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Towards realising the redefined kelvin

G. Machin [a,*], M. Sadli [b], J. Pearce [a], J. Engert [c], R.M. Gavioso [d]

[a] National Physical Laboratory (NPL), Teddington, TW11 0LW, UK
[b] LNE-Cnam, Laboratoire Commun de Métrologie, 93210 Saint-Denis, France
[c] Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587, Berlin, Germany
[d] Istituto Nazionale di Ricerca Metrologica (INRIM), 91 Sd delle Cacce, 10135 Torino, Italy

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ABSTRACT

In 2019 the kelvin was redefined in terms of the Boltzmann constant. Here we outline the implications of that redefinition for the realization and dissemination of the unit of temperature. We describe the progress towards realizing the redefined kelvin and outline the prospects for temperature traceability into the 2030 s.

1. Introduction

In the post kelvin redefinition [1–3] era, instead of temperature traceability being achieved through the calibration of sensors to the defined temperature scales, i.e. the International Temperature Scale of 1990 (ITS-90) [4] or the Provisional Low-Temperature Scale of 2000 (PLTS-2000) [5], the user is presented with a more nuanced traceability choice through the *mise en pratique* for the definition of the kelvin (*MeP*-K-19) [6–8]. Temperature traceability may be achieved either through one of the defined scales or directly to primary thermometry, linked to the redefined kelvin.

In this paper we introduce the kelvin redefinition and the *MeP*-K-19. We then describe progress in realising the redefined kelvin in the context of the European metrology programme for innovation and research (EMPIR) Realising the Redefined Kelvin (Real-K) project [9] the aim of which is to begin to turn the *MeP*-K-19 into a reality. The project has four main objectives:

1) *To demonstrate and establish traceability directly to the redefined kelvin from ~ 1300 K to ~ 3000 K.* Firstly, low uncertainty thermodynamic temperatures of four high-temperature fixed points (HTFPs) [10], namely, Fe-C (1426 K), Pd-C (1765 K), Ru-C (2226 K) and WC-C (3020 K), will be established. Then, through the mechanism of the *MeP*-K-19, these and other low uncertainty HTFPs will be used to demonstrate a realisation and dissemination of thermodynamic temperature with uncertainties competitive with the defined scale (the ITS-90) [11].
2) *To demonstrate practical primary thermometry for realisation and dissemination of temperature below 25 K.* Primary thermometry approaches will be developed with the capability to replace the currently complex ITS-90 scale realisation arrangement below 25 K and to ensure a smooth transition to the PLTS-2000 range < 1 K (target expanded uncertainty of 0.2 mK at 25 K and < 1 % at 1 K) [12–15].
3) *To extend the life of the current defined scale (ITS-90).* The aim of this activity is twofold; a) to give users continued access to low uncertainty realisations of the ITS-90 whilst b) allowing time for primary thermometry methods to mature. Scale non-uniqueness will be investigated, with the objective of reducing its uncertainty by 30 % [16]. A possible replacement fixed-point for the mercury triple point will be identified, constructed and tested and the issue of integration within the ITS-90 will be addressed [17–19].
4) *To reduce the uncertainty in different gas-based primary thermometry methods, approved for use in the MeP-K-19, and so extend their applicability for temperature realisation and dissemination into the temperature region above 25 K.* This will be facilitated through reducing the uncertainties of the measured and calculated thermophysical properties of gases (e.g. He, Ne, Ar) used in primary thermometers [20–23]

Abbreviation: Real-K, Realising the redefined kelvin.

* Corresponding author.
E-mail address: graham.machin@npl.co.uk (G. Machin).

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The primary thermometry methods developed in Real-K will provide users with temperature traceability to the most advanced approaches without any of the disruption caused when new temperature scales were introduced in the past. The ITS-90 remains fit for purpose for at least the coming decade and currently there are no significant groups of users requiring a new temperature scale. Those requiring thermodynamic temperatures from the ITS-90 values can derive it from the published consensus T-T_{90} data [24]. Over the next decade, it is envisaged that the traceability route for temperature will slowly change from defined scales to direct linkage to the redefined kelvin by practical primary thermometry, though there may still be a need for a range restricted ITS-XX in the future.

2. The kelvin redefinition and the *mise en pratique* for the definition of the kelvin

The redefinition of the SI [3,25] in terms of fundamental constants was the culmination of>10 years cooperative activity within the international metrology community. For the temperature unit, the kelvin, a fixed value of the Boltzmann constant k, was used as the basis of the redefinition [1,2,26]. The definition of the kelvin now reads:

> "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, which is equal to kg m2/s^{-2}(−|-) K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$."[1]

More details about the kelvin definition as well as the other units can be found in the 9th edition of the SI brochure [3].

Accompanying the redefinition was the *mise en pratique* for the definition of the kelvin (*MeP*-K-19) [6–8]. The role of the *mise en pratique* is to guide the user from the kelvin definition based on k to a practical realization of the unit. As such the *MeP*-K plays a critical role in the realisation and dissemination of temperature in the post redefinition era. It contains the following: the definition of the kelvin, the definition of terms related to primary thermometry,[2] criteria for inclusion of a thermodynamic method, outlines of CCT endorsed primary thermometry methods for realizing the kelvin based on fundamental laws of physics (which are currently Acoustic gas thermometry [27], Radiometry [28], Dielectric Constant Gas Thermometry [29], Refractive Index Gas Thermometry [30], Johnson Noise Thermometry [31]) and the current defined temperature scales: ITS-90 and PLTS-2000.

