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Original

Summary of achievements of the European Metrology Research Programme Project “Implementing the new Kelvin” (InK 1) / Machin, G.; Engert, J.; Gaviolo, ROBERTO MARIA; Sadli, M.; Woolliams, E.. - In: MEASUREMENT. - ISSN 0263-2241. - 94:(2016), pp. 149-156.

Availability:

This version is available at: 11696/54642 since: 2017-02-27T15:58:21Z

Publisher:

Elsevier

Published

DOI:

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Summary of achievements of the European Metrology Research Programme Project “Implementing the new Kelvin” (InK 1)

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Abstract

We report a summary of the technical achievements of the European Metrology Research Programme project (EMRP) “Implementing the new Kelvin” (InK 1). In short these are:

- The first determination of definitive thermodynamic temperatures for the point of inflection of the high temperature fixed points of Re-C, Pt-C and Co-C as well as a new evaluation of the Cu freezing point.
- The first trial of the new dissemination mechanisms for thermodynamic temperature at high temperatures, as described in the *mise en pratique* for the definition of the kelvin (*MeP-K*)
- A new ultra-low uncertainty thermodynamic evaluation of $T-T_{90}$ from about 30 K to 303 K, with particular emphasis on temperatures around the water triple point (273.16 K)
- The first re-evaluation of $T-T_{2000}$ from 0.02 K to about 1 K with an uncertainty of <1%

Taken together these results represent a significant advance in primary thermometry. We also give a brief introduction to the successor project (InK 2) and discuss the impact of this work on the kelvin redefinition and next version of the *MeP-K* (i.e. the *MeP-K-19*).

Keywords: Primary thermometry; Temperature scales; ITS-90; PLTS-2000, kelvin redefinition

Introduction

Currently almost all traceable temperature measurements around the world are derived from a defined scale, either the International Temperature Scale of 1990 (ITS-90) [1] or, below 1 K, the Provisional Low Temperature Scale of 2000 (PLTS-2000) [2]. These scales are empirical in basis, reliant upon a set of fixed points whose temperatures were determined *a priori* by primary thermometry. However, recent technical advances in temperature metrology, the advent of the evolving *mise en pratique* for the definition of the kelvin (*MeP-K*) [3, 4], and the forthcoming kelvin redefinition in terms of a fixed value of the Boltzmann constant [5] provide a unique opportunity to fundamentally change the practice of temperature measurement.

In the light of this a European Metrology Research Programme (EMRP) project, known as Implementing the new Kelvin (InK 1) [6], was established and ran from October 2012 to September 2015. The project had 13 partners and 8 collaborators/universities from around the world working in the field of primary thermometry.

The research that was performed in the InK project had two broad aims:

- The development of primary thermometry methods that could challenge and even supplant the defined scales at high ($>1000\text{ }^{\circ}\text{C}$) and low ($<1\text{ K}$) temperatures. This could enable, for the first time, a direct realisation and dissemination of thermodynamic temperature, with uncertainties that are competitive with the defined scales.
- Between those temperature extremes facilities were developed and new values of $T - T_{90}$ (by a variety of methods) with the lowest ever uncertainties ($\leq 1\text{ mK}$) determined. Low uncertainty $T - T_{90}$ data is required for the *MeP-K-19* annex and in the longer term to provide low uncertainty thermodynamic temperature data for any successor temperature scale, the so-called ITS-20XX. This research is not complete and will continue in a second InK project (InK 2), which will run from June 2016 to May 2019.

This paper will give an overview of the results of the InK project, starting at high temperatures where new values of high temperature fixed points have been determined, and new dissemination methods at high temperatures, outlined in the *MeP-K*, have been trailed. An overview of the $T - T_{90}$ and $T - T_{2000}$ results will be described. The paper will end with an introduction to the research encompassed within the InK 2 project and how that research and other InK 2 activities will facilitate an effective kelvin redefinition.

Thermodynamic temperatures of high temperature fixed points and the Cu point

High temperature fixed points (HTFPs) have been the subject of extensive research since their inception [7, 8]. Overviews of progress in research in these areas can be found in [9, 10].

Although reliable temperatures have been proposed for the point of inflection (poi) of the melting curve of HTFPs [11], no definitive evaluation of poi thermodynamic temperatures had been undertaken until this work. To maintain linkage with the ITS-90 [1] a new evaluation of the thermodynamic temperature of the Cu freezing point (~1358 K) was also performed.

The HTFPs selected for this study were the Co-C (~1357 K), Pt-C (~2011 K) and Re-C (~2748 K) metal-carbon eutectic points. These were selected because of their relatively mature state of development compared to other HTFPs. A large number of each of the fixed points was constructed [12], these underwent rigorous testing and a subset of five were selected against agreed criteria [13]. A rigorous mathematical framework for data analysis was established [14] to ensure all sources of uncertainty, including possible correlations, could be taken into account. This data analysis took into account significant parallel work performed to understand key sources of uncertainty such as temperature drop across the blackbody cavity backwall [15], and the effective cavity emissivity [16].

