MISE EN PRATIQUE OF THE REALIZATION OF THE KELVIN

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

1. Scope

The text of and supplementary information on the International Temperature Scales constituted until recently the reference guide for the realization of the base unit kelvin. However, recent developments in thermometry and the redefinition of the kelvin have justified the establishment of a broader and flexible document that incorporates the temperature scales in current use and developed primary thermometry methods: the *Mise en Pratique* of the realization of the kelvin (*MeP*-K).

As envisaged by the Consultative Committee for Thermometry (CCT) [Recommendation T3 (2005)] and in accordance with the report of the 97th 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. An *MeP*-K was first adopted by the CCT in April 2006, see the report of the 24th meeting of the CCT. The 2019 version of the *Mise en Pratique* of the realization of the kelvin (*MeP*-K-19) presented here incorporates the redefinition of the kelvin as adopted by the CGPM at its 26th meeting and represents the realization of the redefined kelvin that came into force on 20 May 2019 [REF].

The *MeP*-K-19 consists of the following sections:

- 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 realization 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 realization 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 26th meeting of the General Conference on Weights and Measures (CGPM) in 2018, Resolution X, is as follows:

> **The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be 1.380 6X × 10^{-23} when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.**

(h is the Planck constant, c is the speed of light in vacuum and $\Delta\nu_{Cs}$ is the caesium frequency corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the ^{133}Cs atom.) This definition implies the exact relation k = 1.380 6X × 10^{-23} J/K. Its effect is that one kelvin is equal to the change of thermodynamic temperature T that results in a change of thermal energy kT by 1.380 6X × 10^{-23} J.

Prior to 2018 the kelvin was defined as the fraction 1/273.16 of the thermodynamic temperature T_{TPW} of the triple point of water [13th 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 a measure of the average thermal energy per degree of freedom in the system. In principle, the natural unit of thermodynamic temperature is the joule and a separate base unit for temperature is not required. However, for historical and in particular for practical reasons, the kelvin remains a base unit of the SI. The explicit-constant definition is sufficiently wide to encompass any form of thermometry, where the *MeP*-K provides guidance on the practical realization of the kelvin.

It remains common practice to call the difference T - 273.15 K Celsius temperature, symbol t. The unit of Celsius temperature is the degree Celsius, symbol °C, which is by definition equal in magnitude to the kelvin.

The value of k adopted for the new definition is the 2017 CODATA value [REF]. This ensures that the best estimate of the value of T_{TPW} remains 273.16 K. One consequence of the new definition is that the former relative uncertainty in the determination of k, 0.X × 10^{-6}, is transferred to the temperature of the triple point of water, T_{TPW}. The standard uncertainty of T_{TPW} is hence now $u(T_{TPW})$ = 0.X mK.

The CCT is not aware of any thermometry technology likely to provide a significantly reduced value of $u(T_{TPW})$. Consequently, it is unlikely that the value of T_{TPW} will be modified in a foreseeable future. On the other hand, the reproducibility of T_{TPW}, realized in water triple point cells and applying isotopic corrections[1], is better than 50 μK. Experiments requiring ultimate accuracy at or close to T_{TPW} will continue to rely on the reproducibility of the triple point of water. Although the value T_{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 is usually complicated and time consuming, and is therefore rarely used as a practical means of disseminating the kelvin. As a practical alternative, the International Temperature Scales provide internationally accepted procedures for both realizing and disseminating temperature in a straightforward and reproducible manner, see Section 5.

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[1] 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 the terms that will be used in the following sections on 1) primary thermometry and 2) defined temperature scales. A clear and well-defined nomenclature is essential to support an unambiguous taxonomy of methods in the *MeP*-K. The *MeP*-K uses the following definitions:

1) *Primary thermometry* is carried out 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 expressed 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 allows to measure thermodynamic temperature directly in terms of the definition of the base unit kelvin, i.e. 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 allows to measure 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* allow to assign temperature values, determined by primary thermometry, to a series of naturally occurring and highly reproducible states (e.g., the freezing and triple points of pure substances). They also cover a specification of the interpolating or extrapolating instruments for a particular sub-range 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 are not altered while the scale is in force, even if subsequent research reveals a bias of the values relative to true thermodynamic temperature. Presently, 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 higher and the Provisional Low Temperature Scale covering the temperature range 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 realization of the ITS-90 and the PLTS-2000 are given in the "Guide to the Realization of the ITS-90" and the "Guide to the Realization 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 "Guide 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 ITS-90 and the PLTS-2000, 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 ITS-90 and the PLTS-2000. In the future, as the primary methods evolve and are expected to achieve lower uncertainties, primary thermometers will become more widely used and gradually replace the ITS-90 and the PLTS-2000 as the basis of temperature measurement.