In addition, there is supplementary material such as consensus values of T-T_{90} and T-T_{2000} and agreed thermodynamic temperatures for high temperature fixed points.

At the time of the kelvin redefinition the documentary framework was in place to ensure that the thermometry community could take profit from the redefinition by encouraging direct traceability to the redefined kelvin through promoting mature thermodynamic thermometry approaches for temperature realisation and dissemination instead of the defined scales. This was the intent of the CCT recommendation T1 (2017) [32] which, besides recommending the CIPM proceeds with the kelvin redefinition founded on a defined value of the Boltzmann constant also stated, "that Member State NMIs (National Measurement Institutes) take full advantage of the opportunities for the realization and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the *mise en pratique* for the definition of the kelvin.".

Concurrent to the work to determine the Boltzmann constant, new primary thermometry approaches were being developed to ensure a successful redefinition of the kelvin [33–35]. That work has continued through Real-K [9] whose objectives are; to establish temperature traceability by primary thermometry at high (>1300 K) and low (<25 K) temperatures, ensure that the ITS-90 remains fit-for-purpose for the coming decade and to calculate the required thermophysical properties of gases, confirmed by selected measurement, to facilitate gas based primary thermometry for temperature realisation and dissemination in the future.

3. Progress in realising the redefined kelvin

3.1. Realisation and dissemination of the kelvin above 1300 K

The *MeP*-K-19 recommended approaches to realise and disseminate the kelvin at high temperatures [11] are: a) indirect primary radiation thermometry (or radiometry), b) direct thermodynamic temperature measurement by primary radiometry (which is much more time-consuming and complicated than the former), and c) ITS-90, which requires extrapolation from a fixed-point blackbody of Ag, Au or Cu which can lead to large uncertainties at the highest temperatures.

Here we report on progress towards using indirect primary radiometry based on high-temperature fixed points (HTFPs) [10]. This approach is expected to have competitive uncertainties compared to ITS-90 above 1300 K and will facilitate direct linkage to the kelvin definition. This work builds on earlier work where low uncertainty values for the HTFPs of Co-C (~1597 K), Pt-C (~2011 K) and re-C (~2747 K) were determined [34,36,37].

To expand the temperature range required for implementing the *MeP*-K-19 above 1300 K by indirect primary radiometry additional HTFPs beyond Co-C, Pt-C and re-C are needed. The following four will have low uncertainty thermodynamic temperatures determined; Fe-C (~1426 K), Pd-C (~1765 K), Ru-C (~2227 K) and WC-C (~3020 K). The fixed points have been constructed; a typical furnace used for filling HTFPs is shown in Fig. 1a, whilst the design of the HTFP is shown in Fig. 1b. The piston filling method [38] in vertical furnaces was followed

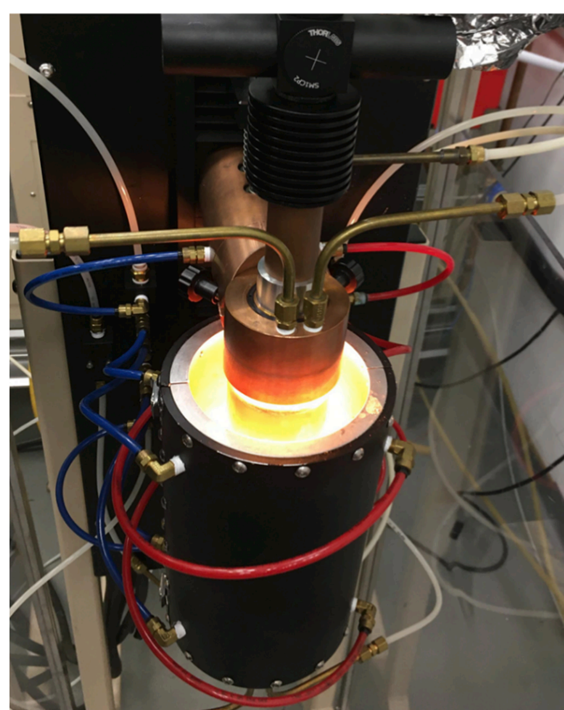

Fig. 1a. Crucible filling furnace at NPL.

[1] h is the Planck constant, value 6.626 070 15 $\times$ 10^{-34} J s, c is the speed of light in a vacuum, value 299792458 m/s and $\Delta\nu_{Cs}$ is the hyperfine transition frequency of Cs namely 9,192,631,770 Hz.

[2] Of particular importance are the two terms "Absolute primary thermometry" where no fixed points are used, and "Relative primary thermometry" where one or more fixed point with an explicit thermodynamic temperature T is used.

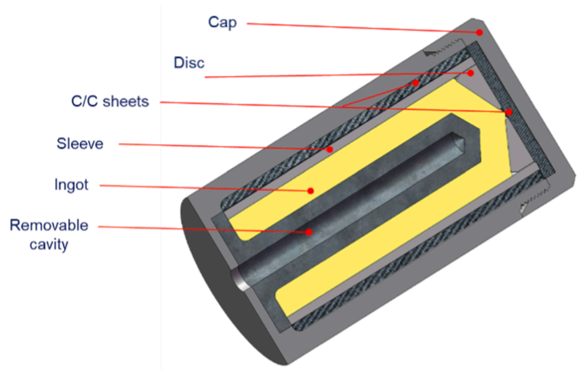

Fig. 1b. Current design of the cells developed at LNE-Cnam.

as this facilitates rapid and complete crucible filling, producing a high-quality ingot and so minimising the sensitivity of the HTFP melting temperature to the temperature steps used for the initiation of the melt [38]. Table 1 shows the cells which have been constructed and by which institute.

