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Dissemination of thermodynamic temperature by gas thermometry below 300 K

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The redefinition of the kelvin motivates the realization of thermodynamic temperature standards and their improvement up to the stage where they become sufficiently accurate, reliable and practically useful for the purpose of disseminating the unit by direct calibration of temperature sensors. We review progress milestones in the development of gas-based primary thermometry methods, assess their current state of the art and discuss the remaining challenges and the perspectives of using thermodynamic methods as an alternative to traditional dissemination based on the realization of the International Temperature Scale. We give an account of research initiatives which are underway to test the maturity of this perspective, including an international blind comparison of thermodynamic calibrations of capsule-type resistance thermometers using different methods of primary gas thermometry in the range 4 to 300 K.

This article is part of the Theo Murphy meeting issue 'The redefined kelvin: progress and prospects'.

1. Introduction

Back in 1999, presenting accurate determinations of thermodynamic temperature using acoustic gas thermometry (AGT), Moldover *et al.* [1] commented that their method: '[...] could be used to calibrate thermometers on the Kelvin thermodynamic scale and, ultimately, this may become accepted practice'. In this work, 25 years later, we argue that the current state of the art of primary thermometry is plausibly mature, at least in the temperature range below 300 K, for Moldover's forecast to become a reality. The conditions which support such a statement can be summarized as follows. In the first place, a new definition of the kelvin was adopted in 2019 [2]. The definition, being based on the attribution of an exact value to the Boltzmann constant *k*, no longer specifies which method should be used in the future for its realization, nor does it define any special temperature or thermodynamic state—e.g. 273.16 K for the triple point of water (TPW)—as a required reference for comparison. Thus, any well-understood and sufficiently accurate thermometry method can be used for the realization of a primary standard, and there are no limits or mandatory prescriptions with regard to the temperature range of its operation. Second, the accuracy that can currently be achieved in the determination of thermodynamic temperature has become comparable or even competitive with the accuracy with which the International Temperature Scale, currently ITS-90 or T_{90} [3], can be realized. We review the research work leading to this progress in the following section. Realization of ITS-90 may still be superior at a discrete number of special temperatures, which correspond to the defining fixed points and particularly at the TPW [4], but the accuracy of thermodynamic methods is smoothly maintained over wide continuous temperature ranges, allowing for custom calibration procedures that may significantly reduce or, depending on a sufficient number of calibration points, even eliminate the contribution of non-uniqueness [5] uncertainties. Finally, the costs and benefits of the alternative dissemination of either the thermodynamic scale or ITS-90 must also be considered in terms of the time and complication required by calibration practice. In these terms, it appears today that thermodynamic methods may be competitive in the lower temperature range, particularly below the Ar point and down to 4 K, where the realization of ITS-90 is cumbersome and time-consuming. We compare the advantages and drawbacks of realizing and disseminating T as an alternative to T_{90} in the central section of this work, along with some considerations regarding ITS-90. In this context, a revised consensus estimate [6] of the differences ($T - T_{90}$) between the thermodynamic temperature T and its approximation T_{90} has become available in 2022 with substantially reduced uncertainty (by a factor of 3 to 10) compared to 2011 [7] (figure 1), suggesting that calibration results obtained by realizing T or T_{90} are now interchangeable with low additional uncertainty. With these premises, the timeliness and usefulness of an international comparison of thermodynamic temperature realization and dissemination capabilities are evident. By the time of writing, one such trial is ongoing in the form of a 3-year research project [8], which will be completed in 2026. The main technical activities and objectives of this project are briefly summarized in the concluding section.

