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Progress with Realizing the Redefined Kelvin

(James F. Schooley Invited Paper)

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Abstract. The redefinition of the kelvin is introduced followed by an overview of progress made towards realizing the redefined kelvin with particular emphasis on using primary thermometry approaches to enable traceability direct to the kelvin definition. Perspectives for temperature traceability in the short-, medium- and long-term are discussed along with the possible requirements for a future temperature scale.

INTRODUCTION

In May 2019 four of the base units of the international system of units (the SI) were redefined in terms of fundamental constants [1]. From that point on the SI was based on atomic properties (the second), fundamental physical constants (the metre, the kilogram, the ampere, the kelvin, the mole) and a conventional constant (the candela). The kelvin was redefined in terms of the Boltzmann constant (k) [2, 3, 4] concluding over a decade long effort by the international thermometry community to redetermine k with low uncertainty [5].

Accompanying the SI unit redefinition were documents whose purpose was to guide the user from the definition of the unit to a practical realization. For the kelvin this document was known as the *mise en pratique* for the definition of the kelvin [4, 6] and was designated *MeP-K-19* to identify that the 2019 version of the *MeP-K* was in force from the time of the redefinition.

The kelvin redefinition, and the associated *MeP-K*, have stimulated new opportunities for realization and dissemination of the temperature unit. Presently almost all temperature traceability is through the defined scales; either the International Temperature Scale of 1990 (ITS-90) [7] or the Provisional Low Temperature Scale of 2000 (PLTS-2000) [8], but in the future, temperature traceability, linked directly to the kelvin definition, is likely to become more widespread [3, 9, 10].

In this paper we give an outline of how the kelvin was redefined and a description of the associated *MeP-K*. We then discuss the progress made in realizing primary thermometry approaches promoted in the *MeP-K-19* that could be used for providing traceability directly to the kelvin definition. This will be done mainly in the context of the European Metrology Programme for Innovation and Research (EMPIR) research project “Realizing the Redefined Kelvin” (Real-K) [11] though other relevant work in the field will also be introduced. The impact of these developments in the short-, medium- and long-term for traceability to the kelvin will be discussed, including the emergence of *in-situ* traceability through self-calibrating thermometers and practical primary thermometry [9, 10].

THE KELVIN REDEFINITION AND ASSOCIATED *MEP-K*

The kelvin redefinition: In May 2019 a historic change to the international system of units (SI) took place [1]. The definitions of four base SI units, the kilogram, the ampere, the mole and the kelvin were all changed and from that time on they were defined in terms of fixed values of fundamental constants of nature, namely the Planck constant (h), the elementary charge (e), the Avogadro number (N_A) and the Boltzmann constant (k) respectively. For the kelvin this change was the culmination of over a decade long global research programme where multiple experimental determinations of k were made, with progressively lower uncertainty using several different approaches. Those that contributed to the final CODATA 2017 [12] consensus value of k were Acoustic Gas Thermometry (AGT) [13], Dielectric Constant Gas Thermometry (DCGT) [14] and Johnson Noise Thermometry (JNT) [15]. The consensus value derived from these experiments was $1.380\,649\,01(51) \times 10^{-23} \text{ J K}^{-1}$ with a relative uncertainty of 0.37 ppm (standard uncertainty). When the definition came into force the value of k was defined as $1.380\,649 \times 10^{-23} \text{ J K}^{-1}$ and the uncertainty was effectively transferred to the water triple point, the value of which became $(273.16 \pm 0.0001) \text{ K}$. After the kelvin redefinition the water triple point, which up until then had been the quasi-artefact that defined the kelvin, became “just another” fixed-point, though in reality it retains its pivotal role in temperature traceability due to the importance it plays in establishing the ITS-90. The formal wording of the kelvin definition is: 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 $1.380\,649 \times 10^{-23}$ when expressed in the unit J K^{-1} , which is equal to $\text{kg m}^2 \text{s}^{-2} \text{K}^{-1}$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{\text{Cs}}$. For more details on the kelvin redefinition the reader is referred to [3, 16].

The mise en pratique for the definition of the kelvin (MeP-K-19): Accompanying the kelvin redefinition a document was prepared, the “*mise en pratique* for the definition of the kelvin” (*MeP-K*) [17]. The purpose of the *MeP-K* was to guide the user from the kelvin definition based on k to a practical realization of the unit. Of course, although not explicitly stated this realization was for a purpose, just as the ITS-90 had a purpose, and that was to effect the dissemination of the temperature unit the kelvin, that is to provide traceability to the unit. The *MeP-K* contains the following sections: the definition of the kelvin, definition of terms related to primary thermometry, criteria for inclusion of a thermodynamic method (within the *MeP-K*), an outline of allowable (that is those that met the selection criteria) primary thermometry methods for realizing the kelvin based on fundamental laws of physics [these were; Acoustic Gas Thermometry, Direct and Relative Primary Radiometry, Dielectric Constant Gas Thermometry, Refractive Index Gas Thermometry, {low temperature} Johnson Noise Thermometry] and the defined temperature scales, ITS-90 and PLTS-2000. The *MeP-K*, whilst supporting on-going use of the defined temperature scales to provide traceability, also encourages the use of primary thermometry approaches to provide traceability directly to the kelvin definition. That is to provide thermodynamic temperature as opposed to a defined scale temperature T_{90} or T_{2000} which requires a correction before thermodynamic temperature is attained through published $T-T_{90}$ [18] or $T-T_{2000}$ [19] values. This last step introduces additional uncertainty which direct use of primary methods would not incur. The interested reader is referred to [6, 17] for more details regarding the *MeP-K*.