To construct the best possible HTFPs, high-purity materials (ideally with a nominal purity of the metal > 99.999 %) are essential to achieve the highest melting temperatures and the smallest melting ranges which are the relevant criteria for the selection of the best cells [39]. Unfortunately, it was not possible to obtain this level of purity for all the materials used in the construction of the Fe-C and the Pd-C cells so the highest available purity was used instead.

The characterisation of the cells has shown the importance of the metal purity. The melting ranges obtained with the Fe-C cells ranged from 180 mK to 320 mK which is much larger than what is readily achievable with the best Co-C cells for instance, which are at the level of 70–80 mK [39]. The purity of the iron used in the construction of these cells was reported to be around 99.99 %, as was the purity for the palladium used here.

The thermal conditions within the furnace are known to affect the performance of the HTFPs [40]. The assessment of these "thermal effects" has been performed in graphite-heater high temperature furnaces and also in three-zone furnaces which allow for close control of the temperature gradient around the HTFP cell up to 1500 °C. This characterisation has been performed at INRIM on Fe-C and Pd-C in a tuneable three-zone furnace and it is planned to perform similar studies on other cells at CMI[3] and TUBITAK-UME[4]. The INRIM results shown in Fig. 2a and 2b below prove, for Fe-C for instance, that with temperature gradients of + 10 K (front of the HTFP hotter than the bottom by 10 K), 0 K (no gradient across cell) and –10 K (bottom of the HTFP hotter than the front by 10 K) the quality of the plateaux, especially the melt run-off, is only affected when the bottom of the cell is hotter that the front.

The next steps will be a) to determine the thermodynamic temperature of the best cells and b) to undertake a dissemination trial using the HTFPs involving industry and other NMIs.

The expected outcome of this work will be to put in place a practical way of realising and disseminating thermodynamic temperature from 1300 K to above 3000 K with uncertainties at the same level as the best realisations of the ITS-90. The availability of several HTFPs of assigned thermodynamic temperature will greatly simplify the realisation and dissemination of high temperatures compared to the current ITS-90 approach. For example, it will be possible to interpolate between the HTFP temperatures with reduced necessity of accurate characterisation of the spectral responsivity of the radiation thermometers. The envisaged dissemination trials will confirm the utility of the *MeP*-K-19 approach of disseminating thermodynamic temperature to users with low uncertainties and increased reliability compared to the current ITS-90.

Table 1
HTFPs constructed for selection and thermodynamic temperature assignment.

HTFP	Institute constructing HTFP blackbody cells, and number of cells					
	CEM[a]	LNE-Cnam	NIM[a]	NMIJ[a]	NPL	PTB	VNIIOFI[a]
Fe-C	4	2				2	
Pd-C	3		3	1			
Ru-C				1	2		2
WC-C		5			2		

[a] CEM = Centro Español de Metrología, Madrid; NIM = National Institute of Metrology, Beijing, China; NMIJ = National Measurement Institute of Japan, Tsukuba, Japan; VNIIOFI = All-Russian Research Institute for Optical and Physical Measurements, Moscow, Russia.

3.2. *Realisation and dissemination of the kelvin below 25 K*

Currently, traceable temperature measurements below 25 K require reference to the international temperature scales ITS-90 [4] and PLTS-2000 [5]. Both scales are based on quite different and elaborate experimental methods such as interpolating gas thermometry, vapour-pressure thermometry and melting pressure thermometry. Moreover, the definition and application ranges are overlapping causing, for example, type 2 non-uniqueness (using different kinds of thermometer in overlapping ranges) with all its problematic implications.

For the practical realisation of these low temperatures, primary methods are required which can cover large parts of the cryogenic temperature range from 25 K to below 1 K and so bringing together the ITS-90 at low temperatures and the PLTS-2000.

To effect this transformation three methods of primary thermometry, namely Coulomb blockade thermometry (CBT) [12], Johnson noise thermometry (JNT) [13], and low-temperature acoustic gas thermometry (AGT) [14] are being developed respectively by Aalto University/VTT-MIKES,[4] PTB, and LNE-Cnam. All these methods have already found numerous applications and reached a mature stage of development in temperature metrology. The aim here is to provide users with practical primary thermometers for the realisation and dissemination of thermodynamic temperature below 25 K. This includes the development of user-friendly thermometers as well as a rigorous validation of the approach including an uncertainty budget.

The CBT and JNT are primary thermometric methods for which full functionality and agreement with the international temperature scales has already been demonstrated in the temperature range below 1 K [15]. However, applying these methods above 1 K poses new technological challenges.

The primary Magnetic Field Fluctuation Thermometer (pMFFT) [13] is a dc SQUID based Johnson noise thermometer. PTB has built a new single-chip pMFFT based on a redesigned layout of the detection and calibration coils, where both coil sets are now located on a single silicon chip instead of two. The full functionality comprising the calibration of the SQUID channels and the *in-situ* measurement of the electrical conductivity is maintained without adding non-thermal noise to the evaluated signal through use of the cross-correlation technique and a fully (anti-)symmetric coil configuration. A reduction by a factor of approximately-two is expected for the uncertainty of the temperature measurement compared to earlier devices. In addition, an extended theory has been developed for more reliable temperature determination from cross-correlation spectra of the pMFFT.

CBTs [12] are typically operated in a weak Coulomb blockade regime, where the single electron charging energy E_C is much less than

[3] CMI = Czech Metrology Institute, Prague, Czech Republic, TUBITAK-UME = Turkish National Measurement Institute, Gebze/Kocaeli, Turkey.