The measurement campaign began at the National Physical Laboratory, UK (NPL), where the temperature difference between the four cells of each type was determined by relative radiometry. This measurement was also performed at the completion of the measurement campaign. The four cells of each type were then split into two groups. These two cell groups were then circulated to participant institutes, each of which was capable of low uncertainty primary radiometry. The participant institutes were NPL, the National Research Council of Canada (NRC), the National Institute of Standards and Technology, USA (NIST), Physikalisch-Technische Bundesanstalt (PTB), the National Measurement Institute of China (NIM), the National Measurement Institute of Australia (NMIA), the All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI), Laboratoire commun de métrologie – Conservatoire National des Arts et Métiers (LNE-Cnam), the Centro Español de Metrología (CEM) and the National Metrology Institute of Japan (NMIJ). Different variants of primary radiometry were performed by the participants, adding to the robustness of the results. Details of these approaches can be found in [17].

It was found that despite the variations in approach, all the radiometry results by all the participants agreed within the two standard deviation uncertainties. This data was then processed using the agreed approach and consensus thermodynamic temperatures values determined for the point of inflection for the three HTFPs, and the freezing point of Cu. The values are given in Table 1.

HTFP	Value (K)	Expanded uncertainty (K)
Re-C	2747.84	0.35
Pt-C	2011.43	0.18
Co-C	1597.39	0.13
Cu	1357.802	0.081

Table 1: The consensus thermodynamic temperature values for the point of inflection of the HTFP melting curves and the Cu freezing point with expanded ($k=2$) uncertainties (adapted from [9])

These values represent the first definitive thermodynamic temperature values for the poi of the melting point of HTFPs and a new low uncertainty evaluation of the Cu freezing point. Note that the poi was chosen, as this is the most easily measured and reproducible feature of the HTFP phase transition curve [18].

Although this work was a significant advance on what had been performed previously it is clear that further research is needed in HTFPs in at least two areas.

Firstly to make these HTFP thermodynamic temperature values of general use to the thermometry community two major sources of uncertainty need to be quantified that were not included, or not completely considered, in the uncertainty analysis reported in [17]. These are the uncertainty associated with the furnace and that associated with the impurities in the fixed point material. These sources of uncertainty are the subject of current study and definitive temperatures of the poi of these HTFPs taking into account these effects will be the subject of a paper currently in preparation [19]. The temperatures and uncertainties reported there will then be recommended to the Consultative Committee for Thermometry (CCT) for incorporation into the *MeP-K-19* [3, 4, 20] to be used for thermodynamic temperature dissemination above the copper point.

Secondly there remain a large number of HTFPs for which definitive temperature values have not been evaluated. A task group of CCT WG-NCTh¹ is being established to propose how to determine these temperatures for the remaining HTFPs in the next few years. It is envisaged that most will be determined by interpolation relative to the temperature values given in [17], taking into account the uncertainties given in [19]. For the HTFPs above the Re-C point, for example the WC-C point (~ 3022 K), the temperature values will be determined by extrapolation [21]. Since this approach is essentially a parameterised form of the Planck function the uncertainties arising from the extrapolation are not thought to be large. It is envisaged that this activity should be completed by around 2019/20.

¹ CCT = Consultative Committee for Thermometry, WG-NCTh = Working Group for Non-contact thermometry

Dissemination of thermodynamic temperature above the freezing point of silver through the proposed *MeP*-K mechanisms

The ITS-90 above the silver freezing point (1234 K) is realised and disseminated using Planck's law in ratio form [1]. It has been clear for some time that alternative approaches based on primary radiometry might well yield lower dissemination uncertainties [22]. There are two main approaches that have been considered, both included in the *MeP*-K [4, 20].

The direct approach: Here radiometers (generally filter radiometers of some type) are calibrated directly traceable to the radiant watt. These are then used to disseminate thermodynamic temperature.

The indirect approach: Here HTFPs whose thermodynamic temperature has been determined *a priori* by primary radiometry are used to disseminate thermodynamic temperature. A small target size radiometer can then be calibrated using these fixed points and used to realise thermodynamic temperature.

Both approaches have, in principle, similar uncertainties (which in turn are similar to those of ITS-90) so it was important to undertake the study described here where both approaches were trialled.

In the direct approach, four filter radiometers were calibrated in their participant institutes. The LNE-Cnam, PTB and CEM used a similar small target size radiation thermometer, whilst the fourth participant the Technical Research Centre of Finland Ltd, Centre for Metrology (VTT-MIKES) used a filter radiometer without lenses. These were all transported to PTB and compared. Each device was set up in front of a variable temperature high temperature blackbody and measured at 10 temperature points between 1275 K and 2770 K. It was found that over the whole range all four instruments agreed within 1 K and well within the overall uncertainty of measurement. This result can be seen in Figure 1 below.