The kelvin redefinition stimulated activity in practical primary thermometry to see if it was possible to provide direct traceability to the kelvin without the need for the intermediate step of the defined scale. This activity has continued after the kelvin was redefined, and it is now clear that at high temperatures ($>1300 \text{ K}$), at low temperatures ($<25 \text{ K}$) and increasingly at intermediate temperatures, traceability direct to the kelvin definition, through use of primary thermometry, is becoming increasingly possible. These developments are discussed in the following sections.

REALIZATION AND DISSEMINATION OF THERMODYNAMIC TEMPERATURE BY RELATIVE RADIOMETRY

At high temperatures (above the silver freezing point) it is perfectly possible to realise and indeed disseminate thermodynamic temperature by direct (no fixed points) or relative (one or more fixed points) primary radiometry [20]. However low uncertainty direct primary radiometry is challenging [21], and it is recognized that relative primary radiometry for the establishment of thermodynamic temperatures is considerably more reliable. This became even more apparent since the advent of high temperature fixed points (HTFPs) [22, 23]. It was quickly realized that if low uncertainty thermodynamic temperatures could be assigned to HTFPs then they would become ideal artefacts through which to perform relative primary radiometry and so establish low uncertainty thermodynamic temperature at high temperatures. After their inception [22] and promising preliminary results [e.g. 24] extensive research was performed to understand important issues regarding effective realization of the HTFPs such as thermal effects [25] and how to

optimize HTFP cell filling [26]. Then through the Implementing the new Kelvin (InK1) project [27] low uncertainty thermodynamic temperature (T) values were obtained for the HTFPs of Co-C, Pt-C and Re-C [28 {point of inflection}, 29 {liquidus}] and these temperature values were included within an annex of the *MeP-K* [30]. For reference, the liquidus point temperature values, for each HTFP are: Co-C (1597.48 ± 0.07) K, Pt-C (2011.50 ± 0.11) K and Re-C (2747.91 ± 0.22) K (standard uncertainties).

This work continues as part of the Real-K project [11]. In Real-K low uncertainty T values of Fe-C (1426 K), Pd-C (1765 K), Ru-C (2227 K) and WC-C (3022 K) (nominal temperatures) are being determined. More than 30 HTFPs were constructed for this endeavor. These cells were first characterized and their sensitivity to a range of thermal conditions assessed according to a common protocol, thus determining the thermal-related uncertainties for these HTFPs [31]. Next the HTFPs were compared and the best (in terms of lowest melting range and highest temperature achieved) HTFP cells were selected for their thermodynamic temperature to be determined. Table 1 shows the main outputs of the selection process for each HTFP and the National Measurement Institutes (NMIs) who performed the measurements.

TABLE 1. Differences between HTFPs of each fixed point from the first comparison prior to circulation

	Fe-C	Pd-C	Ru-C	WC-C
Comparison NMI	INRIM	CEM	NPL	LNE-Cnam
Maximum difference between four best HTFPs	13 mK	190 mK	153 mK	220 mK
Maximum melting temperature difference between the best two cells	2 mK	70 mK	69 mK	50 mK

The selected HTFPs were circulated in two loops for thermodynamic temperature assignment and then compared again to assess possible drift. An example of the quality of the data obtained in this current work is shown in Figure 1 where a preliminary evaluation of the temperature, T , of the point of inflection of WC-C is given. It is envisaged that before the end of 2023 this work will be complete and a full suite of HTFPs with low uncertainty thermodynamic temperature will be available [32] to establish thermodynamic temperature from the Ag (or Cu) freezing point to the WC-C point by the relative primary thermometry approach given in the *MeP-K*.

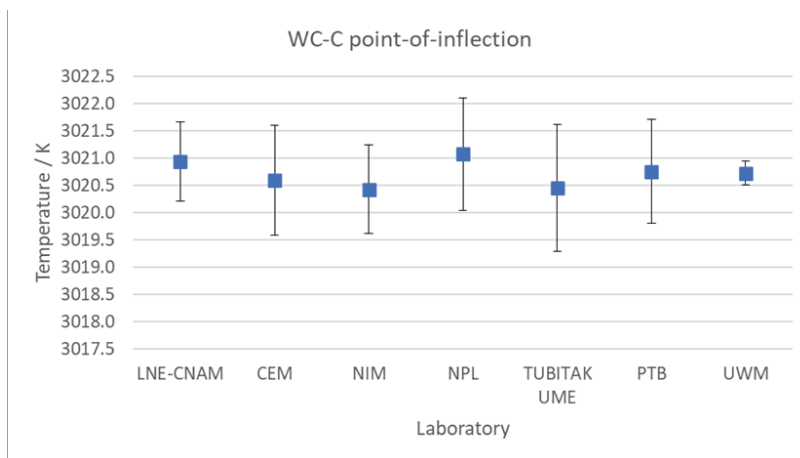


FIGURE 1. Preliminary values for the temperature of the point-of-inflection of the WC-C point, including the weighted mean¹

In the paper by Lowe and Machin [33] an example is given of how to use HTFPs to establish low uncertainty thermodynamic temperatures according to the process specified in the *MeP-K*. It is clear that thermodynamic temperatures by relative primary radiometry have similar or lower uncertainties when compared to the ITS-90

¹ CEM = Centro Español de Metrología, Spain, NIM = National Institute of Metrology, China, TUBITAK UME = National Metrology Institute, Turkey, UWM = Uncertainty Weighted Mean

realization and are more reliable as the temperature values are obtained from interpolation rather than extrapolation. It is likely that dissemination of thermodynamic temperature at high temperatures by relative primary radiometry mediated by HTFPs will become widespread in the next few years.