[4] VTT-MIKES is the Finnish National Measurement Institute.

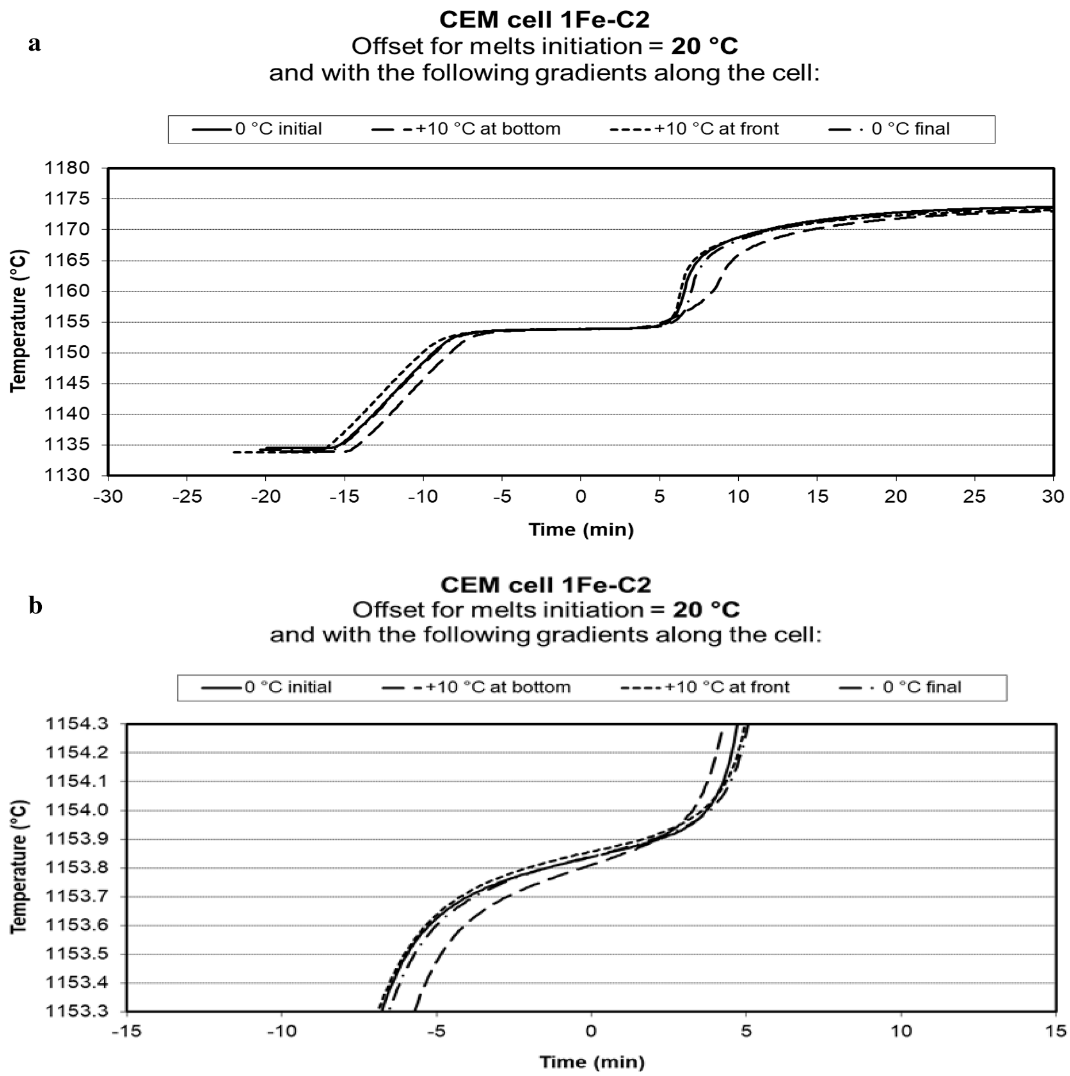

Fig. 2. The effect of a temperature gradient on the melting plateau of an Fe-C cell. a) view showing the deteriorating run-off when the front of the cell is colder than the bottom b) focussed view showing that in this case the melting temperature is also lower than when the temperature is uniform or when the front is hotter than the bottom.

the thermal energy, $E_C \ll kT$. The optimal temperature range for a given CBT can be tailored by appropriately designing the dimensions of the tunnel structures. Therefore, arrays of tunnel structures with extremely small dimensions are required to extend the working range to temperatures up to 25 K. To this end a Ge nanofabrication process for fabricating CBTs with sub-100 nm aluminium tunnel junctions has been established. The first low-temperature characterization measurements of full CBT sensors have been performed and the device parameters appear well-suited for 1 K to 25 K operation.

The capability for the application of the pMFFT and CBT as practical primary thermometers will be tested by comparison against dielectric constant gas thermometry [29] or acoustic gas thermometry [27]. In addition, the realisation of the triple point of Ne at 24.5561 K as well as the lambda transition in superfluid ^{4}He at 2.1768 K will be investigated as reference points for relative primary thermometry. For the Ne point a new determination of thermodynamic temperature was conducted by acoustic gas thermometry (AGT) [41]. Also, a fast, acoustic gas thermometer ("fast-AGT") is being developed for the range from 4 K to 25 K making feasible the application of AGT in practical primary thermometry. In a first step, the performance of a single-pressure refractive-index gas thermometry (SPRIGT) was demonstrated to be comparable to that of other primary gas thermometers at low temperatures [14].