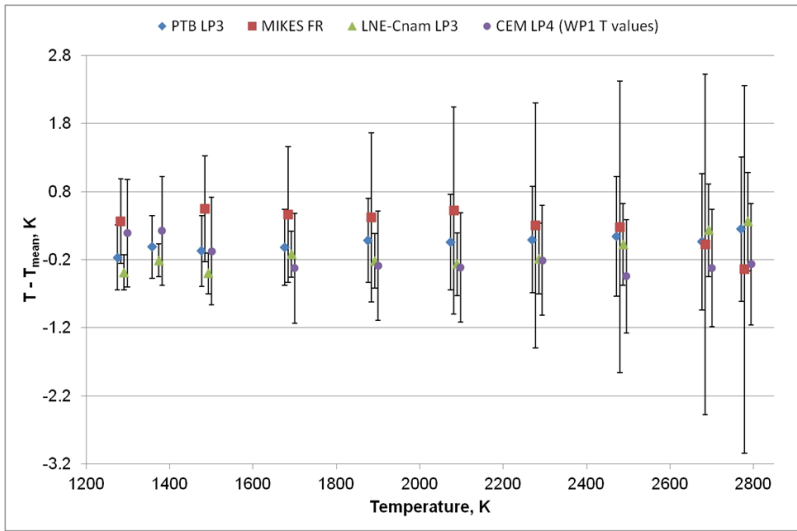


Figure 1: Thermodynamic temperatures measured with three radiation thermometers calibrated by LNE-Cnam, CEM and PTB and with a VTT-MIKES filter radiometer. Uncertainty bars represent expanded measurement uncertainties ($k=2$). The x position of the data points have been slightly offset for clarity.

From these results it is clear that dissemination of thermodynamic temperature using the direct approach is feasible. Nevertheless, undetected long term instability may be possible in these radiometers. This possibility is reflected in the proposed recommendations to CCT WG-NCTh, which are listed at the end of this section.

In the indirect approach a number of HTFP blackbody cells were constructed by NPL and LNE-Cnam; these were Co-C, Pt-C, Ru-C (~ 2226 K) and Re-C. The HTFPs were then assembled at and calibrated by LNE-Cnam and circulated to the participants who were: CEM, PTB, TUBITAK UME (i.e. Ulusal Metroloji Enstitüsü) and NPL. Note that the HTFPs were calibrated in terms of ITS-90. For the purpose of this dissemination study the actual temperature (ITS-90 or thermodynamic) was not important --- what was important was the stability of the artefacts under test.

The results were very satisfactory; the temperatures of all the cells were in good agreement to within 1 K at all temperatures and well within the standard uncertainties of the measurements. Typical results are shown in Figure 2 for the Re-C cell and full details can be found in [23].

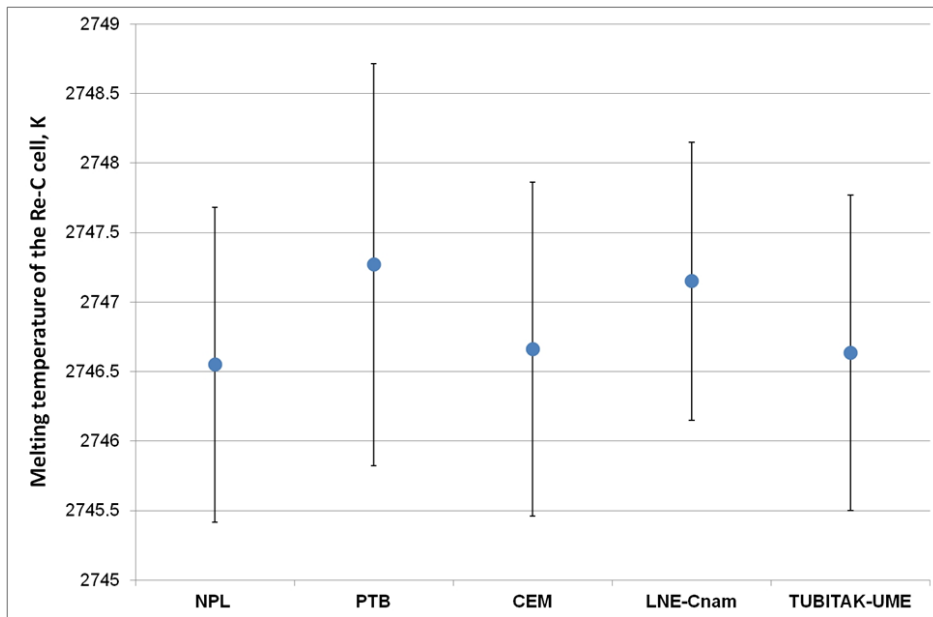


Figure 2: The reported point of inflection melting temperatures for each participant for the Re-C blackbody cell. Uncertainty bars represent expanded measurement uncertainties ($k=2$)

It is considered that the indirect approach trialled here had the more exacting test of the two proposed methods. This is mainly because in the direct approach all the radiometers went to one institute and were measured in that institute over a short time period. This is opposed to the indirect approach where the HTFPs were circulated over a period of more than 1 year and shown to be stable. Nevertheless the results obtained here showed that with care thermodynamic temperature can be disseminated by either approach recommended in the *MeP-K* with uncertainties similar to the ITS-90.

