scale from 0.9 mK to 1 K (PLTS-2000). The temperatures defined by ITS-90 and PLTS-2000 are denoted by  $T_{90}$  and  $T_{2000}$ . Non-prescriptive recommendations for the realisation of the ITS-90 and the PLTS-2000 are given in the “Supplementary information for the International Temperature Scale of 1990” and the “Supplementary information for the realisation of the PLTS-2000”, respectively.

There exist also *approximations of defined scales* where fixed points, interpolating or extrapolating instruments, and interpolating or extrapolating equations are different from those specified in the defined scales, but any differences from a scale are sufficiently well understood. Such methods are described in the “CCT guidelines on secondary thermometry”.

## 4. Primary Thermometry

While the new definition of the kelvin in terms of the Boltzmann constant has no immediate impact on the status of the ITSs, there are significant benefits, particularly for temperature measurements below ~20 K and above ~1300 K where primary thermometers may offer a lower thermodynamic uncertainty than is currently available with the ITSs. In the future, as the primary methods evolve and achieve lower uncertainties they will become more widely used and will gradually replace the ITSs as the basis of temperature measurement.

The primary thermometry methods included in this section fulfil the following criteria:

- A complete uncertainty budget has been approved by the CCT.
- The uncertainty of the realisation of the kelvin is not more than one order of magnitude larger than the state-of-the-art uncertainty achieved with primary thermometry or defined temperature scales, or the uncertainty needed by the stakeholders.
- At least two independent realisations applying the method with the necessary uncertainty exist.
- A comparison of the realisations with the results of already accepted methods has been carried out.
- The methods are applicable over temperature ranges that are acceptable for the stakeholders in metrology, science or industry.
- The experimental technique necessary for applying the methods is documented in sufficient detail in the open literature so that experts in metrology can realise it independently.

### 4.1. Thermodynamic temperature measurement by acoustic gas thermometry to above 550 K

#### 4.1.1 Principle of primary acoustic gas thermometry

Primary acoustic gas thermometry (AGT) exploits the relationship between the speed of sound,  $u$ , in an ideal gas in the limit of zero frequency and the thermodynamic temperature,  $T$ , of the gas,

$$u^2 = \frac{\gamma k T}{m},$$

where  $k$  is the Boltzmann constant,  $m$  is the average molecular mass of the gas, and  $\gamma$  is the ratio of the heat capacity of the gas at constant pressure to its heat capacity at constant volume. For ideal monatomic gasses,  $\gamma = 5/3$ .

#### 4.1.2 Absolute primary acoustic gas thermometry

The speed of sound is deduced from the resonance frequencies of a monatomic gas contained within an isothermal cavity. Accurate determinations of the resonance frequencies require the use of non-degenerate acoustic modes, and often the non-degenerate radially-symmetrical modes of nearly spherical cavities are used. The average radius of the cavity is often determined using microwave resonances. The non-ideal properties of real gasses are accommodated with the use of a virial expansion of the speed-of-sound relation and extrapolation to zero pressure.

Measurements of the acoustic resonance frequencies, pressures, cavity dimensions and molecular mass of the gas must be traceable to the metre, the kilogram and the second. Primary AGT has been conducted at the temperature of the triple point of water with relative uncertainties of the order of  $10^{-6}$ . However, the low uncertainties claimed for AGT have not yet been confirmed by independent measurements. Details are found in the appendix on "Acoustic gas thermometry" and references therein.

### 4.1.3 Relative primary acoustic gas thermometry

Relative AGT determines the ratios of thermodynamic temperatures from measurements of the ratios of speeds of sound. Typically, a temperature is determined as a ratio with respect to the temperature of a fixed point for which the thermodynamic temperature is known. The measured temperature ratios are usually expressible in terms of measured ratios of lengths and frequencies. Relative AGT has been conducted over a wide temperature range from a few kelvin to above 550 K. Independent realizations of relative AGT typically agree within  $3 \times 10^{-6} T$  in the sub-range 234 K to 380 K. A table containing data for the thermodynamic temperature  $T$  of fixed points is given in the appendix “Estimates of the differences  $T-T_{90}$ ”, see Section 5.1.

## 4.2. Spectral-band radiometric thermometry (1235 K and above)

### 4.2.1 Principle of primary radiometric thermometry

The basic equation for spectral radiometric thermometry is the Planck law, which gives the spectral radiance<sup>2</sup>,  $L_{b,\lambda}$ , of an ideal blackbody as a function of temperature,  $T$ ,

$$L_{b,\lambda}(\lambda, T) = \left( \frac{2hc^2}{\lambda^5} \right) \frac{1}{\exp(hc/\lambda kT) - 1},$$

where  $k$  is the Boltzmann constant,  $h$  is the Planck constant,  $c$  is the speed of light *in vacuo*, and  $\lambda$  is the wavelength *in vacuo*. Spectral radiance is the power emitted per unit area per unit solid angle per unit wavelength and is often expressed with the units  $\text{W m}^{-2} \text{sr}^{-1} \text{nm}^{-1}$ .

### 4.2.2 Absolute primary radiometric thermometry

Absolute primary radiometric thermometry requires an accurate determination of the optical power, emitted over a known spectral band and known solid angle, by an isothermal cavity of known emissivity. Measurement of the power requires a radiometer, comprising a detector and spectral filter, with known absolute spectral responsivity. The optical system typically includes two co-aligned circular apertures separated by a known distance to define the solid angle, and may additionally include lenses or mirrors. The refractive index of the medium in which the measurement is made must also be known. All measurements of the quantities involved must be traceable to the corresponding units of the SI, in particular, the watt and the metre.

