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The Kelvin Redefinition and Practical Primary Thermometry

Implications for temperature traceability and sensing

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In May 2019 four of the seven base units of the International System of Units (the SI) were redefined and are now founded on defined values of fundamental physical constants. One of these was the kelvin which is no longer defined by the triple point of water but instead through a fixed value of the Boltzmann constant. In this paper the kelvin redefinition is introduced and the implications for temperature traceability and practical temperature sensing discussed. This will include outlining new approaches for temperature traceability, as well as discussing the rise of in-process calibration through practical primary temperature sensing approaches (where, in principle, no sensor calibration is required). These forthcoming changes are likely to have significant impact on everyone in the temperature calibration chain, whilst the advent of in-process temperature calibration should lead to step change improvements in process control, energy efficiency and product quality consistency and will help facilitate autonomous production.

1. Introduction

In May 2019 the SI underwent what was arguably its biggest change since its introduction when the definition of four of the seven SI base units: the kilogram, the ampere, the kelvin and the mole, were changed to be based on defined values of fundamental physical constants. Since the change, the kelvin has been defined in terms of the Boltzmann constant, the ampere in terms of the electron charge, the kilogram in terms of the Planck constant and the mole in terms of the Avogadro constant (1–3).

The redefinition of the kelvin has opened several new possibilities for traceable thermometry linked directly to the kelvin definition. These could include, in the short- to medium-term, using primary thermometry approaches to calibrate sensors at National Measurement Institutes (NMIs), and eventually in calibration laboratories. Primary thermometry approaches could include acoustic gas thermometry, which deduces thermodynamic temperature from the speed of sound in a known gas, or Johnson noise thermometry which deduces thermodynamic temperature from the thermally induced mean square voltage in a resistor. With the advent of these approaches the defined scales, the International Temperature Scale of 1990 (ITS-90) and the Provisional Low Temperature Scale of 2000 (PLTS-2000) (4, 5) may, for part or all of their ranges, be superseded.

In the longer-term these changes could well lead to the rise in paradigm-changing approaches to temperature sensing such as traceability at-the-point-of-measurement both through self-validating thermometers and, more radically, through the deployment of practical primary thermometry based on fundamental physics. In the latter case the temperature sensor itself will, unlike today, no longer need calibrating to provide traceability.

The ITS-90

The ITS-90 is essentially a 'recipe' which, if followed, yields precise and reproducible temperature values. To be specific the ITS-90 defines procedures by which certain specified practical thermometers (for example, platinum resistance thermometers) are calibrated in such a way (using defined fixed points, for example, metal freezing points such as tin, zinc or aluminium) 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.

In this paper an introduction to the kelvin redefinition and to the *mise en pratique* for the definition of the kelvin (*MeP*-K) (6, 7) is given. In the context of the *MeP*-K, how temperature traceability is attained will be discussed, both presently through the defined scales, and how disseminating thermodynamic temperature may well become increasingly prevalent in the medium- and long-term. More novel approaches to temperature traceability are discussed, including provision of NMI-like uncertainties in calibration laboratories and in the longer-term *in situ* traceability and the implications, particularly in the context of digitalisation and the need for 'points-of-truth' in autonomous sensor networks.

2. The Kelvin Redefinition and the *Mise en Pratique* for the Definition of the Kelvin

2.1 The Kelvin Redefinition

Resolution 3 of the 10th General Conference of Weights and Measures (CGPM) in 1954 defined the kelvin in terms of an exact value of the triple point of water (273.16 K) (8). Note that in 1954 the term "thermodynamic temperature scale" was used and the unit degrees Kelvin written as "°K". Resolution 3 of the 13th CGPM in 1967/68 clarifies the terms related to temperature and henceforth thermodynamic temperature was written "kelvin" (note lower case k) and no degree symbol is used. So thermodynamic temperature is expressed as X kelvin or X K, where X represents the numerical value of the temperature. At the same CGPM the familiar (though now superseded) wording of the kelvin definition was adopted, namely: "The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water". A typical triple point of water ready to use is shown in **Figure 1**.