The outcomes of this research led to the following draft recommendations to be proposed to the CCT WG-NCTherm:

- HTFPs can be used to disseminate either the ITS-90 or thermodynamic temperature from NMIs to users with uncertainties at least comparable with current approaches.
 - However considering that this study (along with others) have shown that there are still some ill understood effects due to the interplay of the furnace and HTFP cell, namely thermal inertia and furnace uniformity, it is clear that if the lowest uncertainties are to be obtained in the dissemination of temperature by this route these effects need further study and, in particular, quantification.
- Filter radiometers and radiation thermometers, directly traceable to the radiant watt, can be used directly to disseminate thermodynamic temperature to users with uncertainties comparable to current methods.
 - However it should be noted that unknown radiometer drift remains a problem and it is recommended that if this approach of dissemination is adopted that a HTFP be used in the institute to periodically assess the stability of the radiometer, or that at least two radiometers be used as the basis of the transfer and periodic cross comparisons be performed to confirm stability.
 - A detailed study should be performed to reliably quantify the corrections and uncertainties for the non-uniformity of high-temperature furnaces used as radiance

sources to transfer the calibration of a reference filter radiometer to a radiation thermometer.

These recommendations are to be discussed and finalised at the CCT WG-NCTherm meeting in July 2016, and proposed to the CCT in May 2017 for adoption. It is envisaged that these will pave the way for either the direct or indirect method to be used to disseminate thermodynamic temperature above the silver freezing point provided the caveats in the recommendations are duly followed.

Low uncertainty determinations of $T - T_{90}$

In the recent past there has been significant improvement in several primary thermometry methods and techniques [24] due to the requirement for the accurate determination of the Boltzmann constant at the triple point of water T_{TPW} [25-30] for the forthcoming kelvin redefinition. These new capabilities have been subsequently used, over an extended temperature range, to determine low uncertainty values of the important quantity, $(T - T_{90})$ the difference between thermodynamic temperature and its approximation by ITS-90. A critical revision of the historical records of $(T - T_{90})$ and their uncertainties [31] revealed some major inconsistencies between data sets and lack of data over certain temperature intervals. To resolve both these deficiencies, new sets of data are needed, ideally determined by more than one method, to assist in the identification of possible undetected systematic uncertainties. Part of the InK project has addressed these objectives through the application of different types of gas thermometers operated in either relative or absolute primary thermometry mode. The expectation that high quality data could be obtained was confirmed by the results shown in Figure 3, which summarises measurements obtained during the course of the InK project using relative acoustic gas thermometry (AGT) between 78 K and 303 K, and dielectric constant gas thermometry (DCGT) between 29 K and 140 K.