REALIZATION AND DISSEMINATION OF THERMODYNAMIC TEMPERATURE BELOW 25 KELVIN

The current arrangements for traceability to the kelvin below 25 K rely on the lower temperature part of the ITS-90 and the PLTS-2000 [34]. The PLTS-2000 ranges from 0.902 mK (the Néel temperature [T_N] of solid ^3He) to 1 K. The PLTS-2000 is, in essence, established by calibrating a ^3He melting pressure thermometer against four fixed points of pressure and temperature with defined temperatures T_N , T_{A-B} , T_A (which denote the temperatures of three phase transitions in solid or liquid ^3He) and a minimum feature found on the ^3He melting pressure curve at pressures between about 2.8 MPa and 4.0 MPa. The ITS-90 begins at 0.65 K and continues upwards meaning there is an overlap region between the PLTS-2000 and the ITS-90 between 0.65 K and 1 K. The difference between T_{90} and T_{2000} has been well characterized by [19] and more recently by [35]. The ITS-90 arrangements for scale realization between 0.65 K and the neon triple point (24.5561 K, ~ 25 K) are three-fold; 1) between 0.65 K and 5.0 K T_{90} is realized in terms of the vapor pressure relations of ^3He (0.65 K to 3.2 K) and ^4He (1.25 K to 5.0 K), 2) between 3.0 K and 24.5561 K T_{90} is realized by means of an interpolating constant volume helium gas thermometer calibrated at three temperatures and 3) between the triple point of hydrogen (13.8033 K) and up to the freezing point of silver (961.78 °C) standard platinum resistance thermometers (SPRTs), calibrated at specified sets of defining fixed points and using a defined interpolation procedure, are used. In practice for this third approach capsule type c-SPRTs are invariably used at low temperatures. This arrangement is complex and gives rise to type 2 non-uniqueness uncertainties, due to the use of different kinds of thermometer (e.g. interpolating gas thermometer and c-SPRT) in overlapping ranges. In reality nearly all current practitioners of low temperature thermometry rely on so-called “wire-scales” to provide traceability to low temperatures. This is where low temperature thermometers were calibrated to (or traceable to) a primary realization of the temperature scales and then those thermometers are subsequently used to provide traceable calibrations relying on their stability for sometimes periods of 20+ years.

The complexity in scale realization and dissemination, the chronic shortage of active primary realizations of temperature scales (and hence over-reliance on “wire-scales”), coupled with the opportunities provided by the *MeP*-K for primary thermometry below 25 K, has led to a resurgence in investigating the use of primary thermometry in that temperature regime as a means of providing direct traceability to the redefined kelvin.

At very low temperatures this has been discussed elsewhere [e.g. 27, 36]. More recent activity, particularly within the Real-K project [11], has focused on the temperature range 1 K to 25 K, seeking to extend the useful temperature range of different primary methods, namely those based on primary Magnetic Field Fluctuation Thermometers (pMFFT) [37], Coulomb Blockade Thermometers (CBT) [38] and a relative primary variant of an Acoustic Gas Thermometer (AGT) [13, 39]. The pMFFT and CBT approaches should enable direct measurement of thermodynamic temperature requiring only a single device over most of the temperature range avoiding reference to the defined scales. AGT meanwhile will provide a means for calibrating practical thermometers at thermodynamic temperatures from 5 K and above.

Outline Description of the Primary Thermometers

The pMFFT (a type of Johnson Noise Thermometer [JNT]) utilizes a superconducting quantum interference device (SQUID)-based magnetometer read-out of the thermal noise currents inside the temperature sensor. The latter is typically a metallic body, where the thermally excited electrical currents flowing inside cause fluctuations of the magnetic field at the outside. Here these field fluctuations are detected by the SQUID magnetometer as thermally induced magnetic flux noise, the spectral density of which is proportional to the thermodynamic temperature T . A cross-correlation readout scheme with two independent channels largely suppresses the influence of intrinsic, non-thermal noise. The useful measurement range of the pMFFT investigated here (and in previous work [27, 36]) ranges from <1 mK to ~ 5 K.

The CBT is, in essence, a series-parallel circuit of $N \times M$ quasi-identical normal metal tunnel junctions and is based on the temperature dependent single electron charging effects in arrays of tunnel junctions. The thermodynamic temperature (T) is derived from the width of the dip in the differential conductance $G = dI/dV$ of the array. Provided the charging energy (E_c) is much smaller than the thermal energy ($E_c \ll kT$) then T is proportional to the width of the

conductance dip. Numerical fitting of the full conductance curve according to the single electron tunneling model [40] is used for an arbitrary ratio of E_c to kT to determine T .

The AGT utilizes the relationship between the speed of sound in an ideal gas and thermodynamic temperature. In classical AGT, the non-ideal properties of real gases are taken into account by a virial expansion of the speed of sound relation and extrapolation to zero pressure. This extrapolation requires time consuming isothermal measurements at several pressures. By way of illustration, absolute primary AGT may take >10 days for a single temperature measurement <25 K. To increase the speed of measurement, the so-called “fast-AGT” method has been developed [39, 41]. Fast-AGT combines relative primary AGT measurements at given temperatures after an initial AGT measurement in the absolute primary mode at an arbitrary single reference temperature T_{ref} . Since all the subsequent measurements in relative primary mode are performed at the same (single) pressure the total measurement time is very significantly reduced so that <25 K, up to three different temperatures can be measured in one day. The uncertainty in the measurement of T by fast-AGT is only slightly larger than that using conventional AGT.