(a) Progress of gas-based thermodynamic temperature standards

While the definition of the kelvin does not entail any particular experimental method for its realization, so does instead the *mise en pratique* for the definition of the kelvin in the SI (*MeP*-K) [9], prepared and periodically updated by the Consultative Committee for Thermometry (CCT) of the International Committee for Weights and Measures. There, a list is presented of the primary methods which are officially recognized, being characterized by a complete and sufficiently small uncertainty budget, directly traceable in terms of SI units, thus not requiring a reference standard to be implemented. The list currently includes three gas-based methods, namely, AGT, dielectric constant gas thermometry (DCGT) and refractive index gas thermometry (RIGT), with DCGT and RIGT discussed as alternative versions of a category collectively referred to as polarizing gas thermometry. The list also includes two methods based on Nyquist's and Planck's laws, namely, Johnson noise thermometry and radiometric thermometry, respectively. Reviews discussing the state of the art of Johnson noise thermometry in terms of achievable uncertainty in different temperature ranges and realization techniques

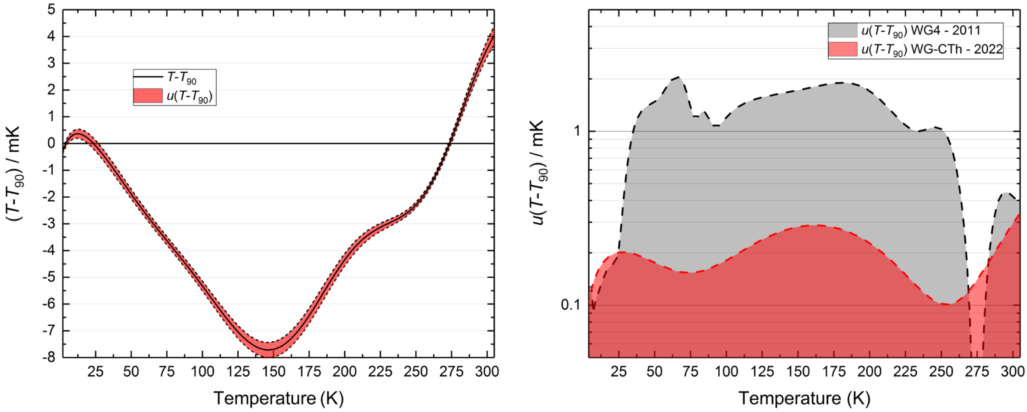

Figure 1. Left: 2022 Consensus estimate [6] of the differences $(T - T_{90})$ between the thermodynamic temperature T and its approximation T_{90}. Right: Comparison of standard uncertainties of 2011 [7] and 2022 estimates of $(T - T_{90})$ differences.

can be found in [10,11]. Realization guidelines and discussions about achievable uncertainty with radiometric thermometry can be found in [12,13].

Gas-based thermometry methods have indeed provided a major contribution towards a direct realization of the kelvin in the temperature range (less than 300 K) of interest here, with an impressive reduction of uncertainty over the last 25 years and an increasingly wider diffusion, with ongoing realizations at several National Metrological Institutes (NMIs). A summarized account of this progress, as well as the implications for primary thermometry, is the object of this section.

Considering AGT first, the simplicity of the relation between the speed of sound w and thermodynamic temperature T,

$$w_0^2(T) = \frac{5}{3}\frac{kT}{m} = \frac{5}{3}\frac{RT}{M}, \tag{1.1}$$

is striking. In equation (1.1), the foot index 0 recalls that equality strictly holds at zero pressure, i.e. for an ideal gas, a condition approached by extremely dilute atomic gases (He, Ar, ...); k and R are the Boltzmann and the gas constants, respectively; m and M are the atomic and molar masses, respectively; γ_0 = 5/3 is the ideal gas heat capacity ratio of an atomic gas. Because the values of k and R are now exactly fixed and the accuracy by which m and M are known only depends on the capability to control the purity of the thermometric gas, equation (1.1) suggests that the accuracy of an acoustic primary thermometer would ultimately be limited by the accuracy of the experiment used for the determination of w. Importantly, because pressure p does not appear in equation (1.1), the acoustic thermometer does not need an accurate determination of this quantity. However, the extreme dilution implied by equation (1.1) does not favour precise acoustics, and work at gas densities on the order of the gas density of ambient air, or higher, is usually required, with corrections needed to account for non-ideality of the gas:

$$w^2(T, p) = \frac{\gamma_0 RT}{M}\left(1 + \beta_a p + \gamma_a p^2 + \backslash\ \ldots \backslash\ \right), \tag{1.2}$$