Fig. 1. A triple point of water

At the 23rd CGPM in 2007 a clarification was made to this definition stating that the water triple point isotopic composition was to be that of "Standard Mean Ocean Water" (8, p.187, Resolution 10).

This definition of the kelvin has stood the test of time and was in place until the redefinition of the kelvin in terms of a fixed value of the Boltzmann constant in May 2019.

The preparatory investigation of the redefinition of the kelvin in terms of the Boltzmann constant began with Resolution 12 of the 23rd CGPM. But it was the 24th CGPM Resolution 1 "On the possible future revision of the International System of Units, the SI" that endorsed modernising the SI in terms of defined constants and gave strong impetus to the global thermometry community to determine low-uncertainty values of the Boltzmann constant, k, on which the redefinition of the kelvin would be founded. Four main experimental approaches were used to determine k. These were:

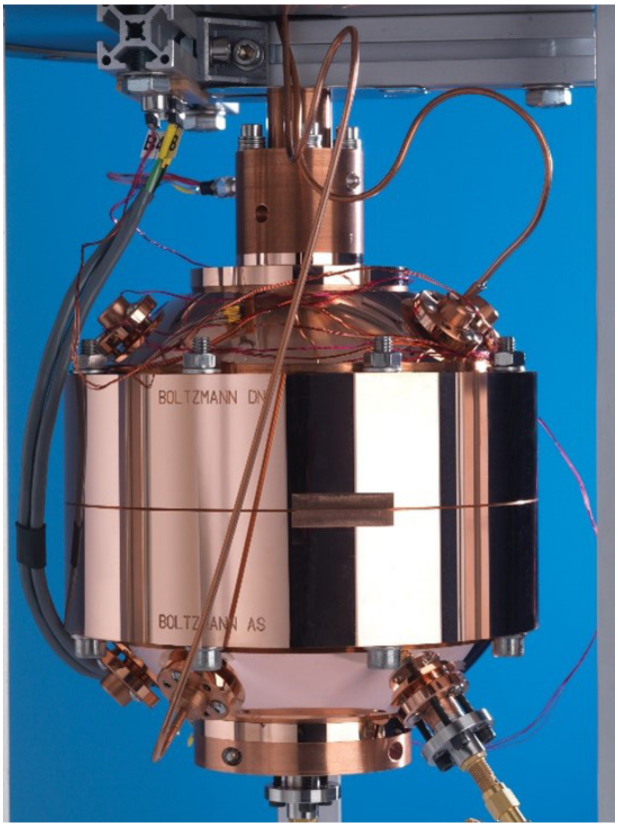

Fig. 2. The diamond turned acoustic resonator used by NPL to determine its low-uncertainty value of the Boltzmann constant

acoustic gas thermometry (AGT) (the acoustic gas thermometer used by NPL to determine its value of the Boltzmann constant is shown in **Figure 2**) (9), dielectric constant gas thermometry (DCGT) (10), Johnson noise thermometry (JNT) (11) and Doppler broadening thermometry (DBT) (12). The former three approaches went on to provide sufficiently low uncertainty values for k to contribute to the Committee on Data for Science and Technology (CODATA) (2) consensus value of k (2, 3) used in the redefinition of the kelvin. The exact wording of the kelvin definition is now (from (8)):

> "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 × 10^{-23} when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$."

where J = joules, K = kelvin, kg = kilogram, m = metre, s = second, h = Planck constant, c = speed of light and $\Delta\nu_{Cs}$ = the unperturbed ground state hyperfine transition frequency of 133 caesium atom.

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

Alongside the unit redefinitions, documents known as *mise en pratiques* (*MeP*s) were produced. The stated purpose of these documents was to "guide the user from the redefinition to a practical realisation of the unit" (13). The formal version of the *MeP* for the kelvin, the *MeP*-K-19 (7), was issued simultaneously with the redefinition on the 20th May 2019. The '19' represents 2019 to distinguish it from earlier versions and later revisions.