Validation of the Primary Thermometers

In the temperature range from 1 K to ~5 K, pMFFT has been compared with ITS-90 *and* primary temperature data from DCGT measurements [42, 43], both maintained on rhodium iron resistance thermometers (RIRT). In addition, the lambda transition ($T_\lambda = 2.1768$ K) [44] in liquid ^4He from normal to superfluid state, with μK stability, was used for this comparison. These comparison measurements were carried out in a dry dilution refrigerator with the thermometers being measured attached to either an additional high-temperature platform or to the λ -point cell.

Measurements on the λ -transition gave excellent results with only very small sub-mK deviations between T_λ and both T and T_{90} , while the observed relative deviation of the pMFFT was <0.1 % with an uncertainty of 0.6 % ($k = 1$). Wider range temperature measurements were equally good with pMFFT between 1.2 K and 4.5 K deviating from the T_{90} values <0.2 % with an uncertainty of 0.6 %. Measurements with the pMFFT in relative primary mode ($T_{\text{ref}} = 0.518$ K) were performed between 0.65 K and 6 K with a relative deviation of <0.4 % from T_{90} values. Since the reference temperature for the relative primary pMFFT was below 1 K *and* traceable to the PLTS-2000, the results demonstrate an excellent extrapolation and smooth overlap between the PLTS-2000 range below 1 K and the ITS-90 range above 1 K. Within the combined standard uncertainties, the pMFFT temperatures show excellent agreement with T_λ , T (via the DCGT measurements) and ITS-90. These results will be elaborated further in [45].

In the range ~1 K to 16 K CBT was compared with ITS-90 using absolute primary mode. Temperature values were determined from a fit to the conductance curves, scaling to N junctions and correcting for the heating of the electron system by the excitation and bias voltages [46]. Between 2.2 K and 16 K the agreement between T and T_{90} was $< \pm 1$ %. Below 2.2 K, a systematic increase of the relative deviation is observed, probably caused by the onset of superconductivity of the Al-based CBT and a non-effective thermal contact of the CBT chip. However, it may well be possible to suppress these observed deviations by means of an external magnetic field and a reliable mounting of the CBT chip.

The fast-AGT method (referenced to the neon triple point) was verified at a set of temperatures between 7 K and 24 K by comparison with a Single-Pressure Refractive Index Gas Thermometer (SPRIGT) [39, 41]. An indirect comparison through the differences of T_{AGT} and T_{SPRIGT} to T_{90} was performed with small deviations <0.6 mK observed.

In summary, significant advances have been made in all three low temperature primary thermometry methods. Johnson noise thermometry, via the pMFFT, has been clearly demonstrated as an eminently practical low uncertainty method to measure thermodynamic temperatures below 5 K. CBT has been demonstrated with uncertainties <1 % which are suitable for most applications (though it must be noted that CBT is not yet a *MeP-K-19* approved primary thermometry approach for temperature realization and dissemination). Fast AGT has been shown to be a viable means for realizing, and by calibration of practical sensors, disseminating thermodynamic temperatures above 5 K up to 25 K, and indeed AGT for such dissemination up to at least ~300 K [47].

EXTENDING THE LONG-TERM USEFULNESS OF THE INTERNATIONAL TEMPERATURE SCALE OF 1990

The ITS-90 [7] has served the needs of the global thermometry community to provide low uncertainty traceable temperatures since it was introduced in 1990. Indeed, it is a remarkable testament to its creators, who in the mid-1980s laboured to create a scale that (to cite its creators) defined “procedures by which certain specified practical thermometers can be calibrated in such a way that the values of temperature obtained from them are precise and

reproducible, while at the same time approximating the corresponding thermodynamic values as closely as possible". As all previous scales were replaced at an interval of around 20 years little did the ITS-90's creators realise that because of their care and efforts, the scale would endure for so long without amendment, unlike previous scales.

However to keep the ITS-90 still able to meet the needs of users in this decade (and beyond) a number of possibly life-limiting issues need to be addressed. These include, quantifying the impact of the main Types (1 and 3) of non-uniqueness which currently limit the uncertainties achievable using SPRTs [48-54], and the need to identify a possible alternative to the mercury triple point ($-38.8344\text{ }^{\circ}\text{C}$), a key fixed point whose use could be banned by an international treaty [55].

As part of the work to ensure the longevity of the ITS-90 a comprehensive evaluation of Type 1 non-uniqueness on many SPRTs and new determinations of Type 3 non-uniqueness in the range $-189\text{ }^{\circ}\text{C}$ to $156\text{ }^{\circ}\text{C}$, and $660.323\text{ }^{\circ}\text{C}$ and $961.78\text{ }^{\circ}\text{C}$ have been performed as part of the Real-K project [11]. The three main candidates for replacing the mercury point are the triple points of Xe (approximately $-111.744\text{ }^{\circ}\text{C}$) [56], CO_2 (approximately $-56.558\text{ }^{\circ}\text{C}$) [57] and SF_6 (approximately $-49.595\text{ }^{\circ}\text{C}$) [58]; the Xe point is difficult to use with long-stem SPRTs so the focus in the Real-K project was on testing new designs of CO_2 and SF_6 cells for use with long-stem SPRTs and investigating what effect replacing (or eliminating) the Hg point had on the ITS-90 interpolating equations and uncertainty propagation.