where the acoustic virial pressure coefficients $\beta_a(T)$, $\gamma_a(T)$, … are functions of the temperature only. Experimentally, this complication is tackled by running the experiment at different pressures along an isotherm and extrapolating the results to zero pressure by a low-order polynomial. On these grounds, the validity of acoustic determinations of thermodynamic temperature was first demonstrated in 1965 at the National Institute for Standards and Technology (NIST), back then the National Bureau of Standards (NBS), by Plumb & Cataland [14], using a variable-length interferometer to establish the (1965) NBS Provisional Temperature

Scale between 2 and 20 K. Because this work marks the origin of modern AGT, a realistic assessment of the uncertainty of this scale would be interesting; unfortunately, the authors made a clear statement only about the achieved precision, in the order of 3 mK; comparison with other temperature scales in use by that time sets an educated guess of the accuracy achieved in [14] somewhere between 5 and 10 mK, relatively in the order of several parts in 10^4 in the explored range. Fourteen years later, in 1979, a variable-path cylindrical interferometer was set up by Colclough *et al.* at the National Physical Laboratory (NPL) and used to measure the squared speed of sound w^2 in Ar at the TPW with 6.1 ppm relative uncertainty [15], leading to the determination of R (in 1985) with 8.4 ppm relative uncertainty upon revision of the molar mass of Ar used in the experiment [16]. While this level of accuracy was already interesting for primary thermometry, an impressive step forward was demonstrated in 1988 by the work of Moldover *et al.* at NIST, using a spherical constant-volume resonator. By this technique, the squared speed of sound in Ar was measured at the TPW, leading to a determination of R and k with 1.8 ppm overall uncertainty [17]. Combined with measurements near 303 K, at the gallium melting point, T could then be determined with 0.5 mK standard uncertainty [18]. By 1999, using a microwave technique to determine the thermal expansion of the cavity, the differences $(T - T_{90})$ between 217 and 303 K were determined at NIST with relative standard uncertainties of 0.6 mK [1]. Two ideas in the work of Moldover *et al.* were seminal to boost the metrological performance of AGT: (i) the use of spherical acoustic constant-volume cavities, which sustain acoustic resonances with quality factors larger by a factor of 10 compared to cylindrical cavities of similar size; (ii) the determination of the cavity volume and thermal expansion using microwave resonances [19], which exploits the exact definition of the speed of light in vacuum, incidentally proving the validity of a system of units based on fundamental constants, as finally agreed upon in 2019 [2]. An additional merit of Moldover *et al.* was the capability to develop both the supporting theory and the experimental techniques at the accuracy level needed to fully exploit these ideas [20]. Further working on these grounds, the uncertainty figures obtained at NIST in 1999 have been today further reduced by approximately a factor of 3, with recent determinations of k accurate down to the level of 0.6 ppm [21] and AGT determinations of $(T - T_{90})$ obtained by several groups over the wide range between 10 and 500 K with standard uncertainties below 0.2 mK [22–27]. A more comprehensive and updated collection of AGT thermometry results is referenced and reviewed in [6].

The basic principle of DCGT is to assume that, in the equation of state, the relative electric permittivity of the gas (dielectric constant) ε_r can be a substitute for density, leading to the following approximation of the Clausius–Mossotti equation:

