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The Roles of the *Mise en Pratique* for the Definition of the Kelvin

D. C. Ripple · R. Davis · B. Fellmuth · J. Fischer · G. Machin · T. Quinn · P. Steur · O. Tamura · D. R. White

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Abstract The *mise en pratique* ("practical realization") for the definition of the kelvin (*MeP*-K) was created by the Consultative Committee for Thermometry (CCT) in 2006 to give practitioners of thermometry a guide to the realization of the kelvin, i.e., measurement of temperature in kelvins, in accord with the International System of Units. In this article, the present and the future content of the *MeP*-K, the relationship of the *MeP*-K to other documents relevant to thermometry, the categorization of thermometry techniques in the *MeP*-K, and the benefits of proposed additions to the 2006 version of the *MeP*-K are discussed. The three categories of measurements within the *MeP*-K are: (1) primary methods for measuring thermodynamic temperature T;

D. C. Ripple
Process Measurements Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

R. Davis · T. Quinn
BIPM, Sèvres, France

B. Fellmuth (✉) · J. Fischer
Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany
e-mail: Bernd.Fellmuth@ptb.de

G. Machin
National Physical Laboratory (NPL), Teddington, Middlesex, UK

P. Steur
Istituto Nazionale di Ricerca Metrologica (INRiM), Turin, Italy

O. Tamura
National Metrology Institute of Japan (NMIJ), AIST, Ibaraki, Japan

D. R. White
Measurement Standards Laboratory of New Zealand (MSL), Lower Hutt, New Zealand

(2) formal approximations to T, in particular, the International Temperature Scale of 1990 (ITS-90) and the Provisional Low Temperature Scale from 0.9 mK to 1 K (PLTS-2000); and (3) indirect approximation methods that are neither primary nor defined on a temperature scale, yet capable of exceptionally low uncertainties or increased reliability. By providing a framework for primary methods and indirect methods, the *MeP*-K will foster development and application of new methods, such as the use of absolute radiometry or high-temperature fixed points. The *MeP*-K provides the CCT with a mechanism to update and to expand the thermometric methods in common use, without imposing on industry the high costs of changing the International Temperature Scale.

Keywords International System of Units · Kelvin · *Mise en Pratique* · SI · Temperature · Temperature scale · Thermodynamic temperature

1 Introduction

In 2006, motivated by the need for a formal document to give definitive guidance for the practical realization of the kelvin, i.e., the measurement of temperature in kelvins, in accordance with the International System of Units (SI), the Consultative Committee for Thermometry (CCT) created the *mise en pratique* for the definition of the kelvin (*MeP*-K) [1]. The International Committee for Weights and Measures (CIPM) foresaw that adoption of the proposed new definition of the kelvin, based on a fixed value for the Boltzmann constant, would require an *MeP*-K [2]. Subsequently, the CCT considered constructing a new International Temperature Scale (ITS) to replace the present ITS-90 and its low-temperature counterpart, the Provisional Low Temperature Scale from 0.9 mK to 1 K (PLTS-2000). However, the CCT decided not to do this because a new temperature scale would impose a large burden on industry, which has a large investment in hardware and process algorithms specific to the ITS-90. Instead, the CCT adopted the *MeP*-K to open a new and flexible path for updating and expanding the range of recognized thermometric methods without changing the status of the ITS-90.

The ITS-90 and PLTS-2000 provide formal approximations to the thermodynamic temperature, T. The 2006 version of the *MeP*-K includes the text of the scales and a Technical Annex of essential additional information.

Future versions of the *MeP*-K, updating the 2006 version, will cover the following:

1. An introduction will outline the definition of the kelvin and its implementation in primary realizations, and its approximation by the ITS.
2. The *MeP*-K will describe primary methods for measuring thermodynamic temperature T. This section will include absolute radiometric methods above the silver point that can, with care, have lower uncertainties than ITS-90 methods.
3. Future versions will include recommended differences between thermodynamic temperature and temperature on the ITS-90, $T - T_{90}$, along with the associated uncertainties. (Equivalent information for PLTS-2000 will likely be added at a later date as more data become available.) This documentation of known ITS-90

biases will support thermodynamically accurate measurements without mandating replacement of the ITS-90 in industry.