Type 1 Non-Uniqueness

As part of the Real-K project, NRC, NPL, IPQ and UL² have performed and published [48] a wide-ranging study of Type 1 non-uniqueness (subrange inconsistency, SRI) associated with SPRTs. The study drew on data from the EURAMET.T-K9 and CCT-K9 comparisons of SPRTs at the ITS-90 fixed points, as well as data from the databases of commercial calibrations at NPL, PTB, NRC and other NMIs, i.e. using SPRTs which are globally representative. In addition, Type 1 non-uniqueness was assessed for all pairs of overlapping ITS-90 sub-ranges between $-189.3442\text{ }^{\circ}\text{C}$ (Ar) and $660.323\text{ }^{\circ}\text{C}$ (Al). It was found that across all the pairs of overlapping sub-ranges, the mean SRI varied from -1.23 mK to $+0.21\text{ mK}$, and the standard deviation varied from 0.04 mK to 0.62 mK . Both the mean and standard deviation of the SRI exhibited a general increase with increasing temperature; this is particularly pronounced when the lower sub-range requires a fixed point which is not included in the higher sub-range.

Importantly, the contribution from the uncertainties propagated from the fixed points was also assessed to determine the significance of the SRI determinations, and it was found that, although the effect of the propagated uncertainty largely cancels out for points common to both sub-ranges, it still accounts for between 59 % and 130 % of the differences between overlapping pairs of sub-ranges. This means that, in general, the SRI is likely to be substantially overestimated, since it is convolved with the measurement uncertainty at the fixed points and propagation thereof. The study [48] will help to reduce the uncertainty of Type 1 non-uniqueness since it provides a characterization of this phenomenon over all ITS-90 subranges with an unprecedentedly large and diverse sample of SPRTs drawn from a global dataset.

Type 3 Non-Uniqueness

To assess the Type 3 non-uniqueness comparison measurements on cohorts of up to ten long-stem SPRTs of different manufacture and design have been performed by NPL, CEM and INTiBS³. Each cohort comprised at least six locally maintained SPRTs, with two SPRTs circulating amongst the participants to provide linkage between them. The comparisons were carried out in a stirred liquid bath at several temperatures between 178 K and 303 K coupled with measurements at the triple point of Ar, 83.8058 K (NPL), at 273 K and 353 K (coupled with measurements at the freezing point of In, 429.7485 K (CEM), and at 84 K and 273 K , coupled with measurements at the triple points of Ar and Hg (INTiBS). Individual SPRTs were compared directly against one of the cohort to render the exercise insensitive to temporal and spatial temperature variations within the bath.

Figure 2 shows the merged NPL and CEM results for the differences between the SPRTs (the apparent non-uniqueness), both with the baseline of the mean of the two common SPRTs, 112 and 275079. These comparisons of long-stem SPRTs rank amongst the most precise ever made. Nonetheless, they still only represent an upper limit, because they represent a convolution of the Type 3 non-uniqueness and experimental measurement uncertainty.

² NRC = National Research Council (Canada), IPQ = Instituto Português da Qualidade (Portugal), UL = University of Ljubljana (Slovenia)

³ INTiBS = Institute of low temperature and structure research (Poland)

However, they do suggest that the Type 3 non-uniqueness uncertainty may be limited to ± 0.1 mK, at least between 178 K and 303 K, rising to ± 0.2 mK at 353 K.

A study of uncertainty propagation when the mercury point is replaced with any of the Xe, CO₂ or SF₆ triple points showed that any of these could replace the mercury point, and the choice should be based on their utility, realization uncertainty, and their location in the subrange. It was shown that while the realization uncertainties of the alternative fixed points are likely to be larger than those for the mercury point, the propagation of the uncertainties would in all cases be somewhat lower [49, 51].

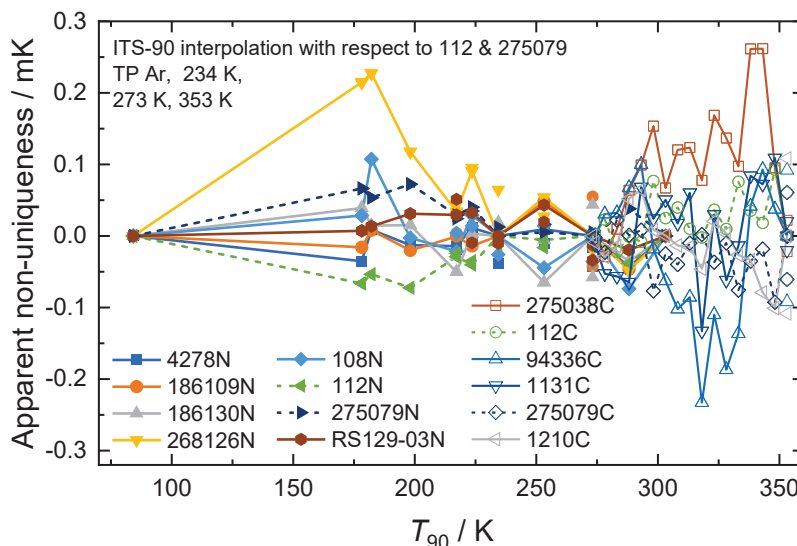


FIGURE 2. Combined results of NPL (from Ar to 303 K) and CEM (from 273 K to 353 K).