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

- At least one example of a complete uncertainty budget has been examined and approved by the CCT.
- The uncertainty of the realization 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 realizations applying the method with the necessary uncertainty exist.
- A comparison of the realizations 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 realize it independently.

4.1. Thermodynamic temperature measurement by acoustic gas thermometry

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,

$$u^2 = \frac{\gamma k T}{m} \ , \qquad (1)$$

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

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 gases 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 review paper "Acoustic gas thermometry" by Moldover *et al.* [Metrologia **51**, R1-R19 (2014)] 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[2], $L_{\mathrm{b},\lambda}$, of an ideal blackbody as a function of temperature, T,

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

where k is the Boltzmann constant, h is the Planck constant, c is the speed of light *in vacuo*, and λ 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 W m^{-2} sr^{-1} 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 realization, 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

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[2] The subscript λ on $L_{\mathrm{b},\lambda}$ in this case indicates that the value is per unit wavelength, and is not a wavelength dependency.

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;
- 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 realization, including typical uncertainty estimates, are found in the appendix "Relative primary radiometric thermometry" and references therein.

4.3. Thermodynamic temperature measurement by polarizing gas thermometry

4.3.1 Principle of primary polarizing gas thermometry

Polarizing gas thermometry (PGT) is based on the in-situ measurement of the gas density via its electromagnetic properties. The basic working equations are the Clausius-Mossotti and Lorentz-Lorenz equation, which have been independently theoretically derived. The Clausius-Mossotti equation describes the gas behaviour in an electric field by the relative dielectric constant (permittivity) ε_r. For an ideal gas, its combination with the equation of state yields the rigorous relationship between ε_r and the gas pressure p:

$$\frac{\varepsilon_\mathrm{r}-1}{\varepsilon_\mathrm{r}+2}=\frac{A_\varepsilon p}{RT}\ , \tag{3}$$

where A_ε is the molar electric polarizability. The Lorentz-Lorenz equation describes the propagation of electromagnetic waves by the refractive index n. Its combination with the equation of state of an ideal gas can be approximated with a relative uncertainty of less than one part per million (ppm) at gas densities up to 0.1 mol/cm^3 by the rigorous relationship between n and p:

$$\frac{n^2-1}{n^2+2}=\frac{(A_\varepsilon+A_\mu)p}{RT}\ , \tag{4}$$

where A_μ is the molar magnetic polarizability. The two relationships are closely related since $n^2 = \varepsilon_\mathrm{r}\mu_\mathrm{r}$, with μ_r being the relative magnetic permeability. At non-zero gas densities, the properties of real gases deviate from the ideal equations above, and power series expansions with different virial coefficients have to be used for the Clausius-Mossotti equation, Lorentz-Lorenz equation and the equation of state. But for primary thermometry, the ideal-gas properties may be determined by extrapolation to zero density.

Each of the two relationships is the physical basis for one kind of PGT. Dielectric-constant gas thermometry (DCGT) measures ε_r by the change of the capacitance of a suitable capacitor by the measuring gas. Refractive-index gas thermometry (RIGT) detects resonances of electromagnetic waves in a cavity resonator. DCGT and RIGT share several challenges. The polarizabilities must be known from ab initio calculations. With sub-ppm uncertainties, this is at present only fulfilled for helium, which has small polarizabilities of order

$A_\varepsilon \approx 0.52\ \mathrm{cm}^3/\mathrm{mol}$ and $A_\mu \approx -0.0000079\ \mathrm{cm}^3/\mathrm{mol}$. Both DCGT and RIGT share the need of accurately measuring the pressure traceably to the SI base units metre, kilogram and the second.

4.3.2 Dielectric-constant gas thermometry

The dielectric constant is determined via the change of the capacitance $C(p)$ of a suitable capacitor measured with and without the measuring gas. This works ideally only for a pressure-independent configuration of the capacitor. In practice, changes of the electrode geometry with pressure are unavoidable and have to be taken into account. This leads for a highly-stable capacitor to a linear experimental equation for the determination of ε_r,

$$\varepsilon_\mathrm{r} = \frac{C(p)}{C(0)(1+\kappa_\mathrm{eff}\, p)} \ , \tag{5}$$

where κ_eff is the negative isothermal effective compressibility and $C(0)$ is the capacitance of the evacuated capacitor[3]. Because of the small A_ε value of helium, the capacitance changes have to be measured using a high-precision ratio-transformer bridge, the quality of which is comparable with those applied for the realization and dissemination of the capacitance unit.

For deriving the complete working equation of DCGT, the experimental equation for ε_r has to be combined with the relationship between ε_r and p. Applying the complete working equation, isotherms $C(p)$ versus p at constant temperature have to be measured for determining the DCGT results in the ideal-gas limit by extrapolation. In this limit, the values of the virial coefficients are not needed and values of the thermodynamic temperature T can be deduced.