4. In a new category of SI realizations, the *MeP*-K will describe realization of the kelvin by indirect approximations, giving the temperatures for selected fixed points (not defined on the ITS-90) and outlining interpolation or extrapolation methods. Realizations using high-temperature fixed points and radiometric interpolation are one example of an indirect approximation promising greater flexibility in traceable temperature measurements.

The category of indirect approximations includes realizations that are neither primary realizations nor scale-defined realizations, although, they might become so in the future. As an example, high-temperature fixed points promise to provide calibration standards with reduced uncertainty above 1235 K for both radiometric and contact thermometers. These fixed points were not available when the ITS-90 was formulated. Because they are now realized as stable and repeatable phase transitions, their inclusion in the *MeP*-K will facilitate a dramatic reduction in uncertainty for high-temperature thermometry. We expect that additional approximation methods will be included in the *MeP*-K, but only when the international community has reached consensus on the value of including a particular method. With an adjustment of interpolating equations and assigned temperatures of phase transitions, indirect methods may be used to approximate either an International Temperature Scale or a primary realization of the kelvin.

With the *MeP*-K endorsement of multiple realization methods, there is a risk that reported values of temperature could be ambiguous. The *MeP*-K will provide clear recommendations on proper notation of temperature (e.g., T_{90} for temperature in degrees Celsius on the ITS-90) and realization method in publications, calibration reports, or other documents.

In this article, we shall discuss the structure and the content of the *MeP*-K as envisioned by the Consultative Committee for Thermometry. Section 2 will examine the relationship of the *MeP*-K to other documents relevant to the realization of the kelvin. Sections 3–5 will then describe the three categories of realizations outlined above: primary methods, formal approximations, and indirect approximations, respectively. Section 6 examines the possible effects of a redefinition of the kelvin on the *MeP*-K, and Sect. 7 presents conclusions.

2 *MeP*-K and Related Documents

The *MeP*-K describes the connection of various documents to the SI definition of the kelvin and recommends particular methods. In large part, the methods themselves are described in separate documents or by citations to literature. Figure 1 shows the relationship between the *MeP*-K and the other documents important for realization of the kelvin.

The International Bureau of Weights and Measures (BIPM) issues “The International System of Units (SI)” (commonly termed the SI brochure) [3] to explain and disseminate the most recent version of the SI. The SI brochure discusses the definition of the kelvin and the subsequent clarifications, briefly describes appropriate

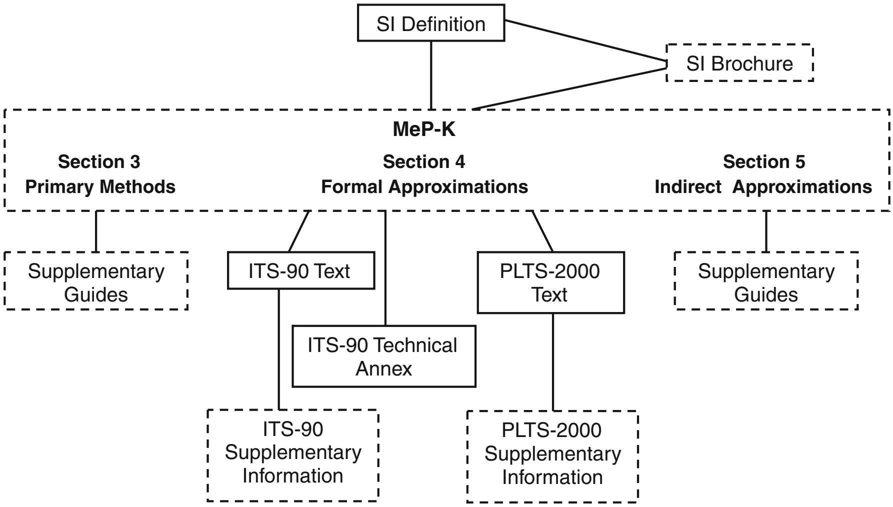

Fig. 1 Schematic representation of the relationships between the *MeP*-K and other documents important for the realization of the kelvin. *Boxes* with *solid borders* represent prescriptive documents; *boxes* with *dashed borders* represent non-prescriptive guidance documents, and *section numbers* refer to sections in this article

nomenclature for expressing temperature in the SI, and references the *MeP*-K and documents related to the International Temperature Scales. Although the main text of the SI brochure is only rarely updated, Appendix 2 of the SI brochure, available on the web only, is updated regularly and contains the most recent version of the *MeP*-K, along with similar documents for other SI units.