Low Uncertainty Alternatives to the Mercury Point

In the Real-K project [11] alternatives to the mercury triple point that can be used to reliably calibrate long stem SPRTs have been investigated. This builds on work reported in for example [57] and [58].

LNE-Cnam manufactured three new SF₆ triple point cells and constructed a quasi-adiabatic calorimeter to realize them. This system permits simultaneous calibration of both long-stem and capsule SPRTs. In addition, the solid-liquid transition of the SF₆ cells has been characterized with both long-stem and capsule SPRTs, to verify the equivalence between the quasi-adiabatic and fully adiabatic realizations. This characterization was undertaken because the thermal environment has been reported to have a strong influence on the measurement uncertainty. This does indeed seem to be the case, with long-stem SPRTs appearing to yield a higher apparent melting temperature (by about 2 mK) than capsule SPRTs. A second aim of this work was to determine the thermodynamic temperature of the triple point of the SF₆ cells with capsule SPRTs calibrated against an acoustic gas thermometer.

TUBITAK-UME have manufactured two new CO₂ triple point cells which were realized in a stirred ethanol bath. The plateau melting range amounted to about 0.3 mK, with repeatability of about 0.15 mK. The overall expanded uncertainty of calibration using the new CO₂ fixed points amounts to about 0.5 mK.

SMU and NPL have investigated how the fixed-point uncertainties propagate in the ITS-90 sub-range to Ar when Hg is replaced with either SF₆, CO₂ or Xe, or with Ga. This has shown that the uncertainty propagation is minimized when Xe is used, followed by, in order of increasing uncertainty propagation, CO₂, SF₆, Hg and Ga [59].

NPL is also investigating alternative interpolations for long-stem SPRTs in which the subranges currently specified in the ITS-90 are extended below the triple point of water without including the mercury triple point or any replacement for it. Cubic interpolations which require only Ar, Sn and Zn are being compared with the ITS-90 as defined over this subrange. It is suggested that this and similar equations could be of interest to provide simplified interpolations over the full range of use of long-stem SPRTs, without incurring the inconsistencies associated with the mercury point [60]. Further investigations are in progress and more details can be found in [61] and references therein.

PREPARING FOR PRIMARY GAS BASED THERMOMETRY AT TEMPERATURES ABOVE 25 K

It is clear that for temperatures above the silver freezing point (~ 1235 K) and below 25 K primary thermometry is becoming a viable alternative for traceability purposes providing direct linkage to the kelvin definition in these temperature regions. In principle the *MeP*-K-19 allows for the dissemination of thermodynamic temperature in any range and such an alternative is attractive because, unlike the ITS-90, calibrations can be performed at temperatures most needed by the user and the uncertainties intrinsic to various types of non-uniqueness are eliminated.

However, before the direct dissemination of thermodynamic temperature above 25 K can become widespread, two basic conditions need to be met. Firstly, that the uncertainty of the primary methods is not significantly larger than that of the ITS-90 realization and, secondly, that the experimental techniques of primary thermometers are simplified to become more economic and less time-consuming. Recent results obtained with gas-based primary thermometers [41-43, 47, 56, 62-69], including constant volume gas thermometry (CVGT) acoustic constant gas thermometry (AGT), dielectric constant gas thermometry (DCGT) and refractive index gas thermometry (RIGT), show that the uncertainty requirements are close to being met, especially for the low temperature range spanning between a few kelvin and ambient temperature, where ITS-90 calibration, certainly below 25 K, requires more time and effort due to the complexity of its implementation.

However, the requirement to simplify the measurement process, and so make it more economic and less time-consuming, was still, until recently, an outstanding issue. To meet this need, advanced calculations of the thermophysical properties of monatomic gases from first principles was included as a key objective of the Real-K project [11]. Improved *ab initio* calculations lead to important simplifications of gas thermometry in several ways. Firstly, they allow for rapid calculation of corrections to account for the non-ideality of the thermometric gas, thus enabling determination of the thermodynamic temperature using the data recorded at a single, conveniently chosen, thermodynamic state rather than by the extrapolation to vacuum of the results obtained at several different pressures along an isotherm. This new approach radically reduces the measurement time (by an order of magnitude) with no appreciable increase of the associated uncertainty [70]. Secondly, the availability of more accurately calculated properties for thermometric gases like Ne and Ar, which are more polarizable than He, extends the working pressure range of DCGT and RIGT and so reduces the uncertainty contribution of the imperfect assessment of the deformation of the apparatus under pressure. Thirdly, and finally, the ability to be flexible concerning the working reference gas depending on the type of trace impurities, which are more likely to be present at a certain temperature range or depending on the materials from which the apparatus is made from, reduces the measurement uncertainty.

The state-of-the-art of electronic structure calculations for atoms (and molecules) and its effect on various fields of fluid metrology has been the subject of a recent extensive review [71]. Among the recent achievements which have had a positive impact on He-based primary thermometry are a fivefold reduction of the uncertainty of both the 2nd virial coefficient and the 2nd acoustic virial coefficient of ^3He and ^4He derived from a highly realistic interaction potential [72], and an improved calculation of the fourth virial coefficient of both He isotopes [73]. In addition, there are anticipated improvements of the three-body potential and therefore of the 3rd density- and acoustic-virial coefficients, a new calculation of the molar polarizability [74] and the 2nd dielectric- and refractivity-virial coefficients [75] and a revised improved estimate of the 3rd dielectric virial coefficient [76] were achieved. These advances reinforce the superiority of He as a calculable reference gas for primary thermometry.