$$T \approx \frac{3A_\varepsilon}{R}\frac{p}{(\varepsilon_r - 1)}, \tag{1.3}$$

where A_ε is the electric molar polarizability of the gas at zero density. Equation (1.3) shows that, to be used for accurate primary thermometry, DCGT has three requirements: the accurate independent knowledge of A_ε, and the accurate experimental determination of p and ε_r. While the first reported use of DCGT in the range between 2 and 27 K was in 1980 by Gugan & Michel [28] at the NPL, most of the subsequent development of the method is a merit of the Physikalisch-Technische Bundesanstalt, starting in 1996 [29] and culminating in the 2017 determination of k with 1.9 ppm standard relative uncertainty [30]. By then, all three requirements of equation (1.3) had been satisfactorily demonstrated: the molar polarizability A_ε of He having been determined from theory with relative uncertainty below 1 ppm, further reduced to 0.1 ppm in 2020 by Puchalski *et al.* [31]; the pressure balances used for the determination of p characterized at the level of 1 ppm [32]; the capacitors and the instrumentation used to measure capacitance ratios as a function of pressure, leading to experimental determinations of ε_r with uncertainty below 1 ppm [33]. One additional requirement of DCGT is the need for an accurate independent determination of the effective linear isothermal compressibility κ_{eff} of the material comprising the capacitors, to account for their dimensional variation induced by pressure. The adjective 'effective' is used to recall that the compressibility of interest is not a property of the material, but rather of the apparatus (e.g. the capacitor) comprising that material. In a well-designed apparatus, such a distinction is negligible, and accurate estimates of the compressibility can be obtained by resonant ultrasound spectroscopy (RUS) of material samples. In the common case that compressibility data are obtained by RUS over a limited temperature range close to ambient, they can be extrapolated over a wider range (e.g. down to a few kelvins) by suitable methods [34]. Determinations of $(T - T_{90})$ obtained by DCGT over the last 25 years cover the wide temperature range between 2.4 and 200 K [29,33,35,36] with uncertainties of 0.2 and 1 mK at the lower and higher ends of the temperature range, respectively.

The basic principle and the most salient features, requirements and limitations of RIGT for primary thermometry are all similar to those applying to DCGT, once the relative dielectric constant in equation (1.3) is replaced by the refractive index n, defined as

$$n = \sqrt{\varepsilon_r \mu_r} = c_0/c, \tag{1.4}$$

where μ_r is the relative magnetic permeability, and c_0 and c are, respectively, the speed of light in vacuum and in the thermometric gas. For RIGT, A_ε must be replaced by $(A_\varepsilon + A_\mu)$, where A_μ is the magnetic contribution to the molar polarizability. Because most gases are diamagnetic, A_μ is much smaller than A_ε and, for accurate thermometry, A_μ does not have to be known with high accuracy. In spite of the strong theoretical similarity with DCGT, the experimental apparatus used for RIGT is rather different, being based on steady-state methods like fixed-volume resonant cavities and fixed- or variable-pathlength interferometers. A Michelson interferometer was, in fact, first suggested to implement RIGT for the cryogenic temperature range from 2 to 20 K in 1974 by Colclough [37]. Interestingly, since 2007, the same apparatus used for AGT determinations, i.e. a quasi-spherical resonator, showed the capability for accurate RIGT at the TPW [38]. This possibility has been further developed and exploited with several extremely accurate $(T - T_{90})$ determinations reported over the wide range between 5 and 161 K by several NMIs [39–41]. Reviews of the state of the art and the perspectives of RIGT for primary thermometry can be found in [42,43]. More recently, RIGT was also demonstrated at optical frequencies (633 nm), using a Fabry–Perot cavity, to determine $T - T_{90}$ between 293 and 433 K within approximately 3 μK K^{-1} standard uncertainty [44].

As a final remark on polarizing gas thermometry, we note that because equation (1.3) can be made explicit for p instead of T, DCGT and RIGT methods and techniques can alternatively be used as primary pressure standards, exploiting the extremely accurate determination of T which can be achieved, for instance, at the TPW or, for operation of the pressure standard near ambient temperature, exploiting the accurate consensus estimate of $(T - T_{90})$ [6]. This possibility was first suggested and demonstrated in [38,45] and recently used to achieve a standard relative uncertainty of 1 ppm in the determination of p up to 7 MPa [46]. The same equation (1.3) shows that when using state-of-the-art calibrated thermometers and pressure transducers, accurate determinations of the molar electrical polarizability A_ε can be obtained and, in fact, our best knowledge of this quantity for Ne and Ar was obtained by DCGT [47]. The same concept can be applied to AGT, using equation (1.2), for the determination of the acoustic virial coefficient of monatomic gases, e.g. for Ne [48]. Obviously, these possibilities are of interest for gases other than He, where the accuracy achieved by theoretical calculations of thermodynamic and electromagnetic properties, usually called *ab initio* or 'first-principles' calculations, is by far superior to the uncertainty of any experimental method.