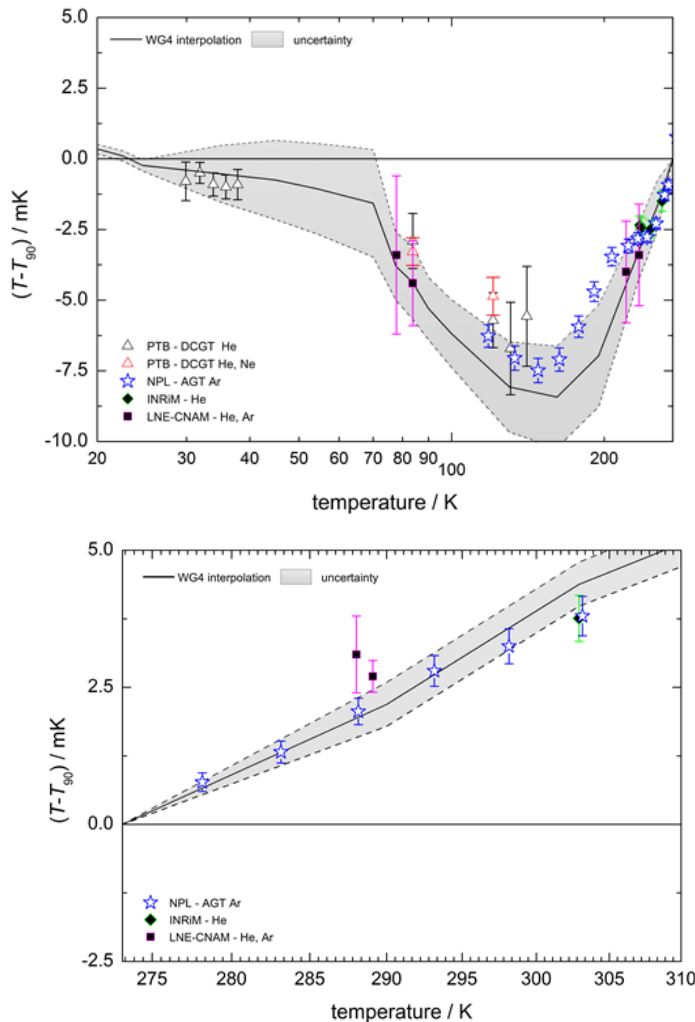


Figure 3: Recent determinations of $T - T_{90}$ using DCGT and AGT by various laboratories. The black line and the shaded area display the interpolation of previous $T - T_{90}$ data by CCT Working Group 4 [31] and its uncertainty. (Upper) Comparison of determinations of $T - T_{90}$ by DCGT and AGT between 28 K and 273.16 K. (Lower) Comparison of determinations of $T - T_{90}$ by AGT between 273.16 K and 303 K.

This data ensemble included several new $T - T_{90}$ evaluations from 25 K to 303 K.

The temperature interval between 25 K and 255 K, which is of particular interest due to the unexplained inconsistencies of some previous constant volume gas thermometry results [31]. Despite the very low uncertainties of these measurements and the fact that two different thermometric methods have been used, the new results are mutually consistent with each other. In addition, the results are broadly consistent with the previous consensus estimate of $T - T_{90}$ critically evaluated by the then CCT-WG4 [31]. In the range between 78 K and 84 K, the new DCGT results obtained at the PTB were in agreement with new AGT results of the LNE-CNAM (pending their final revision and uncertainty estimate). Also new AGT results obtained at NPL [32] between 120 K and 140 K were consistent with the new DCGT results of PTB in the same range. Finally, the consistency of various AGT data below *and above* the water triple point temperature ($T_{TPW} = 273.16$ K) and, in particular, near the mercury triple point (234.3156 K) and gallium melting point (302.9146 K) is remarkable, considering the weak correlation of the three different AGT experiments [33].

We now discuss some of the important details of the individual results.

Firstly, consider the AGT thermodynamic temperature determinations obtained at NPL, in argon, between 118 K and 303 K. These results, displayed as stars on Figure 3, stand out because they have exceptionally low uncertainties. In particular the thermodynamic temperature uncertainty is lower than those intrinsic to the ITS-90 (different types of non-uniqueness) and in the realization of ITS-90 (uncertainty of reference fixed points) [32]. Such extraordinary performance demonstrates the progress made in the implementation of AGT [34] and in NPL's case was made possible by the outstanding acoustic quality of the resonator realized in cooperation between NPL and Cranfield University [32]. In addition, the set of thermodynamic temperatures obtained by NPL, being composed of several closely spaced results, allows the development of a smooth interpolation function for $T - T_{90}$ which observed for the first time previously undetected features below and across the T_{TPW} temperature [32].

Next LNE-CNAM has been employing a variety of cryogenic apparatus suitable to conduct AGT experiments between 4 K and 350 K. At the conclusion of the InK project results were reported at six temperatures between 77 K and 290 K. These results and their uncertainties, as displayed in Figure 3, are preliminary, pending the results of the calibration of the capsule standard platinum thermometers used in the experiments.

The AGT results between 235 K and 303 K from INRiM, in helium, were obtained using the apparatus previously used for a precise determination of the Boltzmann constant [30].

PTB has conducted extensive modelling and experimental work to improve the overall accuracy of their DCGT experiments. In particular they have reduced critical uncertainty contributions, including from the dead weight balances used as primary pressure standards, the instrumentation used for capacitance measurements and the total pressure distortion of the cryo-capacitor by the characterization of its compressibility as a function of temperature [35]. Also, careful checks were conducted looking for possible undetected systematic sources of uncertainty by repeating measurements with different capacitors and using both He and Ne as measurement gases. The results obtained from all these combinations were found to be mutually consistent.

Considering the current state and the future perspectives of the primary thermometry experiments described above, the further extension of the working temperature range of each technique aims at significantly increasing the set of accurate $T - T_{90}$ determinations. PTB is working to extend DCGT to higher, near ambient, temperatures and AGT experiments are currently being developed, at NPL, LNE-CNAM and INRiM, collectively spanning an overall temperature range between 4 K and 1000 K. In addition the feasibility of AGT up to the freezing point of copper (1358 K) has been demonstrated by pioneering cooperative work by NIST and the National Metrology Institute of China (NIM) [36]. Together these research efforts will have a deep impact on the practice of

primary thermometry, reducing the errors of a future revised temperature scale and/or providing multiple, alternative routes for the direct dissemination of thermodynamic temperature.

Low uncertainty determinations of $T-T_{2000}$ between 0.02 K and 1 K

The Provisional Low Temperature Scale (PLTS-2000), ranging from 0.9 mK to 1 K [2, 37], is the international temperature scale currently in force for low temperatures. The PLTS-2000 is mainly based on input data from three different sources [2], which disagree by 6% at the lowest temperatures. For more than a decade since the adoption of the PLTS-2000, no attempt has been made to resolve this discrepancy. For the first time, within the InK project, new values of $T-T_{2000}$ have been obtained between 0.02 K and 1 K.