In the field of thermometry, International Temperature Scales have long been the consensus means of disseminating the kelvin. Although existence of International Temperature Scales did not rule out alternative disseminations based on primary methods, the lack of formal recognition of alternatives has led to confusion. By discussing International Temperature Scales in the context of other methods, the *MeP*-K seeks to remedy this confusion.

When the *MeP*-K was first implemented, the International Temperature Scale of 1990 [4] and the Provisional Low-Temperature Scale of 2000 [5] both existed as formal documents approved by the CIPM. The *MeP*-K recommends both the ITS-90 and the PLTS-2000 as formally defined, internationally accepted approximations to realizations of thermodynamic temperature.

Supplementary information for each of these scales provides non-prescriptive guidance on practical methods for implementing the scales. In the words of the "Supplementary Information for the International Temperature Scale of 1990" [6]:

> This document describes methods by which the ITS-90 can be realized successfully. However, it should not be taken as laying down how it must be done.

Unlike the Supplementary Information, the Technical Annex for the ITS-90 is prescriptive, containing important clarifications to the original ITS-90 text, such as the isotopic compositions and corrections of fixed-point elements. Although historically the Technical Annex for the ITS-90 was created as part of the *MeP*-K, the Technical Annex appears in the published text of the *MeP*-K as an additional document referenced by the *MeP*-K and accessed by a link, similar to the text of the ITS-90 itself.

In contrast to the approach of the ITS-90 and the PLTS-2000, the *MeP*-K does not mandate how primary or indirect, approximate methods are to be realized; the corresponding sections of the *MeP*-K provide recommended practice but do not exclude other methods or variations on the methods included. The discussion in the *MeP*-K may be very brief and cite relevant literature, or the detail necessary may warrant publication of a separate guidance document.

3 Primary Methods for Determining Thermodynamic Temperature

3.1 General Considerations for Primary Methods

Measurements of thermodynamic temperature require a primary thermometer[1] based on a well-understood physical system for which the equation of state can be written down explicitly without having to introduce unknown, temperature-dependent constants. By measuring other independent quantities in the equation of state, the thermodynamic temperature may be obtained. Accurate temperature values require not only accurate measurements of the independent quantities, but also a full understanding of the system including departures from the ideal and the application of appropriate corrections.

The *MeP*-K will describe only those methods that have proven reproducibility and that can achieve uncertainties comparable to the best methods. Methods that meet these criteria at the present include several variations of gas thermometry, absolute spectral radiance thermometry, and Johnson noise thermometry. For each of these methods, the text of the *MeP*-K will give the principle, the equation of state (e.g., Planck's Law), and note any defining conditions (e.g., in vacuum). Other methods may be included as needed.

The only primary methods in present use for actual dissemination of calibrated standards are $p - V - T$ gas thermometry and high-temperature radiometry. The lack of use of the other techniques, such as acoustic thermometry, for routine dissemination of the kelvin should not be construed as questioning the value or reliability of the method. Rather, in the approximate range of 10 K to 900 K, primary methods have their greatest value in determining the bias of the formal approximations to thermodynamic temperature (as described in Sect. 4), and not in directly disseminating calibrated

[1] Primary thermometers may determine values of thermodynamic temperature directly in terms of the definition of the kelvin, or may determine ratios of thermodynamic temperatures. Methods relying on the definitions of the International Temperature Scales or the indirect approximations given in Sect. 5 are not included.

standards. As primary methods become easier to use and more attractive as a means of dissemination, we expect a corresponding revision of *MeP*-K recommendations.

The most appropriate primary method will depend greatly on the temperature range of interest. Absolute spectral-band radiometry, for example, is highly appropriate for temperatures above 1200 K; acoustic thermometry has excellent demonstrated reproducibility in the range of 150 K to 300 K; and Johnson noise thermometry works well at temperatures <1 K.