At the final stage of the project the aim is to demonstrate dissemination of thermodynamic temperatures by the developed practical primary thermometers, and hence confirm the validity of the approach. The aim is to include measurements at facilities by industry stakeholders, for instance Entropy GmbH [42] or Bluefors [43], which are established suppliers of cryogenic equipment.

3.3. Extending the life of the international temperature scale of 1990

The current main temperature scale in use around the world is the ITS-90 [4]. It has been in place since 1990 and has served the global temperature measurement community well, providing reliable, low uncertainty traceability for over 30 years. However, there are a number of potentially life-limiting issues for the ITS-90, chief among these are; the impact of the main types (1 and 3) of non-uniqueness which currently limit the uncertainties possible by the ITS-90 [44–48], and the need to identify a possible alternative to the mercury triple point (a key fixed point of the ITS-90) whose use could be banned by an international treaty,[5] potentially posing an existential threat to the ITS-90.

Type 1 non-uniqueness is associated with the difference between the interpolations over different, overlapping ITS-90 sub-ranges for the same SPRT [44–46]; there is currently a paucity of reliable data for the assessment of the uncertainty arising from this effect. Type 3 non-uniqueness arises from the difference between individual SPRTs over the same sub-range [47] because of the differences in their resistance characteristics. Here too there is a paucity of reliable data, particularly between −189 °C and 156 °C.

The three main candidates for replacing the mercury point (-38.8344 °C) are the triple points of Xe (~-111.744 °C) [49], CO_2 (~-56.558 °C) [19] and SF_6 (~-49.595 °C) [50]. Investigations so far have mainly been for capsule SPRTs, which is a significant limitation as nearly all commercial calibrations are for long-stem SPRTs.

The research described here addresses these problems through:

- A comprehensive evaluation of Type 1 non-uniqueness, performed for the first time on a large number of SPRTs;
- New determinations of Type 3 non-uniqueness have been undertaken in the range –189 °C to 156 °C;
- New designs of CO_2 and SF_6 cells for use with long-stem SPRTs. These have been improved by using purer gases and more stable and uniform temperature-controlled baths, and by the development of a flexible set-up that can accommodate both capsule and long-stem SPRTs. The effect of replacing mercury on the ITS-90 interpolating equations and uncertainty propagation is also being investigated.

There are two important supplementary reasons why the ITS-90 life needs to be extended. Firstly, to give time for primary thermometry approaches to mature (particularly ones which could supersede ITS-90) and, secondly, to prevent the premature introduction of a new temperature scale until sufficient research has been performed to clearly demonstrate whether a new scale is needed or not.

3.3.1. Reducing the ITS-90 non-uniqueness uncertainty

3.3.1.1. Type 3 non-uniqueness. NPL, CEM and INTiBS[6] have performed comparison measurements on cohorts of up to ten long-stem SPRTs of different manufacture and design. Each cohort comprised at least six locally-maintained SPRTs, and two SPRTs which were circulated amongst the participants, to provide linkage between the three local investigations.

The NPL comparisons were carried out in a stirred silicone oil bath at 10 temperatures between −95 °C and 30 °C. The comparisons were made by measuring the ratios R_x/R_{ref}, where R_{ref} is the resistance of an SPRT chosen as the reference, and the R_x ($x = 2$ to 8) are the resistances of the other 7. As the SPRTs have very similar characteristics, these ratios are all close to 1 and are not sensitive to (uniform) changes in the bath temperature. Self-heating corrections were applied.

Similar comparisons have been made at CEM at 18 temperatures between 0 °C and 80 °C, coupled with In fixed-point measurements at 156 °C. Comparisons at INTiBS in the range from 0 °C down to −189 °C, using a temperature-controlled cryostat, are still in progress.

The upper graph in Fig. 3, from NPL, shows the apparent non-uniqueness for the 8 SPRTs in the range from the argon point to 0 °C, and from 0 °C to 30 °C. According to the ITS-90 this temperature range requires measurements at the triple points of argon, mercury and water, and at the melting point of gallium. However, the analysis used the *comparison* results at the approximate fixed-point temperatures (except

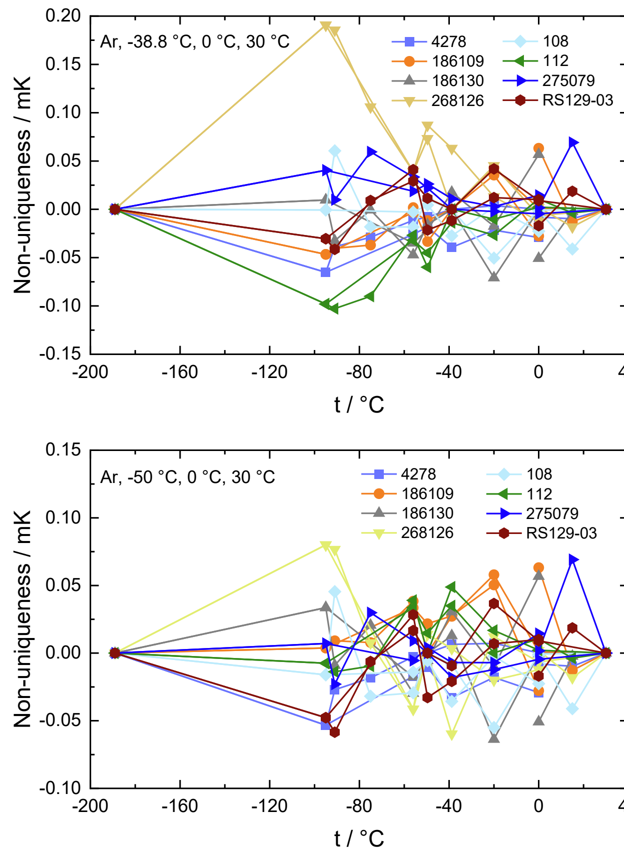

Fig. 3. Interpolations between the triple-points of argon and water using the comparisons at −38.8 °C (above), and with the 'mercury' point replaced by the 'SF_6' point (~-50 °C, below). Similar results are obtained using the 'CO_2' point at −56 °C or the point at −95 °C (about 17 °C above the Xe point).

at the argon point, which is below the range of the comparisons): the interpolations are not sensitive to the exact 'fixed-point' temperatures, and it would not have been possible to achieve the same consistency of the data if real fixed-point data had been incorporated into the experiment.