To facilitate these measurements, new designs of three different types of primary thermometer were investigated and tested. Specifically, two new electrical noise thermometers; a current sensing noise thermometer (CSNT) [38] and a primary magnetic field fluctuation thermometer (pMFFT) [39] - as well as a Coulomb blockade thermometer (CBT) [40] have been designed and constructed.

The noise thermometers exploit the fundamental relation between voltage fluctuations and thermodynamic temperature in an unbiased electrical conductor at equilibrium given by the Nyquist formula. At temperatures below 1 K the thermal noise signals are so small that only superconducting quantum interference device (SQUID) sensors are sensitive enough to measure them. An important design consideration during the development of the CSNT and pMFFT was keeping the non-thermal (i.e. white) noise sources of the SQUIDs and the connected electronics to a negligible level. Both the CSNT and pMFFT take advantage of low-noise SQUIDs developed by PTB to measure the thermal noise spectra of a metallic noise sensor. The PTB SQUIDs have specific design features to minimise non-thermal noise sources such as by a new design of shunt resistor, cooling fins and strip-line connections between the SQUID and the distant shunt resistors.

For the CSNT, the main uncertainty contributions for thermodynamic temperature measurement come from the determination of the resistance of the noise sensor and the measurement of the mutual inductances between the SQUID and the input and feedback coils [38]. For the pMFFT, the main uncertainty contributions come from the determination of the geometric dimensions of the noise sensor and its distance to the measurement and calibration coils [39]. In the temperature range measured here the relative combined standard uncertainties of 1.51% and 0.59% (coverage factor $k=1$) were reached for the measurement of thermodynamic temperatures using the CSNT and the pMFFT, respectively.

The CBT works on a different principle to the above two noise thermometers, namely, it is based on single electron charging effects in normal metal tunnel junctions. The thermodynamic temperature is derived from the measurement of the differential conductance of an array of tunnel junctions in series as a function of bias voltage. In the limit of small charging energy compared to the thermal energy of the tunnelling electrons, the differential conductance shows a dip around zero bias. Its full width at half minimum is directly proportional to thermodynamic temperature [40]. The technological challenge for the CBT is to produce stable arrays of tunnel junctions with defined and equal junction parameters. The electron-phonon coupling, which is critical for thermalizing the electrons, was improved in this new design, by enlarging the volumes of appropriate material attached to the tunnelling structures of the CBT. The main uncertainty components for CBT come from the determination of the charging energy of the electrons in the

array and the repeatability of the measurements. The resulting relative combined standard uncertainty of the measured thermodynamic temperatures is less than 0.48% ($k=1$) for the CBT (with an array of 99 junctions) used for the measurements described in this paper.

The difference between $T-T_{2000}$ was determined through comparison measurements at VTT-MIKES and PTB between the primary thermometers and a realisation of PLTS-2000. At VTT-MIKES, a superconductive reference point device (SRD) was used to provide T_{2000} temperatures according to the PLTS-2000. The SRD carried a calibration of the PLTS-2000 with relative standard uncertainties of 0.1%. In the experiments at VTT-MIKES a CSNT, two CBTs and a pMFFT were compared with each other and with the T_{2000} temperatures from the SRD. At PTB, another pMFFT was compared against T_{2000} temperatures, which were provided by a MFFT calibrated according to the PLTS-2000 with a relative standard uncertainty of 0.04%. All experiments were carried out in dry dilution refrigerators.

The comparison measurements at VTT-MIKES showed good agreement between all thermometers within the expanded uncertainties ($k=2$) in the temperature range from 20 mK to 207 mK. The individual temperature readings of the primary thermometers measured at each T_{2000} reference temperature were combined into a corrected weighted mean, which agrees with the T_{2000} values better than 0.53% with uncertainties of 0.64% and less. The comparison measurements at PTB showed agreement between thermodynamic temperatures obtained by the pMFFT and the T_{2000} reference temperatures of better than 0.28% with an uncertainty of 0.59% in the temperature range from 20 mK to 700 mK. A more detailed description and analysis of the comparison experiments is given in [41], and the results are summarised on Figure 4.