Given the greater expense and difficulty of directly measuring thermodynamic temperature compared to use of an approximation (Sects. 4, 5), the use of primary methods should not be adopted without careful thought. Applications where primary methods have clear advantages are:

1. The temperature is below the range of the formal scales.
2. Lower uncertainties, especially with respect to thermodynamic temperature, may be obtained with a primary method.
3. A laboratory already has the technical capability to carry out thermodynamic measurements, but not ITS measurements.
4. A user wishes to use the equation of state to relate temperature to another related quantity (e.g., the calibration of a radiometer response in units of thermodynamic temperature may be converted to absolute units of radiance).

In Sects. 3.2–3.4, we briefly describe several primary methods that will be incorporated in the *MeP*-K in the near future.

3.2 Radiometric Methods

There are two primary non-contact[2] thermometry methods that may be used to measure temperatures above the silver point; these are total radiometry and absolute spectral (or spectral-band or filter) radiometry.

Total radiometry is not routinely practiced as a method of thermometry as it is too difficult and time-consuming, and so will not be included in the *MeP*-K. Filter radiometry is, however, widespread in use, and sufficiently developed to be included as a primary method in the *MeP*-K capable of yielding uncertainties equal to or, in its most highly developed forms, better than the ITS-90.

Because of the significant advantages of absolute spectral radiometry, inclusion of this method in the *MeP*-K is a high priority. A task group of CCT-WG5 (radiation thermometry) has prepared text for the next version of the *MeP*-K, together with a larger supplementary guide that describes the possible methods of high-temperature realization [7].

To implement filter radiometry, well-characterized blackbody sources (with high emissivity) and a precise measurement of spectral radiance of the blackbody traceable to the units of the SI are required. The latter, in turn requires a precise determination

[2] Non-contact thermometers refer to those instruments that exploit thermal exchange by electromagnetic radiation only between the measured object and the thermometer. Contact thermometers have direct contact with the object being measured.

of the configuration (also known as the geometric or form) factor that depends upon the blackbody aperture, the detector aperture, and their separation.

The actual implementation of absolute spectral-band radiometry to measure the temperature of a blackbody differs in important details; four different approaches are outlined in [8]. However, despite these differences in the detail of the calibration and subsequent implementation of the method, the uncertainties attained by the practitioners for T are similar or even somewhat less than the uncertainties for T_{90} using the ITS-90 method (see Sect. 5.2).

3.3 Gas Thermometry

All kinds of gas thermometry are based on simple relations between the properties of an ideal gas and thermodynamic temperature T [9]. Though many gases exhibit a nearly ideal behavior at and above the triple point of water, the small departures from the ideal behavior must be carefully considered for the highest level of accuracy even at these temperatures. This is done by measuring the dependence of the relevant property on gas density (measurement of isotherms). The ideal behavior is then deduced by fitting an appropriate virial expansion to the measured isotherm and extrapolating to zero density. If the change in apparatus dimensions with pressure is well understood and corrected for, gas non-ideality may be predicted from theory as an alternative [10,11]. Three kinds of gas thermometry are widely used: acoustic gas thermometry (AGT), constant-volume gas thermometry (CVGT) being a special version of $p - V - T$ gas thermometry, and dielectric-constant gas thermometry (DCGT). CVGT is also an interpolation method of the ITS-90; see Sect. 4. Differences between these techniques have important metrological consequences. AGT and DCGT are based upon the variation with T of an intensive property of the gas (speed of sound and dielectric constant, respectively), whereas primary CVGT requires a knowledge of the number of moles of gas present in the gas bulb. Due to the need to determine the number of moles, CVGT is incapable of reaching the part per million uncertainty level. Second, for AGT the dependence of the speed of sound on the pressure is a second-order effect, whereas DCGT and CVGT have a first-order dependence on pressure that may limit attainable uncertainties.

In gas thermometry, the temperature measured is the thermodynamic temperature of the gas in kelvins, but this realized temperature must be transferred to a portable thermometer for practical use. Platinum resistance thermometers thermally anchored to the cavity walls indirectly measure the temperature of the gas in the cavity, thereby transferring the realization to a transportable, repeatable thermometer.

3.3.1 Acoustic Gas Thermometry

Acoustic gas thermometry (AGT) exploits the simple relationship between the speed of sound of a monatomic gas (such as argon) and the thermodynamic temperature of the gas. The frequencies of acoustic resonances within a nearly spherical, gas-filled cavity are proportional to the speed of sound or the square root of thermodynamic temperature. Although numerous corrections must be applied to the raw data, the corrections are well documented and theoretically well understood.