The state of the art and the importance of *ab initio* calculations for fluid metrology have been recently reviewed [49] and outline truly outstanding progress in the reduction of the associated uncertainty. Calculated thermodynamic properties of interest for AGT, DCGT and RIGT include density virial coefficients, needed to accurately define the equation of state of real gases at increasingly high pressure, and the corresponding acoustic virial coefficients, as in equation (1.2). Calculated electromagnetic properties include electrical and magnetic polarizabilities and the dielectric virial coefficients as needed to define the dielectric constant and the refractive index as a function of density. The most important consequence for gas-based primary thermometry is that the current availability of these theoretical definitions removes the need to measure gas properties at multiple (several) pressures along isotherms for the sake of extrapolating them to zero pressure, where equations (1.2) and (1.3) hold. It is now possible to run a single measurement of speed of sound in He, Ne or Ar (or a single measurement of dielectric constant, or refractive index, in He) at a suitably chosen pressure and to directly apply a theoretically calculated correction to derive the corresponding zero-pressure quantity. By reducing the time needed to achieve a determination of the thermodynamic temperature by a factor of 10, this possibility much favours the practical application of thermodynamic methods for the direct calibration of thermometers and dissemination practice. Examples of T determinations obtained at a single thermodynamic state by AGT and RIGT can be found in [41,50]. Finally, we remark that this simplification would also apply to constant-volume gas thermometry (CVGT), a primary method based on the ideal gas law which determines T from pressure, amount of substance and volume measurements [51,52]. This method is not currently included in the *MeP*-K, mainly because of insufficiently low uncertainties, but was one of the main contributors to the establishment of ITS-90. Today, because the density and the refractive index of monatomic gases are calculable from first principles with high accuracy, and because the volume of cavities of various geometries can be accurately and simply determined by the microwave techniques developed for AGT, it is likely that CVGT may be developed to become an alternative to the other gas-based methods discussed above.

2. Realization of T versus T_{90}

(a) Procedures for the realization of T

As a basic alternative choice when considering the realization of thermodynamic temperature, all the primary thermometry methods discussed in the previous section can be implemented absolutely or relatively. In absolute thermometry, T is directly determined from a measured physical property of the gas, like the speed of sound from equation (1.1), or the relative dielectric constant from equation (1.3). While absolute determinations best embody the new definition of the kelvin, they do require the measurements to be traceable to other base units that are linked to the kelvin by the current SI definition, namely, the metre, the second and the kilogram. Depending on the method, such traceability can be more or less challenging to achieve. To make but one example, in AGT, the measured speed of sound must be made traceable to the metre and the second. Because the speed of light in vacuum is exactly defined, and extremely accurate frequency standards are commercially available at low cost, this requirement is not challenging. In equation (1.1), traceability to the kilogram enters through the definition of the molar mass M of the gas, substantially a requirement that the composition of the gas must be accurately known, with equal amounts of different impurities having different uncertainty effect on the measured property, depending on the particular choice made for the thermometric gas. The latter requirement becomes more challenging at high temperatures because of significant outgassing of impurities from the metal components of the apparatus.

In relative thermometry, measurements must be repeated both at the temperature T of interest and at some reference temperature T_{ref}, which is most often, but not necessarily, chosen to be coincident with the temperature of the TPW, $T_{\mathrm{TPW}} = 273.16$ K. Thus, taking again the basic principle of AGT in equation (1.1) as an example:

$$T/\mathrm{K} = T_{\mathrm{ref}}\frac{w_0^2(T)}{w_0^2(T_{\mathrm{ref}})} = 273.16\frac{w_0^2(T)}{w_0^2(273.16)}\,. \tag{2.1}$$

The advantage of relative thermometry is, in addition to not requiring traceability to other units, that it largely eliminates the uncertainty contribution of systematic errors that remain the same at T and T_{ref}, typically leading to a significant reduction of the overall uncertainty. However, the condition that systematic errors do not vary with temperature becomes more and more challenging as the temperature difference between T and T_{ref} increases.