Uncertainties of around 0.1 K ( $k = 1$ ) at 2800 K are possible with primary radiometric thermometry. Practical guidelines for the realisation, including typical uncertainty estimates, are found in the appendix “Absolute primary radiometric thermometry” and references therein.

### 4.2.3 Relative primary radiometric thermometry

For relative primary radiometric thermometry, the absolute spectral responsivity of the radiometer is not required, nor is quantification of the geometric factors defining the solid angle. Instead, the optical power is measured relative to optical power measurements made of one or more fixed-point blackbodies, each with known thermodynamic temperature. There are three recognisable approaches to relative primary thermometry:

- extrapolation from one fixed point, which requires only knowledge of the relative spectral responsivity of the detector and filter;

<sup>2</sup> The subscript  $\lambda$  on  $L_{b,\lambda}$  in this case indicates that the value is per unit wavelength, and is not a wavelength dependency.

- interpolation or extrapolation from two fixed points, which requires only the bandwidth of the responsivity;
- interpolation or extrapolation from three or more fixed points, for which detailed measurements of responsivity are not required.

The interpolation and extrapolation is greatly simplified with the use of a well-understood parametric approximation of the integral expression of the optical power (e.g., by the Planck form of the Sakuma–Hattori equation), which eliminates the need to iteratively solve the integral equation describing the measured optical power.

Relative primary radiometric thermometry gives uncertainties that are only slightly higher than absolute primary radiometric thermometry. Guidelines for the realisation, including typical uncertainty estimates, are found in the appendix “Relative primary radiometric thermometry” and references therein.

## 5. Defined Temperature Scales

The CIPM has adopted a series of International Temperature Scales (ITSs); firstly in 1927, acting under the authority of the CGPM and, since 1937, on the advice of its CCT. Subsequent to the 1927 scale, new scales have been adopted in 1948, 1968, 1990, and 2000, with occasional minor revisions in intervening years.

Note that the fixed-point temperatures assigned in all of the ITSs are exact with respect to the respective scale temperature (there is no assigned uncertainty) and fixed (the value remains unchanged throughout the life of the scale). As a consequence, the definition of the kelvin in terms of the Boltzmann constant has no effect on the temperature values or realisation uncertainties of the ITSs.

The International Temperature Scale of 1990 (ITS-90) from 0.65 K upwards and the Provisional Low Temperature Scale from 0.9 mK to 1 K (PLTS-2000) will remain in use in the foreseeable future allowing precise, reproducible and practical approximations to thermodynamic temperature. In particular, the most precise temperature measurements in the temperature range from approximately -250 °C to 960 °C will, at least initially, continue to be traceable to standard platinum resistance thermometers calibrated according to the ITS-90.

### 5.1. International Temperature Scale of 1990 (ITS-90) for temperatures above 0.65 K

The ITS-90 [Recommendation 5, CI-1989] is the most recent descendant of the original International Temperature Scale of 1927 and replaced the International Practical Temperature Scale of 1968 (IPTS-68) and its extension, the 1976 Provisional 0.5 K to 30 K Temperature Scale (EPT-76). The ITS-90 covers the temperature range from 0.65 K to the highest temperatures that can be determined practically by radiometric means. Supplementary information is available for both the ITS-90 and approximating methods to the ITS-90.

Besides the text of the ITS-90, the Technical Annex of the *MeP-K* is mandatory for the realisation of the ITS-90. This annex specifies the isotopic composition of the three fixed-point substances water, hydrogen and neon. Such a specification is not included in the scale definition itself. For the former definition of the base unit kelvin via the temperature of the triple point of water, the same isotopic composition as that given in the annex was specified by the CIPM at its 94<sup>th</sup> meeting in 2005. Furthermore, the Technical Annex contains equations, which facilitate corrections for the results obtained with fixed-point samples having other isotopic compositions.

Recommended differences between thermodynamic temperature  $T$  and temperature  $T_{90}$  on the ITS-90,  $T-T_{90}$ , together with their uncertainties are given in the *MeP-K* appendix “Estimates of the differences  $T-T_{90}$ ”. They support the requirement for highly accurate measurements of  $T$ . The user can easily convert measurements obtained in terms of  $T_{90}$  to  $T$  and vice versa. Since the fixed-point temperatures assigned in the ITS-90 have no uncertainty, the differences  $T-T_{90}$  allow directly to deduce  $T$  values for the fixed points and their uncertainties.

### 5.2. Provisional Low Temperature Scale from 0.9 mK to 1 K (PLTS-2000)

Considerable research has been conducted on establishing a temperature scale extending to temperatures lower than 0.65 K. The PLTS-2000 is the resulting outcome, adopted in 2000 by the CIPM [Recommendation 1, CI-2000]. The PLTS-2000 defines temperature from 1 K down to 0.9 mK. It is explicitly a provisional scale, recognising that the data sets comprising the basis of the scale were somewhat inconsistent below 10 mK. In the temperature range 0.65 K to 1 K, temperature may be defined on either the ITS-90 or the PLTS-2000. Either scale is acceptable; the choice of scale typically is dictated by convenience or the attainable uncertainty of realisation. In those rare cases where use of either scale is convenient,  $T_{2000}$  is a better approximation of thermodynamic temperature than  $T_{90}$  in the region of overlap.

In contrast to the ITS-90, for which the Technical Annex of the *MeP-K* contains important specifications, only the text of the scale is mandatory for the realisation of temperatures  $T_{2000}$  on the PLTS-2000. Supplementary information for the realisation of the PLTS-2000 describes methods by which the PLTS-2000 can be realised successfully.