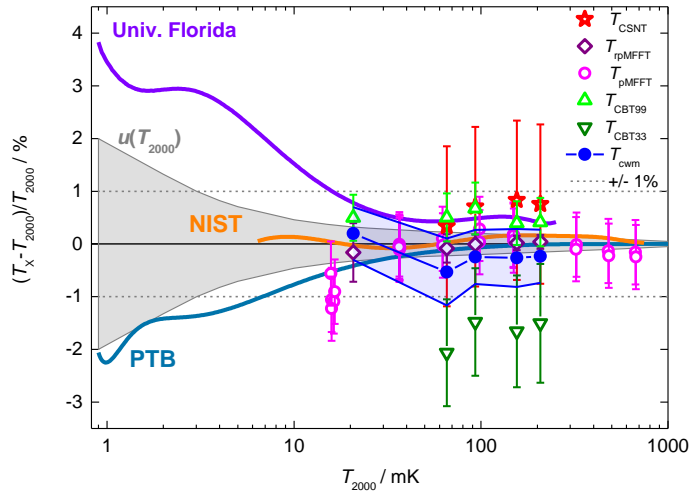


Figure 4: Compilation of thermodynamic temperature determinations at temperature below 1 K obtained in the InK project. Shown are the results measured at VTT-MIKES with different primary thermometers (CSNT (T_{CSNT}), two CBTs (T_{CBT99} , T_{CBT33}), pMFFT (T_{pMFFT})), corrected weighted mean [cwm] of all T_{cwm}) as relative deviations from the PLTS-2000. Also shown are measurements at PTB with a pMFFT operated in absolute primary mode (T_{pMFFT}). In addition, the relative deviations are shown of the background data of the PLTS-2000 obtained by NIST, the University of Florida and PTB [41]. The grey shadowed area depicts the uncertainty of the PLTS-2000 in thermodynamic terms (coverage factor $k=1$). The dashed grey lines mark a $\pm 1\%$ deviation band from the PLTS-2000. Error bars denote combined standard uncertainties ($k=1$).

The results taken together confirm the correctness of the PLTS-2000 in the temperature range from 20 mK to 700 mK. In addition it has been shown that the CSNT, CBT and pMFFT have all been developed to a sufficiently advanced state that any can be used as primary low-temperature thermometers for direct dissemination of the kelvin down to at least 20 mK.

The kelvin redefinition, the second InK project and outlook

The kelvin redefinition in terms of a defined value of the Boltzmann constant [5] is leading to a fundamental re-evaluation of the role of defined scales and primary thermometry in the international metrology domain. It is envisaged that there will be a growing role for primary thermometry, whilst at the same time the defined scales, ITS-90 and PLTS-2000 will continue to be in use. This evolving situation will be regulated by the *mise en pratique* for the definition of the kelvin, the next version of which will be issued in Spring 2019 (hence known as the *MeP-K-19*) to coincide with the unit redefinition [4].

The InK 1 project has determined for the first time definitive thermodynamic temperature values for the point of inflection of a selected set of HTFPs. More work needs to be performed to establish the fundamental liquidus temperatures of these fixed points and also to establish the thermodynamic temperatures of the remaining HTFPs. This has already started [19] and will be pursued under the CCT WG NCTherm research plan for HTFPs [20]. This work is anticipated to be completed by around 2020 and lead to the introduction of new HTFP references into routine thermometry practice.

In addition a new low uncertainty value for the thermodynamic temperature of the Cu freezing point was determined in the InK 1 project, which will influence any re-evaluation of that important thermometric fixed point.

Dissemination of high temperatures by direct and indirect primary thermometry were successfully trialled in the InK 1 project. This work has shown how both temperature realisation and dissemination can be undertaken in the future without recourse to any defined scale. Further work in this field is likely to be stimulated by the recommendations in this area flowing from the InK 1 project, ultimately leading to routine dissemination of thermodynamic temperature, at least above the silver freezing point (1234 K), by the close of the decade.

It was clear that by the end of the InK 1 project that significant work remained to be performed in primary thermometry to undertake a complete evaluation of $T-T_{90}$ and $T-T_{2000}$. The majority of this work will be performed in the successor InK 2 project [42, 43]. In this successor project $T-T_{90}$ and $T-T_{2000}$ will be determined in temperature regions not covered by InK 1 and by at least two primary thermometry methods. Above 300 K to the Cu freezing point, acoustic gas thermometry and primary radiometry will be used to determine $T-T_{90}$ with some overlap of measurements. Below about 200 K to around 5 K, $T-T_{90}$ will be measured by refractive index, dielectric constant and acoustic gas thermometry. In addition the primary thermometers developed for determining $T-T_{2000}$ will be used to evaluate the temperature range below 0.02 K down to 0.9 mK.

On completion of the experimental work in the InK 2 project taken together with the results of the InK 1 project a comprehensive low uncertainty evaluation of the thermodynamic accuracy of both the ITS-90 and PLTS-2000 will have been performed. It is envisaged that this data will be assembled into one low uncertainty reference data set of $T-T_{90}$ and $T-T_{2000}$ at a CCT workshop in Spring 2019 for inclusion in the Annex of the *MeP-K-19*. This data would then be available for any user requiring thermodynamic temperatures from sensors calibrated against ITS-90 or PLTS-

2000 and may well ultimately be used as the background data for any successor scale, the ITS-20XX, to the current defined scales.

Conclusions

The InK projects have, for the first time, drawn together a significant grouping of thermodynamic thermometry researchers in the world into one coordinated activity.