With some exceptions, the majority of $(T - T_{90})$ determinations reported during the last decade were obtained by relative thermometry. Exceptions include all DCGT results, most of RIGT results [39,41,42] and a minority of AGT results [25,27], particularly in the temperature range below 160 K. With an interesting combination of methods, to achieve very accurate determinations of $(T - T_{90})$ between 5 and 24.5 K, relative RIGT was performed at constant pressure [40] with T_{ref} determined from absolute AGT at 24.5 K [25]. Other relatively advantageous combinations are possible. For instance, as suggested in [49], RIGT results obtained along different isotherms keeping pressure or frequency constant may be combined to largely eliminate the need for extremely accurate pressure measurements, or to reduce the influence induced by imperfections in microwave electronics. Because such a variety of measurement schemes and procedures can be realized without the need to modify the apparatus, they help to identify possible sources of uncertainties while reducing, at the same time, the cost of the realization.

(b) Procedures for the realization of T_{90}

Ever since its promulgation, ITS-90 has been considered the only *practical* means of obtaining reliable temperature values with precision on the mK level or below. Here, ‘practical’ implies that a calibration of sufficient precision can be obtained with a limited effort in time and resources. In fact, the (limited number of) defining fixed points of the scale can be realized with much better precision than by any other method. The best published realizations have typical uncertainties of 0.1–0.2 mK. Only between fixed points does the situation get somewhat worse, owing to the non-uniqueness of type 1 and type 3 [5] and, to a minor extent, the propagation of calibration uncertainties. These issues cannot be avoided since they depend both on the way the ITS-90 is defined (by ranges and subranges) and on the variability of its interpolation devices, the standard platinum resistance thermometers (SPRTs). Any calibration on ITS-90 at temperatures above 13.8 K only requires determinations of the thermometer resistance at the defining fixed points, while the structure of the ITS-90 itself takes care of the regions in between the fixed points. Thus, ITS-90 is really a practical scale, although, unlike its predecessors, the word ‘practical’ was dropped from the name.

Around the year 2000, the mutual recognition agreement was instituted, where NMIs were obliged to publish so-called calibration and measurement capabilities (CMCs) on a dedicated website of the Bureau International des Poids et Mesures (BIPM) [53]. CMCs can only be published on the basis of either a corresponding Key Comparison, organized by the BIPM, or Regional Key Comparisons, organized within a particular metrological region (Europe, the Americas, Asia, Africa, the former Soviet Union area). Initially, these CMCs were intended as the best calibrations an NMI could offer to its customers. With time, however, this interpretation was relaxed. They are now mainly intended as the uncertainty with which a ‘regular’ or ‘standardized’ calibration can be offered. Nowadays, some NMIs use two types of uncertainty levels, the mutual recognition agreement uncertainty and a so-called ‘best’ uncertainty. The latter is used for research purposes and, as such, it requires an extra amount of time and effort. As an example, the plots in figure 2 show the difference between these uncertainty levels (and their propagation) assessed for INRiM from a recent bilateral comparison in the cryogenic range between 13 and 273 K [54].

In the absence of a sufficient number of triple points in the temperature range below 25 K, ITS-90 calibrations of a capsule-type SPRT (CSPRT) in that range require two extra ‘fixed’ points, one at approximately 17.035 K and the other at approximately 20.27 K. These can be