The figure shows that, with the exception of one SPRT, the Type 3 non-uniqueness (the dispersion of the results for the SPRTs) is within ± 0.1 mK, which is significantly better than has been achieved before. Even so, this must still be regarded as an upper limit because the differences are compounded by the measurement precision as well as real non-uniqueness. Note that the main measurements were made on cooling, but repeat measurements were made on warming, at −56 °C, −50 °C, −38.8 °C, and at 0 °C. These showed that the repeatability was generally very good, though the interpolation of SPRT 268,126 was significantly affected by an error propagated from −38.8 °C.

The lower graph in Fig. 3 shows the results when the 'mercury' point is replaced with the 'SF6′ point. The data are even more tightly grouped (the 'errant' measurement at −38.8 °C is no longer propagated). Similar results are obtained if the interpolation uses the point at −56 °C, or at −95 °C (the lowest comparison temperature, ~17 °C above the Xe point). The conclusion is that any of these points could replace the mercury point: the realisation uncertainties would be somewhat larger, but the uncertainties of their propagation would be lower [45,51].

3.3.1.2. Type 1 non-uniqueness. A wide-ranging study of Type 1 non-uniqueness (Subrange inconsistency, SRI) has already been conducted and published by NRC, NPL and UL [44] as part of the Real-K project. The study drew on a wide range of data from the EURAMET.T-K9 and CCT-K9 comparisons of SPRTs at the ITS-90 fixed points. In addition,

[5] The use of mercury, even for scientific purposes, could be severely restricted or even banned by international convention (UN Minamata Convention on Mercury which introduces controls over a myriad of products containing mercury).

[6] INTiBS = Instytut Niskich Temperatur I Badan Strukturalnych etc, Poland.

NPL, PTB, NRC and other NMIs provided data from their commercial calibration databases. A comprehensive evaluation of Type 1 non-uniqueness was performed for all pairs of overlapping ITS-90 sub-ranges between −189.3442 °C (Ar) and 660.323 °C (Al). The SPRTs were representative of manufacturers across the globe. Across all the pairs of overlapping sub-ranges, the mean SRI varied from −1.23 mK to + 0.21 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. To determine the significance of the SRI determinations, the contribution from the uncertainties propagated from the fixed points were also assessed, 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 the SRI is probably substantially overestimated, since it is convolved with the measurement uncertainty at the fixed points and propagation thereof. The study [44] will help to reduce the uncertainty of Type 1 non-uniqueness since it provides a characterisation of this phenomenon over all ITS-90 subranges with an unprecedentedly large and diverse sample of SPRTs[7] drawn from a global dataset, including CCT and regional metrology organisation (RMO) key comparison data and commercial calibration data from several leading NMIs.

Table 2 shows a comparison of the statistical parameters obtained in the current work [44] to those reported in the literature, for the overlapping sub-ranges from the triple point of water (TPW) to Zn and TPW to Al. All values are in units of mK.

3.3.2. Replacing the mercury fixed point with alternative fixed points

LNE-Cnam have manufactured three new SF_6 triple point cells, and also constructed a quasi-adiabatic calorimeter to realise them; this system permits simultaneous calibration of both long-stem and capsule SPRTs (Fig. 4). TUBITAK have manufactured two new CO_2 triple point cells to be realised in a stirred ethanol bath (Fig. 4). Chemical analysis was performed on samples of the gases used to fill the respective cells (gas chromatography with discharge ionisation detector, GC-DID, was used for the CO_2). All cells are currently undergoing metrological characterisation, with particular attention to the plateau temperature range and reproducibility. In addition, LNE/Cnam will characterise the solid–liquid transition of the SF_6 cells with both long-stem and capsule SPRTs, verify the equivalence between the quasi-adiabatic and fully adiabatic realisations (the thermal environment has been reported as being a major contribution to the measurement uncertainty), and determine the thermodynamic temperature of the triple point of the SF_6 cells with capsule SPRTs calibrated against an acoustic gas thermometer.

SMU and NPL are currently investigating how the fixed-point uncertainty propagates in the different ITS-90 sub-ranges when mercury is replaced with either SF_6 or CO_2, or simply eliminated altogether. NPL is also investigating alternative interpolations for long-stem SPRTs in which the range is extended below the triple point of water without including the mercury fixed point.

Table 2
Comparison of statistical parameters obtained in the current work, and in the literature.