By sweeping the frequency of the acoustic excitation and monitoring the acoustic response of the gas, the resonance frequency may be located to within a precision of 1 part in 10^6 (e.g., 0.3 mK at 300 K). Resonator-based acoustic thermometers have another advantage: the resonance frequencies of many modes may be measured. The consistency between modes provides an important cross-check on the data.

By flowing gas continuously through the spherical cavity, the effects of outgassing from the cavity wall can be minimized. Simultaneous measurements of microwave resonances enable a straightforward correction for the thermal expansion of the cavity walls.

The demonstrated agreement among different AGT realizations with widely different experimental details is excellent over the temperature range of 130 K to 380 K [12,13]. AGT results have been published over a much wider range, 4 K to 552 K [12,14]. Over this wider range, AGT data agree with other primary methods; however, the low uncertainties claimed for AGT in this expanded range have not yet been confirmed by independent measurements.

3.3.2 Constant-Volume Gas Thermometry

CVGT is based on the virial expansion of the equation of state. For absolute *pV*-isotherm CVGT, the gas bulb at a constant temperature is filled with a series of increasing amounts of gas to obtain a series of pressures. Performing high-accuracy CVGT, several sources of error must be taken into account; see the overview given in [9]. The main practical problems are connected with the need to measure the number of moles of gas present in the gas bulb. All recent primary CVGT experiments have been, therefore, performed by measuring relative isotherms, i.e., by determining the amount of gas using a reference volume at a known temperature, measuring the pressure, and solving an appropriate virial expansion. Critical systematic effects are related to gas sorption, to the measurement of the gas-bulb volume and to the pressure and temperature dilatation of the bulb. Thus, the relative uncertainty of absolute measurements of the temperature has been limited to approximately 10^{-5}. At this level, for example, CVGT data below 30 K presented in [15] have been confirmed by independent measurements.

3.3.3 Dielectric-Constant Gas Thermometry

DCGT is based on the idea of replacing the density in the state equation of a gas by the dielectric constant. If the polarizability of the measuring gas is known, DCGT is a primary thermometry method. The dielectric constant is determined via the change of the capacitance of a suitable capacitor measured with and without the measuring gas. The polarizability of only one gas, helium, can be calculated theoretically with the necessary uncertainty, one part in 10^6. But the polarizability of helium is very small, and this sets a lower bound on the density of helium and a corresponding (temperature-dependent) range of pressures at which DCGT measurements are made. A problem of DCGT measurements is accounting for the deformation of the capacitor under pressure, i.e., the effective compressibility of the capacitor must be determined with the necessary small uncertainty by measuring the volume compressibility of the construction materials and using special capacitor designs. The uncertainty is further mainly limited by the measurement of pressure and small capacitance changes as well as the influence of impurities present in the measuring gas. Nevertheless, a level of 10^{-5} has already been verified at temperatures around 30 K by comparison with the results obtained with other methods [16].

3.4 Johnson Noise Thermometry

Johnson noise thermometry exploits Nyquist's relationship between thermodynamic temperature and the variance of the thermally induced fluctuations in noise current or voltage generated by a resistor. Noise thermometers are appealing because they are entirely electronic and have a simple and accurate equation of state. However, noise thermometers have the disadvantage of a small and easily corrupted noise signal spread across a wide bandwidth. Also, because the measured signal is random, the statistical contribution to uncertainty is proportional to the square root of the number of measurements. To achieve low relative uncertainties, very long measurement times and/or wide bandwidths are needed.

There are two main classes of noise thermometers. The first, based on a noise-voltage measurement using cross correlators, has been used to measure temperatures in the range from a few kelvins to 2500 K. Although it provides useful experimental validation of other methods (e.g., [17,18]), it cannot easily achieve the low relative uncertainties (<0.002 %) obtainable with other direct methods such as acoustic gas thermometry. The second class of noise thermometer is based on noise measurement using superconductive quantum interference devices (SQUID) at temperatures of a few kelvins down to a few millikelvins [19–22]. At these temperatures where relative uncertainties of 0.1 % are very useful, a well-behaved, primary noise thermometer has considerable appeal.