Besides knowledge of the polarizability of the measuring gas and a traceable pressure measurement as mentioned above, absolute primary DCGT requires calculation of the effective compressibility of the measuring capacitor from the individual elastic constants of the construction materials. Traceability to the capacitance unit is not necessary because only capacitance ratios are needed. Primary DCGT has been conducted at the triple point of water with relative uncertainty of order 1 ppm. The relative uncertainty of primary DCGT results in the low-temperature range decreases from about 40 ppm at 2.5 K to about 10 ppm around 100 K. All results are confirmed by independent thermodynamic measurements within the uncertainty estimates. Details are found in the review paper "Dielectric-constant gas thermometry" by Gaiser *et al.* [Metrologia **52**, 217-S226 (2015)] and the references therein.

The requirement for SI-traceable, low-uncertainty pressure measurements can be relaxed by conducting relative primary DCGT. For instance, measurements on isobars require only that p is stabilized by the aid of an uncalibrated pressure balance. But due to the complicated temperature dependence of the elastic constants of the construction materials, and thus of κ_eff of the measuring capacitor, simple ratio measurements are not sufficient.

4.3.3 Refractive-index gas thermometry

In the context of absolute primary microwave RIGT, the refractive index is determined from measurements of microwave resonance frequencies $f_m(p)$ of a gas-filled isothermal cavity. (The subscript "m" specifies a particular microwave mode.) Quasi-spherical or cylindrical cavity shapes are typically employed, with the cavity dimensions at the working gas pressure calculated by combining the positive isothermal effective compressibility κ_eff of the resonator shell with cavity resonance measurements performed in vacuum $f_m(0)$ (the sign of κ_eff depends on the design of the cavity resonator):

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[3] The term "effective" indicates the fact that each capacitor is a composite because small pieces of insulator materials are necessary to isolate the electrodes electrically.

$$n^2 = \frac{f_m^2(0)}{f_m^2(p)(1-\kappa_{\text{eff}}\,p)^2} \approx \frac{f_m^2(0)}{f_m^2(p)}(1+2\kappa_{\text{eff}}\,p) \ , \tag{6}$$

This experimental equation for the determination of n^2 is similar to that of DCGT for ε_{r}, except that the influence of the negative effective compressibility κ_{eff} is twice as large. The equation contains ratios of microwave resonance frequencies $f_m(0)/f_m(p)$. These ratios can be measured accurately using a clock that is stable for the interval required for thermally-equilibrated measurements of $f_m(0)$ and $f_m(p)$ to be completed (usually days to weeks for an isotherm).

For deriving the complete working equation of RIGT, the experimental equation for n^2 has to be combined with the relationship between n^2 and p. Furthermore, for describing the real-gas properties of helium, power series with different virial coefficients have to be used both for the Lorentz-Lorenz equation and the equation of state. Applying the complete working equation, isotherms n^2 versus p at constant temperature may be measured for determining the RIGT results in the ideal-gas limit by extrapolation. In this limit, the values of the virial coefficients are not needed and values of the thermodynamic temperature T can be deduced.

Besides the knowledge of the polarizability of the measuring gas and a traceable low-uncertainty pressure measurement as mentioned above, absolute primary RIGT requires calculation of the effective compressibility of the measuring resonator shell from the individual elastic constants of the construction materials. Absolute primary RIGT has been conducted using helium gas at the temperature of the triple point of water with relative uncertainty of the order of 10 ppm, and at the temperatures of the triple points of neon, oxygen, and argon with relative uncertainties of the order 20 ppm. All results are confirmed by independent thermodynamic measurements within the uncertainty estimates. Details are found in the appendix “Refractive-index gas thermometry” and the references therein.

The requirement for SI-traceable, low-uncertainty pressure measurements can be relaxed by conducting relative primary RIGT. For instance, measurements on isobars require only that p is stabilized by the aid of a pressure balance with weaker calibration constraints than required for absolute primary RIGT. However, the complicated temperature dependence of the elastic constants of the construction materials, and thus of κ_{eff} of the measuring resonator, must be taken into account and simple ratio measurements may not be sufficient.

4.4. Thermodynamic temperature measurement by Johnson noise thermometry

4.4.1 Principle of primary Johnson noise thermometry

Primary Johnson noise thermometry (JNT) is based on the thermal agitation of the charge carriers inside an electrical conductor and the fluctuation-dissipation theorem as its theoretical description. The power spectral density $S_V(f, T)$ of the noise voltage V across a complex electrical impedance $Z(f)$ is given by

$$S_V\left(f,T\right) = 4hf\ \text{Re}(Z(f))\left[\frac{1}{2}+\frac{1}{\exp(hf\,/\,kT)}\right] , \tag{7}$$

where f is frequency, T is the thermodynamic temperature, h is Planck’s constant, k is Boltzmann’s constant, and Re means the real part. The impedance can be, but is not necessarily a resistor with resistance $\text{Re}(Z(f)) = R$. Neglecting for $hf \ll kT$ the quantum corrections, this equation yields the Nyquist formula

$$\left\langle V^2 \right\rangle = 4kT\,R\,\Delta f \ \ , \tag{8}$$

where Δf is the bandwidth over which the noise voltage is measured. To the lowest order, the quantum effects introduce a relative correction equal to $(hf/kT)^2/12$, which amounts for instance to 2×10^{-10} at 1 mK and 1 kHz or less than 2×10^{-9} for temperatures near 300 K and frequencies below 1 GHz.