The *MeP*-K-19 contains all the essential information regarding allowable traceability routes to the kelvin. It includes some important preamble such as sections on the definition of the kelvin, definition of terms related to primary thermometry and the criteria for inclusion of a thermodynamic method within the *MeP*-K-19. The definition of terms section of the *MeP*-K-19 includes two important definitions for primary thermometry:

(a) Absolute primary thermometry. Here the background physics of the recommended primary thermometry approach is well known that it can be used to give low uncertainty thermodynamic temperature values without reference to a fixed point

(b) Relative primary thermometry. Here the recommended primary thermometry approach is rendered much more straightforward to implement if one or more fixed points with an explicit thermodynamic temperature value are used. The fundamental physics of the method is then used to obtain other thermodynamic temperature values either by extrapolation if one fixed point is used, or interpolation (and possibly extrapolation) if more than one fixed point is used. The criteria for inclusion are given, for example, in Section 4 of Fellmuth *et al*. (6). There follows the main part of the *MeP*-K-19 document where an outline of primary thermometry methods for realising the kelvin based on fundamental laws of physics are given, this currently includes AGT, primary radiometry, DCGT, refractive index gas thermometry (RIGT) and JNT. Other approaches to primary thermometry could be added in future provided they meet the inclusion criteria. The *MeP*-K-19 also includes the defined temperature scales ITS-90 and PLTS-2000 which currently remain the most used traceability routes for the kelvin at the present time. There are also some supplementary annexes such as recommended values of $T–T_{90}$ and $T–T_{2000}$ and temperature values for high temperature fixed points (14). $T–T_{90}$ and $T–T_{2000}$ represent the accepted documented differences between thermodynamic temperature, T, and that of the current defined scales either ITS-90 temperatures, T_{90}, or at low temperatures PLTS-2000 temperatures, T_{2000}. These values allow one to obtain thermodynamic temperature values from measurements taken with thermometers calibrated using the defined scales.

3. Temperature Traceability and the Impact of the Kelvin Redefinition and the *MeP*-K

3.1 Current Approach to Temperature Traceability

The SI system of units is used in the vast majority of countries around the world to provide a truly globalised uniform metrology infrastructure. As far as the kelvin is concerned traceability to the SI unit is generally obtained through an unbroken chain of calibrated artefacts with the ultimate reference standard (thermometer) being calibrated at the local NMI. Current temperature traceability is through calibration of that reference standard thermometer to one of the defined scales either ITS-90 or the low-temperature scale PLTS-2000. A typical high-level calibration artefact, typical of those used in NMIs would be a standard platinum resistance thermometer (SPRT). The sensing element of a typical SPRT is shown in **Figure 3**.

Once calibrated the SPRT would then be used by a calibration laboratory as their reference standard against which working standard thermometers are calibrated which are then used as references within the laboratory to calibrate customer artefacts.

However, to ensure calibrations are performed correctly requires more than just reliable traceable artefacts. There is also a quality infrastructure to be put in place and this is generally assured through the international standard ISO/IEC 17025:2017 (15). This ensures that the calibration laboratory has the appropriate calibration procedures, suitably qualified staff and many other aspects in place to make sure reliable calibrations are performed. This is usually guaranteed through third party accreditation. In the UK the responsibility for accreditation to ISO/IEC 17025:2017 resides with the United Kingdom Accreditation Service (UKAS).

The ITS-90 has been the backbone of reliable temperature traceability, from 0.65 K to the highest temperatures, on a global basis ever since it was introduced in 1990. It is a testament to its creators in the 1980s that it has endured for so long. Recent deliberations in the Consultative Committee for Thermometry (CCT), the global custodian of the SI unit the kelvin and hence also the ITS-90, whilst identifying minor issues with the scale, could see no good reason for change in the short- to medium-term, as to all intents and purposes it still meets the vast majority of customer requirements.