In addition, remarkable progress in the calculated properties of neon has also been achieved, with published estimates of the density, acoustic, and dielectric virial coefficients and the dilute gas shear viscosity and thermal conductivity with the calculated values now being more accurate than any available experimental data [77]. However, it is extremely challenging to reduce the uncertainties in the calculated values of electromagnetic and thermal properties of Ar due to the atom having a large number of electrons and the increasing complexity and the computational effort required to reduce the uncertainty of the calculated properties. The most accurate values of the electromagnetic and thermophysical properties of Ar still rely on revised estimates [76] of experimental results.

It is vital that theoretical calculations are confirmed through selected experimental validation, and this was undertaken as part of the Real-K project [11], but not necessarily always using primary thermometers. For instance, speed-of-sound measurements in Ne using a double pulse-echo technique were reported for pressures up to 100 MPa over the wide temperature range between 200 K and 420 K with further measurements ongoing to extend the lower temperature range down to 90 K. The accuracy of these results over a wide range of pressures provide a careful test of the equation of state of Ne up to a high virial order. In addition, analysis of previously published AGT measurements in Ar in the range 120 K to 330 K [47, 78] provides accurate estimates of the 2nd and 3rd acoustic virial coefficients

of Ne and Ar which should help confirm the validity of improved *ab initio* calculations of the same properties when they become available.

Primary thermometers are sometimes used in combination with other thermodynamic experimental methods to provide more accurate estimates of virial coefficients. Recently, a custom apparatus was developed by PTB whose design allows conventional DCGT measurements as well as gas expansion experiments [79]. Such a combination enables the distinction between density and dielectric virial coefficients, which would otherwise be entangled within the density variation of the gas permittivity. Results for the 2nd and 3rd virial coefficients of He, Ne and Ar, obtained by this method have been recently reported [79-81] over the range of temperatures spanning between 240 K and 360 K. Particularly, for He the relative standard uncertainty of the 2nd virial is lower than 1% and the results were found to be consistent with the most recent theoretical estimate [72]; while for Ar, relative standard uncertainties for the 2nd and 3rd virial were obtained of the order of 0.5 % and 2 % respectively.

To confirm the validity of the assumption that gas-based primary thermometry can be simplified and speeded up through use of theoretically calculated thermometric gas properties simplified versions of DCGT and RIGT for the range between a few kelvin and ambient temperature were established. Measurements are on-going but preliminary results were encouraging. It was demonstrated that a simplified version of DCGT demonstrated could perform measurements with overall uncertainties of 7 mK ($k=1$) when operated with Ar at temperatures up to 303 K, and a RIGT primary thermometer, operated between 13.5 K and 161 K, gave an uncertainty of 1.8 mK ($k=1$) at 161 K [67].

Given the outstanding progress with theoretical calculation of the required thermophysical properties of thermometric gases, it is becoming apparent that, certainly up to 300 K, gas-based primary thermometry approaches are likely to become competitive with ITS-90 for realization and dissemination of temperature in the latter part of the decade.

SHORT-, MEDIUM-, LONG-TERM PERSPECTIVES FOR TEMPERATURE TRACEABILITY

Here we discuss how traceability to the SI unit of temperature could be delivered in the coming years. In this context short-term means 2-5 years, medium-term to the end of the 2020s and long-term into the 2030s and beyond.

Short-Term Perspectives for Temperature Traceability

It is clear that, in the short-term, temperature traceability will be firmly anchored in the current defined temperature scales (ITS-90 and PLTS-2000). Although niche thermodynamic approaches may emerge the vast majority of traceable temperature measurements will continue to be through the defined scales. Anyone requiring thermodynamic temperatures will need to correct their data using published values of $T-T_{90}$ and $T-T_{2000}$. Although it is clear that the ITS-90 has some minor limitations, chiefly through, for example, uncertainties arising from Type 1 and 3 non-uniqueness and the possible future ban on use of mercury, these have been adequately addressed (see above section) ensuring the ITS-90 has a useful life to the end of the 2020s and beyond.

Medium-Term Perspectives for Temperature Traceability

In the medium-term it will become increasingly possible for primary thermometry to supplant the defined scales for realization and dissemination of the unit by National Metrology Institutes. This is especially where similar or lower uncertainties can be attained, or more robust or simpler means of dissemination become available. Thus, for temperatures above the silver freezing point, indirect primary radiometry, in-part or wholly mediated by HTFPs, could well become the accepted means of disseminating high temperature. This would be either, through calibrating transfer radiation thermometers against selected HTFPs with assigned thermodynamic temperatures [33], or through the use of the HTFPs directly for dissemination. Similarly for temperatures below 25 K, the cumbersome arrangement of two scales (ITS-90 down to 0.65 K and the PLTS-2000 up to 1 K), and with different approaches for realizing ITS-90 below the neon point, it may well be possible for primary thermometry techniques such as JNT (below 5 K) and RIGT and AGT (above 5 K) to supplant the defined scales for provision of traceability. This would lead to gains both in thermodynamic veracity and also simplicity in realization. In principle such an approach could lead to the PLTS-2000 being supplanted by JNT by the end of the 2020s (something envisaged by the Consultative Committee for Thermometry (CCT) Strategy [82]). Also, with recent advances in the understanding of gas properties [71], and advances in the state-of-the-art in AGT showing very low uncertainties are possible (much smaller than the values of

$T-T_{90}$) at higher temperatures, it could be possible that, by the end of the decade, gas based primary thermometry up to at least 300 K would be capable of providing traceability in a competitive way compared to ITS-90. These latter approaches are the focus of a new European Partnership on Metrology (EPM) [83] research project known as Disseminating the Redefined Kelvin (DireK-T) which starts in September 2023. This project will seek to demonstrate the feasibility of dissemination of thermodynamic temperature from around 4 K to 300 K, develop a robust framework to facilitate that dissemination and investigate the possible means for extending thermodynamic temperature traceability above 300 K in the future [84].