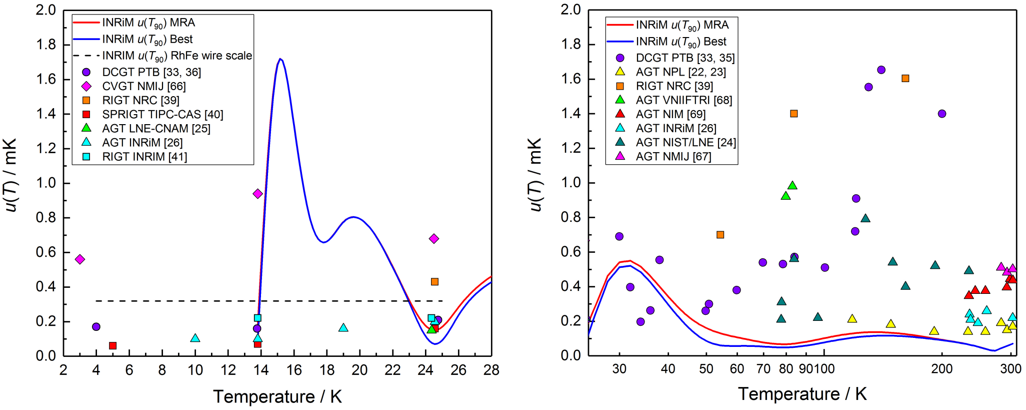

Figure 2. Standard uncertainty for ITS-90 realizations at INRiM in comparison with the standard uncertainty of the realization of T by various NMIs with different gas-based thermodynamic methods.

obtained by two different methods. The first requires the realization of a hydrogen vapour pressure scale at those temperatures: on the basis of the measured vapour pressure, T_{90} is then calculated using the defined equations. This method requires an effort that few NMIs are ready to make. The second method requires that a reference be provided by an interpolating gas thermometer (IGT) realization. In this case, the required extra fixed points are taken by comparison with one or more Rh-Fe thermometers carrying that IGT realization. Reference can be provided either by a local IGT realization, or by a realization made in another NMI.

At temperatures below the argon (Ar) triple point (83.058 K), the use of CSPRTs is mandatory, while above that temperature the widely used long-stem SPRT is also applied. This distinction implies different thermal considerations. While CSPRTs are mounted inside the cryogenic apparatus with only the measurement leads reaching up to room temperature, the use of long-stem SPRTs requires that the stem of the thermometer reach from room temperature down to the measurement zone, such as a comparison block or a resonator. This fact causes an important heat flow from high temperatures to the measurement area, while ideally this area should be isothermal and adiabatic. Thus, the use of a long-stem SPRT is usually accompanied by definitely higher uncertainties than with CSPRTs.

In the cryogenic range, only Key Comparison CCT-K2 has been organized, in 2000, with the exchange of SPRTs at the fixed points realized locally at each NMI [55]. In due time, it was found that some of the variability in realizations was due to insufficient knowledge of the isotopic composition of the fixed-point material. The results of a later comparison of fixed-point cells [56] reinforced this conjecture. Isotopic composition was addressed for hydrogen [57], water [4,58,59] and neon [60], while for oxygen its dependence on Ar content was determined [61]. All these studies led to increased accuracy in the reproducibility of fixed points, significantly reducing the variability of ITS-90 realizations. The dependencies on isotopic composition were afterwards incorporated in the *mise-en-pratique* of the kelvin [9] by reference to the ITS-90 Technical Annex [62].

(c) Uncertainty of *T* and T_{90} realizations

At the time when the ITS-90 was defined, it was a common belief that the scale was both accurate and precise to within 1 mK. Unfortunately, shortly thereafter, a recalculation of the VNIIFTRI CVGT results [63]—one of the ingredients for the definition at temperatures below 300 K—hinted at inaccuracy of the ITS-90, by as much as 10 mK, in the range above 80 K. Further evidence of this imperfection was bolstered by following thermodynamic measurements (essentially AGT) of increasing precision. The revision of the results [63] emphasizes the difficulty of accurately determining the temperature dependence of the CVGT volume from measurements of the linear thermal expansion of samples of the metal used for its construction. The expansion of metal samples might be anisotropic, and the assembled volume might deform under complicated, temperature-dependent strain from welds. Microwave determinations of the temperature dependence of the assembled volume could circumvent these difficulties.

The increased accuracy obtained with different thermodynamic methods in the following years motivated their use for the determination of the Boltzmann constant k in a cooperative research project [64]. Owing to an impressive effort by all the participants, the uncertainties at the TPW were reduced to the point where a redefinition of the kelvin became possible [65].