3.2 Temperature Traceability Shift from Defined Scales to Primary Thermometry

Although providing the framework for reliable temperature traceability the defined scales are still empirical in nature. Also there are undeniably some limitations with the ITS-90: poorly characterised uncertainties arising from non-uniqueness (16), the possible ban on use of mercury and hence loss of the use of the mercury triple point (which is a key defining fixed point of the ITS-90), the fact that T_{90} closely approximates but is not fully equivalent to T and that $T–T_{90}$ is around 0.01 K at 100 K rising to around 0.05 K at the silver freezing point (17).

There are three different types of non-uniqueness, all of which are sources of uncertainty in the

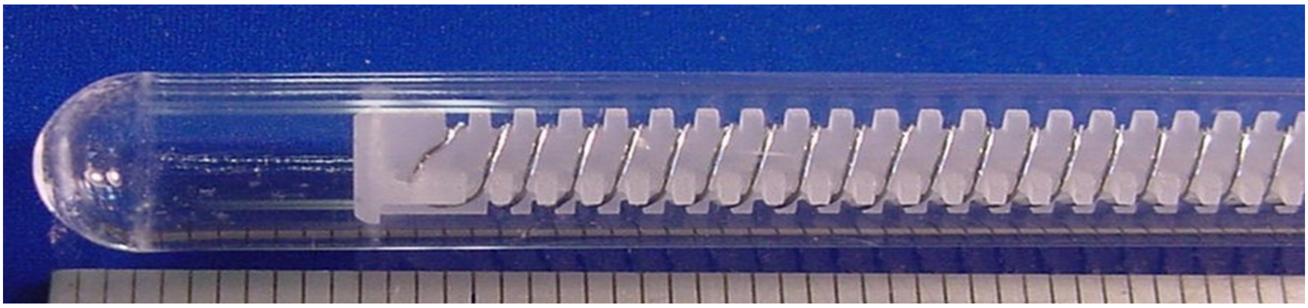

Fig. 3. The sensing element of a typical high quality standard platinum resistance thermometer

realisation of the ITS-90. The three types are: Type 1 non-uniqueness arises from the application of different equations in overlapping ranges but using the same thermometer; Type 2 non-uniqueness arises from the use of different kinds of thermometer (for example, interpolating gas thermometer and standard platinum resistance thermometer) in overlapping ranges; and Type 3 non-uniqueness arises from the use of different interpolating thermometers of the same kind (for example two standard platinum resistance thermometers) in the same range. 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 which will be altogether prohibited by 2020, except where exemption is requested for initial five years).

With the introduction of the redefined kelvin and the *MeP*-K-19 alternative routes for temperature traceability are now possible. Indeed, one of the explicit purposes of the *MeP*-K-19 is to allow temperature traceability directly to the kelvin without the intermediate means of using one of the defined scales. This could convey, in some circumstances, particular benefits for example if the user explicitly required direct thermodynamic temperatures as opposed to obtaining them through a defined scale calibrated thermometer and then applying a *post hoc* correction (from published $T–T_{90}$ or $T–T_{2000}$ values) to obtain thermodynamic temperature values. Or if direct traceability to the kelvin conveyed some other advantage such as giving lower uncertainties, or more long-term temperature measurement reliability.

In the near term, benefit could be gained in taking temperature traceability from primary thermometry at high (above the silver freezing point, approximately 1235 K) and low temperatures (below the triple point of neon, approximately 24.6 K). This is discussed in more detail elsewhere (18, 19) so will only be described briefly here.