4.4.2 Absolute primary low-temperature Johnson noise thermometry (below 4 K)

Absolute primary JNT at low temperatures requires the measurement of the power spectral density on a noise source with an exactly known impedance $Z(f)$, which generally may be frequency dependent. The noise source is usually made of a high-purity metal containing negligible amounts of magnetic impurities to ensure a temperature-independent impedance. At low temperatures, the noise signals are very small and preferably measured with a sensor based on a superconducting quantum interference device (SQUID). In the evaluated frequency band, the electronic transfer function of the whole circuit including the noise source and the SQUID sensor must be precisely determined. Relative combined standard uncertainties of order 1×10^{-3} have been achieved for thermodynamic temperatures determined by absolute primary low-temperature JNT. Details are found in the appendix “Low-temperature Johnson noise thermometry” and the references therein.

4.4.3 Relative primary low-temperature Johnson noise thermometry (below 4 K)

In relative primary low-temperature JNT, ratios of temperatures are determined from the ratio of the measured noise power spectral density to the noise power spectral density measured at a reference temperature for which the thermodynamic value is known. The uncertainty of relative primary JNT may be of the same level or lower as for absolute primary JNT provided the uncertainty for the thermodynamic reference temperature is sufficiently low. Details are found in the appendix “Low-temperature Johnson noise thermometry” and the references therein.

4.4.4 Absolute primary Johnson noise thermometry (above 1 K)

The power spectral density is deduced from measurements of the root-mean-square noise voltage (or noise current) over the measured bandwidth of the measurement system, and from measurement of the resistance. The non-ideal ac properties of real resistors and connecting leads may be accommodated with the use of a frequency-dependent model and extrapolation to zero frequency.

Measurements of the voltage, resistance, and bandwidth must all be traceable to the ampere, the kilogram, and the second. Absolute primary JNT has been conducted at the temperature of the triple point of water with relative uncertainties of the order of 4×10^{-6}. Purely electronic measurements have been performed by comparing the thermal noise power with the noise power of a quantum-accurate pseudo-random noise waveform generated with a superconducting Josephson-junction waveform synthesizer. The low uncertainties claimed for JNT have been confirmed by independent measurements using absolute primary acoustic gas thermometry. Details on absolute primary JNT can be found in the appendix “Primary Johnson noise thermometry” and references therein.

4.4.5 Relative primary Johnson noise thermometry (above 1 K)

Relative primary JNT determines the ratios of thermodynamic temperatures from measurements of the ratios of the power spectral densities. 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 noise power and resistance. Relative primary JNT has been conducted over a wide temperature range to above 2500 K. Details on relative primary JNT can be found in the appendix “Primary Johnson noise thermometry” and references therein.

5. Defined Temperature Scales

The CIPM has adopted a series of International Temperature Scales; 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, and 1990, with occasional minor revisions in intervening years. In 2000 a Provisional Low Temperature Scale PLTS-2000 was adopted for temperatures below 1 K.

It should be noted that the fixed-point temperatures assigned in an International Temperature Scale 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 realization uncertainties of the International Temperature Scales.

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. Guides are available for both the ITS-90 and approximating methods to the ITS-90.

Besides the text of the ITS-90[4], the Technical Annex of the *MeP*-K is mandatory for the realization 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 94th 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 appendix "Estimates of the differences T-T_{90}" of the *MeP*-K. They constitute a support to high-accuracy 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 deducing 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 carried out to establish a temperature scale extending to temperatures lower than 0.65 K. This has resulted in PLTS-2000, 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 from 0.65 K to 1 K, temperature may be defined using either the ITS-90 or the PLTS-2000. Either scale is acceptable; the choice of scale is oriented by convenience or the attainable uncertainty of realization. In those rare cases where use of both scales is convenient, T_{2000} offers a better approximation of thermodynamic temperature than T_{90} in the overlapping region.

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[4] The first sentence of Section 1 *Units of Temperature* of this text has been superseded by the explicit-constant definition of the SI unit of thermodynamic temperature given in Section 2.

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 realization of temperatures T_{2000} on the PLTS-2000. A guide for the realization of the PLTS-2000 describes methods by which the PLTS-2000 can be realized successfully.