The improvement in the uncertainty of gas-based primary thermometers is well documented by the updates of $(T - T_{90})$ determinations by the Working Group for Contact Thermometry [6,7]. From a representative, but incomplete, set of these results [22–26,33,35,36,39–41,66–69], obtained in the range between 3 and 300 K, the standard uncertainty of the realization of T is extracted and plotted in figure 2 for comparison with the uncertainty of T_{90}. Note that although the realization and the dissemination of both T and T_{90} rely on SPRTs, below 25 K capsule-type SPRTs are no longer privileged for the realization of ITS-90 and the dissemination of $T - T_{90}$, owing to their very low resistance, and Rh-Fe thermometers represent a more convenient choice. Figure 2 gives visual evidence that, overall, thermodynamic and T_{90} uncertainties are of the same order of magnitude. Remarkably, the accuracy achieved in the realization of T is superior in the temperature range below 25 K, where the realization of T_{90} is particularly cumbersome, or where ITS-90 is affected by issues related to the non-uniqueness. However, since a larger practical effort is required for operation with thermodynamic methods, and because the resistance/temperature characteristic sensitivity may require, depending on the type of thermometer and temperature range, a larger number of calibration points with respect to a few selected fixed points, the choice for the realization of either the thermodynamic or the ITS-90 scale should still be carefully considered.

(d) Perspectives on thermodynamic dissemination

The results obtained by gas-based primary thermometry give evidence that thermodynamic methods, at least in the range below 300 K, are today sufficiently performing to represent a useful alternative for the dissemination of the kelvin. The inherent advantages of a direct realization of thermodynamic temperature, without intermediacy of an approximated scale which exhibits very high precision at a scant set of special reference temperatures (the fixed points), but shows relevant systematic deviations over wide continuous temperature ranges in between, are evident. On the other hand, when considering costs, both in economic and time-consumption terms, the advantages of maintaining fixed-point cells, in comparison to maintaining the complex apparatus needed by gas-based primary thermometry methods, are just as evident. It is probable that an alternative dissemination of T and of T_{90} will coexist in the future [70], with one or the other being preferred depending on the temperature range and the particular application, which is the objective of dissemination.

Several NMIs worldwide are currently working to extend the temperature range of gas-based primary thermometers or are at an initial stage of development of these apparatus. As primary methods will become more widespread, further simplification of design, engineering and measurement techniques is expected. Working towards these goals, an international cooperative research work has been organized in a 3-year project entitled ‘Dissemination of the redefined kelvin’ (DireK-T) [8], under the auspices and with funding provided by the European Association of National Metrology Institutes (Euramet). An important objective of the project is to test, in the range 4 to 300 K, the consistency of calibrations by gas-based thermodynamic methods using different kinds of capsule-type resistance thermometers (Pt, Pt-Co, Rh-Fe) as transfer standards. Because the previous ITS-90 calibration of the thermometers will not be disclosed to the laboratories that are responsible for thermodynamic calibrations, direct comparison of their calibration results will be unbiased by previous $(T - T_{90})$ determinations. As such, the results of the comparison, which should be accomplished and published by August 2026, will provide a realistic estimate of the uncertainty of gas-based thermometry. As an interesting follow-up to this work, the dissemination of thermodynamically calibrated CSPRTs to NMIs without thermodynamic temperature capabilities is expected to confirm that, based on the consensus estimate of $(T - T_{90})$, the realizations of T and T_{90} are indeed mutually consistent within their combined uncertainties.

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Authors' contributions. R.M.G.: conceptualization, funding acquisition, investigation, resources, supervision, writing—original draft, writing—review and editing; P.S.: data curation, formal analysis, investigation, supervision, validation, writing—original draft, writing—review and editing; G.L.: data curation, formal analysis, methodology, validation, writing—review and editing; D.I.: conceptualization, data curation, formal analysis, investigation, validation, writing—original draft, writing—review and editing.

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