In the past 20 years a significant development that has led to the improvement of high temperature measurement has taken place. The innovation and introduction of low uncertainty high temperature fixed points (HTFPs), based for example on metal-carbon eutectic (for example, Co-C (1324 K) or Pt-C (1938 K)) or metal-carbide carbon eutectic phase transitions (especially WC-C (2749 K)) (19), into temperature metrology has led to step change improvements in temperature traceability and measurement at high temperatures. Presently low uncertainty thermodynamic temperatures have been assigned to the Co-C, Pt-C and Re-C eutectic fixed points (14, 20). Low uncertainty thermodynamic temperatures are currently being determined for Fe-C, Pd-C, Ru-C and WC-C fixed points (21). How such fixed points can be used to realise and disseminate thermodynamic temperature at high temperatures is outlined in for example (22), but in essence this would be through relative primary thermometry using Planck's law, in combination with one or more HTFP(s) of known thermodynamic temperature to establish direct traceability to the kelvin. Uncertainties by this approach would be competitive with the best current ITS-90 realisation approaches but with none of the limitations. Crucially thermodynamic temperature could, by this means, be easily disseminated to calibration laboratories who would then be able to realise thermodynamic temperatures above the silver point with low (NMI-level) uncertainties.

At temperatures below the neon triple point the situation for obtaining traceability to the defined scales is complex. The ITS-90 has three different recommended thermometry approaches to provide traceability from 0.65 K to the neon triple point. In brief these are: between 0.65 K and 5.0 K T_{90} is defined in terms of the vapour pressure temperature relations of ^{3}He and ^{4}He, between 3.0 K and the triple point of neon (24.5561 K) T_{90} is defined by means of a helium interpolating gas thermometer and between the triple point of equilibrium hydrogen (13.8033 K) and the freezing point of silver (1234.93 K) T_{90} is defined by means of platinum resistance thermometers (4, 5). These different approaches overlap at different temperature ranges giving rise to uncertainty sources from Type 2 non-uniqueness. In addition, there is more complexity caused by the overlap of PLTS-2000 and ITS-90 between 0.65 K and 1 K, though the difference of $T_{90}–T_{2000}$ is well characterised (23). All these approaches are rather complex and cumbersome and only a few specialist NMIs round the world actually perform a full realisation of PLTS-2000 (which goes down to 0.9 mK) and ITS-90.

Alternatively, to the complexity surrounding realising and disseminating the defined scale, the *MeP*-K-19 allows direct traceability at low temperatures by JNT. There are several approaches; for example, current sensing noise thermometry (CSNT) (24) and primary magnetic field fluctuation thermometry (pMFFT) (25) either of which could be used to provide direct traceability to the kelvin below around 5 K. Above 5 K AGT (or RIGT (26)) are certainly possible alternatives for providing thermodynamic temperature traceability at least to the neon triple point. The introduction of these thermodynamic approaches would simplify temperature realisation and dissemination and could, in the medium- to long-term, lead to the demise of the PLTS-2000 and the ITS-90 below the neon triple point for temperature traceability.

In the long- to very long-term, it is likely that NMIs will offer traceability to thermodynamic temperature at temperatures above the neon triple point as an alternative to the ITS-90. The most likely primary thermometry approach is by AGT at least up to around 300 K. This would be for users that could benefit from taking direct traceability to the kelvin rather than having to apply *post hoc* corrections to the measurement. However, saying all that, the ITS-90 will, in all probability, still be the dominant source of temperature traceability at least until the late 2020s and into the early 2030s.

3.3 What are the Benefits of Temperature Traceability Direct to the Kelvin Definition?

The shift to providing traceability from the defined scales directly to the kelvin has several important benefits. Firstly, being approximations (albeit good ones), the temperature values the defined scales give always have differences from thermodynamic temperature. These are characterised by the quantities $T–T_{90}$ and $T–T_{2000}$ for the ITS-90 and PLTS-2000 respectively. If temperature sensors are calibrated directly to thermodynamic temperature, then neither this correction, nor its associated uncertainty, need be applied to the measured values. This will simplify important temperature measurement activities such as deep ocean and other climate measurements. Secondly, it would be costly to change to a new defined scale, many standards would need to be updated, industrial process controls changed, especially the software. Moving to thermodynamic temperature would allow for temperature measurement to be future proofed, meaning no further changes would be required as direct traceability to the unit definition would be attained. Then of course, thirdly, obtaining traceability directly to the fundamental physics of the measurement setting is ultimately the most direct and desirable approach from a scientific perspective.