4 Formal Approximations to Thermodynamic Temperature

In principle, the kelvin can be disseminated by

1. setting up a primary thermometer;
2. ensuring thermal equilibrium between the primary thermometer and a working standard thermometer; and
3. calibrating the working-standard thermometer against the readings of the primary thermometer.

In practice, primary thermometers are difficult and time-consuming to operate, large in size, and limited in temperature range. As an alternative, the International Temperature Scales (ITSs) provide internationally accepted procedures for making practical temperature measurements. Each scale assigns exact temperature values to a series of naturally occurring, highly reproducible states (e.g., the freezing point of zinc), specifies the type of interpolating instrument for a particular subrange of temperature, and defines any necessary interpolating equations. Thus, the International Temperature Scales are highly prescriptive and formal.

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

The ITS-90 is the most recent International Temperature Scale [4]. 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 approximations to the ITS-90 [6,23]. The ITS-90 was extended downward in temperature in 2000, when the CIPM adopted the Provisional Low Temperature Scale (PLTS-2000) from 1 K to 0.9 mK [5,24].

Where scales overlap (such as the range of 0.65 K to 1 K for the ITS-90 and the PLTS-2000) the scales will differ in reproducibility and uncertainty. In the rare cases where temperature lies within a range of overlap and either scale may be specified, the *MeP*-K may provide guidance on the best scale choice.

The *MeP*-K also serves as a repository for important extensions or clarifications of the International Temperature Scales. Over time, the definitions within the text of the ITS-90 have proven to be incomplete. For example, the ITS-90 largely ignores the effects of isotopic variation of thermometric fixed points. The Technical Annex for the ITS-90, contained within the *MeP*-K, includes the additional prescriptive information necessary for the realization of the ITS-90 at the highest level of accuracy. This Technical Annex, and any future Annex for the PLTS-2000, are deemed to have the same formal status as the temperature scales themselves.

Because both the International Temperature Scales and the kelvin are defined, we cannot introduce a third independent definition of the difference between ITS and primary realizations—the difference can only be measured and reported. The *MeP*-K will provide consensus values for the difference between the ITS-90 and thermodynamic temperature, along with the associated uncertainty. Use of these consensus values will allow ready conversion between temperatures reported on the International Temperature Scales and thermodynamic temperatures. Additionally, the values will inform users of the International Temperature Scales of the likely bias of these scales relative to the true thermodynamic temperature. Use of the International Temperature Scales is so widespread that even sophisticated users are likely to forget that the T_{90} is only an approximation to T. Report of the likely bias in the *MeP*-K reminds users of the extent of the approximation.

5 Indirect Approximations for Realizing the Kelvin

5.1 General Considerations for Indirect Approximations

Indirect, approximate methods are those where temperatures are measured without direct application of a fundamental equation of state with all appropriate corrections.

Typically, parameters in an interpolating equation are determined from calibration measurements at fixed points, rather than from non-thermometric subsidiary experiments or theory. Thus, a calibration equation interpolates between or extrapolates from tabulated fixed-point temperatures. Such methods can usually be realized with a much simpler technical capability than primary methods with only a modest increase in uncertainty. There are many established, broadly used indirect methods [23], such as thermocouples, that will not be included in the *MeP*-K. The *MeP*-K will document only those methods that provide users with proven low uncertainties or unique advantages.

The text of the *MeP*-K will present the basic principle of the method, the accepted interpolating equations, and any defining conditions or limitations. Unlike the equations of state for primary methods, interpolating equations may be empirical or approximations of more exact equations. The text will also tabulate recognized fixed points with the values and associated uncertainties for both thermodynamic temperature and ITS temperature. Note that these fixed points are not defined by either the ITS-90 or PLTS-2000, and thus the assigned values will have non-zero uncertainty.

5.2 Radiometric Realizations Using High-Temperature Fixed Points

The ITS-90 above the silver point is realized by one defining fixed-point blackbody of either silver, gold, or copper, and the use of Planck's law in ratio form to develop the temperature scale by extrapolation. This was done because at the time ITS-90 was formulated, no reliable high-temperature fixed points (HTFPs) existed above the Cu point. However, with the advent of HTFPs, such as metal-carbon eutectics [25], this situation no longer persists and it will soon be possible to measure thermodynamic temperatures indirectly above the silver point by either extrapolation from a single fixed point ($n = 1$), or interpolation between two or more fixed points ($n = 2, 3, \ldots$) using Planck's law. (Here, n designates the number of fixed points that are used in the particular interpolation/extrapolation scheme.)