The CCT has considered these matters and documented them in its renewed strategy (2021 to 2030+) [82] with, in essence, a slow evolutionary approach advocated to possible changes to temperature traceability. With regards the *MeP-K-19* the CCT decided that a review into its operation would be undertaken in the period 2025-2027 with the aim of giving recommendations about how to proceed regarding thermodynamic temperature realization and dissemination. Any revision of the *MeP-K-19* would be after that date and a chief driver in any revision would be if new practical primary thermometers, beyond those already given in the current *MeP-K*, became available with sufficiently low uncertainty to provide alternative approaches to dissemination of thermodynamic temperature. Also addressed in the CCT Strategy was the position of the defined scales. It was recognized that the defined scales will, at least for the medium-term, be the enduring means of providing temperature traceability. As a result, CCT targeted the period 2027-2030 to perform a review into the on-going relevance of the current temperature scales PLTS-2000 and ITS-90. That review will primarily examine the requirement for any future temperature scale (ITS-XX). Importantly, the review will not just examine the scientific case for a new scale but also will encompass, as a minimum, an examination of stakeholder needs (i.e. is there a significant group of users who need improved thermometry beyond what the defined scales can provide), the cost of implementation (i.e. how disruptive to human endeavor across the globe would introduction of any new scale be) and the actual need (has there been sufficient progress with basing temperature realization and dissemination on thermodynamic approaches to render any new scale un-necessary). This slow approach was deliberately adopted to give time for the new kelvin definition and the *MeP-K-19* to get established and provide stability for the temperature measurement community.

Finally in this mid-term period it is likely that temperature sensors with self-calibrating capability will become commercially available and deployed [85, 86, 87]. Such sensors rely on incorporating, within the sensor itself, one or more temperature references (such as a miniature fixed-point) whose transition can be used to continuously validate the performance of and, if necessary, re-calibrate the temperature sensor *in situ*. It is important to note that such sensing approaches challenge the concept of traceability as linked by an unbroken chain of measurement to an NMI as the sensors themselves should not need removal for recalibration. The advent of such sensors is important to optimize process control for energy efficiency. Indeed, true autonomous production and reliable networks of temperature sensors may not be possible without such innovations.

Long-Term Perspectives for Temperature Traceability

In the long-term (2030s-2040s) temperature traceability from an NMI could be through the defined scales but increasingly it is likely that for some parts of the scale, i.e. up to 300 K and above the silver freezing point traceability will be provided via thermodynamic thermometry approaches. However, due to the increasing challenges for performing routine low uncertainty thermodynamic thermometry at temperatures above 300 K and below the silver freezing point it may be that a range restricted new temperature scale, the ITS-20XX is required. Alternatively, it is possible that, after the CCT has undertaken its review that it becomes clear that the ITS-90 should continue to provide traceability in the parts of the scale where thermodynamic thermometry has not yet become competitive. If this is the situation that emerges then ensuring on-going global uniformity of temperature measurements in the mixed environment of dissemination of T_{90} and T will need to be addressed by the CCT.

But there is an even more fundamental issue regarding temperature traceability, which is already raised in part through the advent of self-calibrating sensors; that is, by the potential introduction of practical primary thermometers. Such primary thermometer sensors could provide genuine *in-situ* traceability at the point of measurement using the fundamental physics pertaining to the sensor to derive genuine thermodynamic temperatures. It is true that the *measurement system* used to extract the temperatures from the sensor may well require periodic calibration, but this would be much easier than calibration of the sensor itself in situations where the sensor is difficult, if not impossible, to retrieve (for example if it is embedded in a nuclear reactor, or aircraft engine or industrial process). This is because the measurement system is generally not located in the harsh measurement environment and so can be easily recalibrated.

Although primary thermometer sensors are unlikely to attain very low uncertainties compared to freshly calibrated conventional sensors their great virtue would be that they could provide reliable very long-term primary thermometry with uncertainties in the 0.1 K to 1 K range in the measurement setting. Such approaches are already in active development, examples include practical JNT [88, 89], practical Doppler Broadening Thermometry [90] and other novel photonic approaches [91]. These new approaches are technology disruptors since they break the concept of traceability linked by unbroken chain of measurement to NMI by providing true traceability *in-situ* by exploiting the thermodynamics of the sensor to obtain thermodynamic temperature directly.

If such sensors are successfully developed and become widely available this raises interesting questions for the CCT; for example, how are such *in-situ* practical primary thermometers to be viewed? Do they genuinely provide traceability to thermodynamic temperature? How does one validate such traceability? It is clear that there is much for the CCT to do in the coming decades to ensure on-going global traceability for temperature.

CONCLUSION

In this paper we have sought to give a brief overview of how the kelvin was redefined and how through the associated *MeP*-K-19 temperature traceability can be obtained through the defined scales or through CCT approved primary thermometry approaches. We then gave an update on work that has been focused on facilitating primary thermometry approaches for temperature traceability. Finally, we have given a forward look into the possible ways temperature traceability might be provided to users in the future. It is clear that the kelvin redefinition has given strong stimulus to the field of primary thermometry and has driven innovations in new approaches to temperature traceability.

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