4. The Future of Temperature Measurement: Traceability at the Point of Measurement?

In the medium-term temperature traceability will still be primarily through the NMI. However, there are several innovative developments underway that, in the medium- to long-term, could deliver temperature traceability ‘at-the-point-of-measurement’. These are of two main types: either through incorporated miniature metallic fixed points of known melting temperature within the sensing element of a conventional temperature sensor (27, 28, 29) or, more radically, the deployment of practical primary thermometry (30, 31). The latter could be, for example, a practical application of JNT where the mean square thermally induced noise voltage in a resistor is directly related to its thermodynamic temperature. Most of these approaches (self-validating sensors and practical primary thermometry) are discussed by Pearce *et al*. (30), in this volume, where technical details can be found. The main practical primary thermometry not described in (30) is small scale DBT. This is described by Dedyulin *et al*. (31).

There are great benefits to be gained from providing self-validation and even traceability at-the-point-of-measurement. Firstly, temperature is one of the most, if not the most, widely used industrial process control parameter. However, because temperature sensors drift during use, the control thermometers require periodic recalibration. This is to ensure energy use is optimised, product quality is maintained, emissions are minimised and scrappage is avoided. If self-validation or traceability at-the-point-of-measurement was used sensors would not need recalibrating (which often necessitates sensor removal) and industrial processes would always run optimally leading to improved process efficiency and effectiveness. As an extension of that principle, temperature sensors are sometimes required in situations that are subsequently inaccessible and hence not retrievable for recalibration. Examples of this include in a nuclear power plant or long-term nuclear waste repository. The benefits of self-validation and traceability at-the-point-of-measurement is obvious in those cases. For example, a nuclear reactor could be operated both optimally from an efficiency point of view and safely, whereas if the sensor drifted in an unknown way the reactor would be run suboptimally (i.e. at a lower indicated temperature) to maintain safe operation. Finally, there is an inevitable rise in digitisation and the use of sensor networks to monitor and control complex systems such as steel plants and oil refineries. These rely on many temperature sensors to form a measurement network. In this setting self-validation and traceability at-the-point-of-measurement will provide those all-important 'points-of-truth' within the measurement network to assure ongoing effective measurement. In fact, without such developments fully autonomous production will never become possible.

5. Conclusion

In this paper I have introduced the kelvin redefinition and the *MeP*-K. I have discussed how these changes are likely to have a major impact on the provision of temperature traceability in the medium- to long-term. In particular it is clear that in the medium-term at low and high temperatures traceability to the NMI will be increasingly delivered by primary (thermodynamic) temperature approaches. In the longer-term this may extend to the middle part of the temperature range, though it is likely that the ITS-90 will still be in use to provide routine traceability into the 2030s. In the longer-term there is likely to be widespread availability of temperature sensors which provide self-validation and traceability at-the-point-of-measurement and such innovations will be essential if truly autonomous production is to be achieved.

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Glossary

AGT	acoustic gas thermometry
CCT	Consultative Committee for Thermometry
CGPM	General Conference of Weights and Measures
CODATA	Committee on Data for Science and Technology
CSNT	current sensing noise thermometry
DBT	Doppler broadening thermometry
DCGT	dielectric constant gas thermometry
HTFP	high temperature fixed point
ITS-90	International Temperature Scale of 1990
JNT	Johnson noise thermometry
MeP-K	*mise en pratique* for the definition of the kelvin
NMI	National Measurement Institute
NPL	National Physical Laboratory
PLTS-2000	Provisional Low Temperature Scale of 2000
pMFFT	primary magnetic field fluctuation thermometry
RIGT	refractive index gas thermometry
SI	International System of Units
SPRT	standard platinum resistance thermometer
UKAS	United Kingdom Accreditation Service

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