Author	No. SPRTs	Min	Max	Mean	Standard deviation
This work [44]	15	−0.47	0.70	0.04	0.30
Strouse [52]	13	−0.27	0.40	–	–
Zhiru [53]	58	−0.89	1.00	0.06	0.32
White [46]	60	−0.80	1.70	0.12	0.48
Sun [54]	60	−1.58	0.96	0.20	0.37
Rusby [55]	159	−1.3	1.2	−0.12	0.41

3.4. Facilitating full range gas based primary thermometry

A key feature of the redefinition of the kelvin is the impact it has on temperature traceability. Prior to the redefinition, traceability was almost exclusively attended through of one of the defined scales (ITS-90 or PLTS-2000). However, after the redefinition a more nuanced approach to temperature traceability has been encouraged. The defined scales can still be used but primary thermometry can alternatively be used provided it is by a means authorised through the *MeP*-K-19. This more flexible approach gives the user access to the most up to date primary thermometry methods for achieving temperature traceability and may in the longer-term lead to lower uncertainties than are currently obtainable through the defined scales.

For high temperatures this is discussed in Section 3.1 above, but for lower temperatures (above around 5 K) gas-based thermometers are the most promising primary thermometry approaches to facilitate traceability directly to the redefined kelvin. Within the (*MeP*-K-19) [7,8] three approaches are mandated having the necessary thermodynamic characteristics and required accuracy below 1300 K, these are: Acoustic Gas Thermometry (AGT) [27], Dielectric Constant Gas Thermometry (DCGT) [29] and Refractive Index Gas Thermometry (RIGT) [30].

Before 2019, extremely refined realizations of these methods were used at 273.16 K, or over restricted temperature ranges, to determine the Boltzmann constant with ultra-low uncertainty for the new definition of the kelvin. Building on that activity so as to make gas-based primary thermometry accessible for temperature traceability requires extending the working temperature range of these approaches while maintaining or even further improving their accuracy. The latter is necessary so that they become competitive compared to the realization uncertainty of the ITS-90.

One of the major issues preventing the more routine deployment of gas-based primary thermometry for traceability purposes is that the thermodynamic properties of monatomic gases like helium, neon and argon, which are generally used in primary thermometry, are not known with sufficiently low uncertainty. But such data is essential to account for the non-ideality of the gases at the experimental thermodynamic conditions. These gaseous properties in the main are density and acoustic virial coefficients, thermal conductivity, and viscosity. However, to measure them with sufficiently low uncertainty to facilitate practical primary thermometry over the wide range of pressures and temperatures required would be a massive undertaking. So, the aim here is to calculate their values from first physical principles and to measure a limited sub-set of values by experiment to confirm the modelling values.

Very significant progress in this area of theoretical chemistry has been made during the last 20 years. Indeed, several remarkable advances have already been achieved. These include for helium: a fivefold reduction of the second density and acoustic virial coefficients [56] and a path integral calculation of the 4th density virial coefficient [57]. In addition, and despite the increasing theoretical and computational effort required to model gases with many more electrons than He, significant progress has recently been achieved for Ne [58]. Also, *ab initio* calculation of electromagnetic properties of monatomic gases, like polarizabilities and dielectric virials, which are essential for the deployment of DCGT and RIGT, have been significantly improved [59–62].

Several experimental determinations of thermodynamic properties are in progress, either focused on determining the properties themselves or incidentally as part of another experiment. Determination of low uncertainty values of the third and fourth order acoustic virial coefficients of Ne are underway between 100 K and 430 K for pressures up to 100 MPa at the Helmut Schmidt University (HSU). But in most other cases, thermodynamic properties like density, acoustic and dielectric virials are obtained as an important additional outcome from AGT,

[7] Data used in previous studies have mostly been on a regional basis.

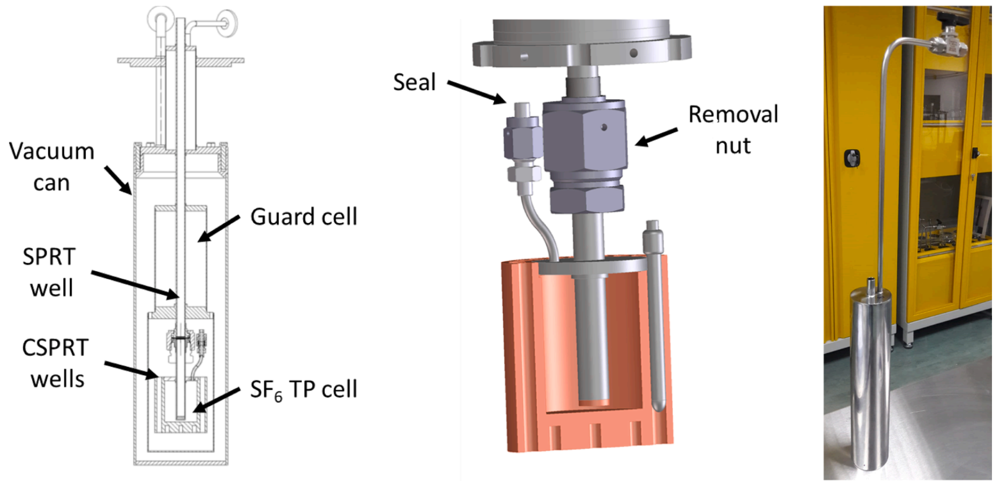

Fig. 4. Left: Calorimeter for simultaneous calibration of long-stem and capsule SPRTs developed at LNE-Cnam. Centre: SF_6 triple point cell of LNE-Cnam. Right: CO_2 cell of TUBITAK/UME.

DCGT and RIGT primary thermometry experiments. These thermometers are being continuously improved to increase their accuracy in the determination of thermodynamic temperature *T*, and their results and methods are cross checked by mutual comparisons of the differences $T - T_{90}$ [63]. Recent such determinations include: the AGT result obtained at LNE-Cnam at 25 K [41] which served as a thermodynamic temperature reference for single-pressure RIGT between 5 K and 25 K at TIPC-CAS [57]; the RIGT results obtained between 14 K and 161 K at NRC and INRiM [49,64] and the DCGT results obtained at PTB between 4 K and 200 K [63,65].