The use of the HTFPs to calibrate spectral-band radiometers illustrates the benefits of the indirect approach. A direct measurement of temperature by absolute radiometry involves a number of technically demanding measurements of the radiometer attributes, including the absolute spectral responsivity. The use of a single fixed point ($n = 1$), in a similar manner to ITS-90, means that only the relative spectral responsivity is required: a much easier measurement. If two fixed points ($n = 2$) are used [26], only a good estimate of the bandwidth is required. With three fixed points ($n = 3$), the spectral responsivity need not be measured, and with more than three fixed points ($n > 3$) and a least-squares approach, the redundancy provides additional security in scale realization. The cost of indirect methods is that the uncertainty cannot be less than the propagated uncertainties in the tabulated values of fixed-point temperatures (P. Saunders, Int. J. Thermophys., under review). Nevertheless, with due care to the various sources of uncertainty, it may be possible to approach the accuracy of primary measurements, with a much reduced investment in technical capability.

The situation regarding the use of HTFPs in high-temperature metrology is still the subject of research. Although they do not yet have officially sanctioned temperatures, we expect assignment of consensus fixed-point temperatures in the next few years. It is in anticipation of this that material on HTFPs and interpolation schemes have been drafted for inclusion in the indirect approximations section of the main *MeP*-K document [8].

6 Effects of Proposed Changes to the Definition of the Kelvin

The kelvin is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water, T_{TPW}. The kelvin will likely be redefined in the next few years [2]. As currently envisioned, the kelvin will be defined in terms of the SI unit of energy, the joule, by fixing the value of the Boltzmann constant k, which is the proportionality constant between temperature expressed in kelvins and the associated thermal energy kT [27]. 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 value of k adopted for the new definition will be the most recent CODATA value. This ensures that the best estimate of the value of T_{TPW} would remain 273.16 K. One consequence of the new definition is that the relative uncertainty in the determination of $k(1.8 \times 10^{-6}$ at present), will be transferred to the thermodynamic temperature of the triple point of water, T_{TPW}, resulting in an approximate uncertainty of $u(T_{\text{TPW}}) = 0.49\,\text{mK}$.

Note that the fixed-point temperatures assigned in all the International Temperature Scales 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 redefinition of the kelvin in terms of the Boltzmann constant has no effect on the temperature values or realization uncertainties of the present International Temperature Scales, ITS-90 and PLTS-2000. In particular, the uncertainty of realization of the triple point of water on the ITS-90 will not include the additional uncertainty of k.

Adoption of the new definition of the kelvin requires only modest changes in the *MeP*-K. The introduction of the *MeP*-K will explain the basis of the definition and the consequences on the uncertainty and temperature of the triple point of water.

The CCT is not aware of any new technology for a thermometer that is likely to provide a significantly improved uncertainty $u(T_{\text{TPW}})$. Consequently, the assigned value of T_{TPW} is unlikely to change in the foreseeable future. Although the triple point of water will lose its special status as the defining point of the kelvin, the high reproducibility of the triple point of water ensures its continued use in many practical realizations (e.g., the ITS-90).

While the new definition for the kelvin has no immediate impact on the status of the ITS-90 or 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. However, the ITS-90 and PLTS-2000 will remain in use for the foreseeable future as precise, reproducible, and convenient approximations to thermodynamic temperature. In particular, the most precise temperature measurements in the core temperature range from approximately 13 K to 1235 K will, at least initially, continue to be traceable to standard platinum resistance thermometers calibrated according to the ITS-90.

The new definition of the kelvin in terms of the Boltzmann constant does not require the replacement of the ITS-90 or the PLTS-2000 with an improved temperature scale nor does it prevent such a replacement. In the future, as the primary methods evolve and achieve lower uncertainties, they will become more widely used and may, in many ranges, gradually replace the International Temperature Scales as the basis of temperature measurement.

7 Conclusions

The *MeP*-K is a flexible document that will grow substantially during the next few years in accordance with the CCT's plan. As our knowledge and international consensus develops, new and refined methods will be added. The *MeP*-K enables the CCT to promote the use of new methods as they become suitably validated, while at the same time supporting the established International Temperature Scales.

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