With minor exceptions, the thermodynamic properties which are derived from these experiments show remarkable consistency with the available theoretical estimates. The quality of the agreement suggests that a revised consensus estimate of the differences $T - T_{90}$ below 300 K might soon become available and will significantly improve with respect to the 2011 estimation [24]. Also, recent determinations of thermodynamic temperature by these gas-based approaches indicate that the realization uncertainty and the repeatability of such approaches is superior with respect to that of T_{90} at least for the range below 25 K. Indeed, the possibility that the temperature range where the calibration uncertainty of *T* will be less than that of T_{90} may be significantly extended on the time scale of the next few years, as results such as [21] indicate. This bodes well for using gas-based primary thermometry for traceability up to at least 300 K in the medium term.

4. Future temperature realisation and dissemination

By the end of the Real-K project [9] in Spring 2023 significant progress will have been made towards establishing primary thermometry as a means for delivering temperature traceability over parts of the temperature scale. Above the silver point relative primary thermometry (radiometry) will have been firmly established as a realistic competing approach for delivering temperature traceability compared to the ITS-90. It is envisaged that use of ITS-90 above the silver point will decline in the latter half of this decade as an increasing number of NMIs, and indeed a number of high level calibration laboratories, will use the relative primary radiometry approach. Below 25 K it will have been shown that primary thermometry approaches based on Johnson Noise and Coulomb Blockade could work in tandem to provide a realistic alternative to the complex current arrangements of obtaining traceability by the ITS-90 and PLTS-2000.

Gas-based primary thermometry approaches may well have demonstrated the feasibility of delivering temperature traceability up to around 300 K with the possibility of extending to higher temperatures in the future. However, extension to high temperatures by gas-based approaches will be challenging, and progress may slow or even stall as the technological and engineering challenges in attaining the required uncertainties grow.

So, whilst it seems clear that primary thermometry to around 300 K can be superior to ITS-90 in terms of uncertainty [20,21], time will tell if expansion to the higher temperature regime is even possible. An alternative and entirely realistic scenario is that primary thermometry will provide traceability around 300 K and below, and above the silver freeing point (or possibly aluminium freezing point), but a range-restricted temperature scale (the so-called International Temperature Scale of XX (ITS-XX) [1,66]) may be needed to fill the gap.

So currently there is no need to decide which is the best approach for temperature traceability in the coming decade (or even two). There are currently no groups of users requiring better uncertainties or even better thermodynamic consistency of the current scale, whilst any requiring access to thermodynamic values from ITS-90 temperatures can get these from the published T-T_{90} values.

This means the community has time to work on all these approaches and debate which is most appropriate for the user community. If a future scale is required much of the framework is in place to facilitate its introduction [67]. However, it must be kept in mind that the potential cost of introducing a new scale needs to be seriously considered, as does the potential disruption to users. This point is made clear in the CCT Strategy 2021–2030+ [68] where it states a CCT review in the period 2027–2030 will be performed; "… into on-going relevance of current temperature scales PLTS-2000 and ITS-90 and examining the requirement for ITS-XX, review to encompass stakeholder needs, cost of implementation and need".

Much of the discussion above focuses on the provision of temperature traceability obtained by traditional means, that of calibrating a reference sensor at a single point of reference (i.e. the National Measurement Institute or accredited laboratory) which is then used to calibrate working standards and ultimately sensors in use. However, the kelvin redefinition has opened the possibility of practical primary thermometry that could well lead to *in-situ* traceability at the point of measurement. Such an approach will be needed to make autonomous production truly a reality. Such approaches could be through practical Johnson Noise Thermometry (where practical demonstrator devices already exist) [69,70] and in the longer-term small-scale Doppler Broadening Thermometry [71,72] as well as other photonic based approaches [73].

The potential disruption to the traditional approach to traceability of being an unbroken chain of measurements to a national reference raises important questions about how, if *in-situ* traceability becomes a reality, it will be regulated and demonstrated in the future. The CCT is in the process of establishing a task group on how to respond to this challenge in the future so as to ensure it is able to support users into the 2030 s, assuring on-going reliability of thermometry for the foreseeable future.

5. Summary

The redefinition of the kelvin has led to significant research activity around the world in seeking to deliver traceability and dissemination of temperature by primary approaches. By the middle of the 2020 s it is clear that the current ITS-90 will be increasingly supplanted at high temperatures by indirect primary radiometry, whilst in the later parts of the decade the lower part of the scale (<25 K) and PLTS-2000 could well be challenged by more practical approaches to low temperature primary thermometry. Gas-based primary thermometry will increasingly take on the role of providing traceability between these two extremes, but it is entirely possible that a range restricted ITS-XX will be needed in the mid-temperature range.

However, in the very long term (2030 s and beyond) it is possible that there will be a rise in practical primary thermometry with the capability of delivering *in-situ* traceability. If this is the case then the long term goal of linking practical temperature measurement directly to the redefined kelvin will have been achieved.

CRediT authorship contribution statement

G. Machin: Conceptualization, Funding acquisition, Writing – original draft. **M. Sadli:** Investigation, Methodology, Writing – review & editing. **J. Pearce:** Investigation, Methodology, Writing – review & editing. **J. Engert:** Investigation, Methodology, Writing – review & editing. **R.M. Gavioso:** Investigation, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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