A number of primary thermometry methods have been developed to have unprecedentedly low uncertainties leading to a comprehensive evaluation of the thermodynamic basis of the current temperature scales. In the short to medium term the outcome of this activity will be a soundly founded *MeP*-K-19, which will be used by the world thermometry community to guide its realisation and dissemination of the kelvin. In the longer term the activity stimulated by the InK projects will lead to temperature realisation and dissemination by practical thermodynamic thermometry, especially at the extremes of temperature, above the silver freezing point (1234 K) and below around 1 K, and will provide the sound thermodynamic background data for any future temperature scale.

Acknowledgements

GM and EW acknowledge funding from the Engineering and Flow Programme funded by the National Measurement Office.

This project was partly funded by the EMRP which is jointly funded by the EMRP participating countries within Euramet and the European Union.

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

References

- [1] Preston-Thomas, H, *Metrologia*, **27**, 1990, 3-10 corr. 127, doi:10.1088/0026-1394/27/1/002
- [2] Rusby, R.L., Durieux, M., Reesink, A.L., Hudson, R.P., Schuster, G., Kühne, M., Fogle, W.E., Soulen R.J., & Adams, E.D., *J. Low. Temp. Phys.* **126**, 2002, 633-642, doi:10.1023/A:1013791823354
- [3] Ripple, D.C., Davis, R., Fellmuth, B., Fischer, J., Machin, G., Quinn, T., Steur, P., Tamura, O. & White, D. R., *Int. J. Thermophys.*, **31**, 2010, 1795-1808, DOI: 10.1007/s10765-010-0837-2
- [4] Fellmuth, B., Fischer, J., Machin, G., Picard, S., Steur, P., Tamura, O., White, R., Yoon H., *Phil. Trans R. Soc. A.* **374**: 20150037, 2016, <http://dx.doi.org/10.1098/rsta.2015.0037>
- [5] Fischer, J., *Phil. Trans R. Soc. A.* **374**: 20150038, 2016, <http://dx.doi.org/10.1098/rsta.2015.0038>
- [6] Machin, G., Sadli, M., Gavioso, R., Engert, J., Woolliams, E.R., *Int J Thermophys*, **35**, 2014, 405–416, DOI 10.1007/s10765-014-1606-4
- [7] Yamada, Y., Sakate, H., Sakuma, F., Ono, A., *Metrologia*, **36**, 1999, 207-209, <http://dx.doi.org/10.1088/0026-1394/36/3/6>
- [8] Yamada, Y., Sakate, H., Sakuma, F., Ono, A., *Metrologia*, **38**, 2001, 213-219, <http://dx.doi.org/10.1088/0026-1394/38/3/3>
- [9] Woolliams, E., Machin, G., Lowe, D., & Winkler, R., *Metrologia*, **43**, 2006, R11-R25, <http://dx.doi.org/10.1088/0026-1394/43/6/R01>
- [10] Machin, G., AIP Conf. Proc. **1552**, 2013, 305-322; doi: 10.1063/1.4821383
- [11] Sadli, M., Fischer, J., Yamada, Y., Sapritsky, V., Lowe, D., & Machin, G., In: *Tempmeko 04, The 9th International Symposium on Temperature and Thermal Measurements in Industry and Science*, Zagreb, Croatia, Editor in Chief Davor Zvizdic, Published: LPM/FSB, 205, 341-348
- [12] Yamada, Y., Anhalt, K., Battuello, M., Bloembergen, P., Khlevnoy, B., Machin, G., Matveyev, M. Sadli, M. & Wang T., AIP Conf. Proc. **1552**, 2013, 335 - 339; doi: 10.1063/1.4821385
- [13] Yamada, Y., Anhalt, K., Battuello, M., Bloembergen, P., Khlevnoy, B., Machin, G., Matveyev, M., Sadli, M., Todd, A., Wang, T., *Int. J. Thermophys.* **36**, 2015, 1834-1847 doi: 10.1007/s10765-015-1860-0
- [14] Woolliams, E.R., Bloembergen, P., Machin, G., *Int. J. Thermophys.*, **36**, 2015, 347-360, DOI 10.1007/s10765-014-1800-4
- [15] Castro P., Machin, G., Villamañan, M.A. & Lowe, D., *Int. J. Thermophys.*, **32**, 2011, 1773-1785, DOI: 10.1007/s10765-011-1019-6

[16] Castro, P., Machin, G., Bloembergen, P., Lowe, D., *Int. J. Thermophys.* **35**, 2014, 1341-1352, DOI 10.1007/s10765-014-1677-2

[17] Woolliams, E., Anhalt, K., Ballico, M., Bloembergen, P., Bourson, F., Briaudeau, S., Campos, J., Cox, M. G., del Campo, D., Dury, M.R., Gavrilov, V., Grigoryeva, I., Hernandez, M.L., Jahan, F., Khlevnoy, B., Khromchenko, V., Lowe, D.H., Lu, X., Machin, G., Mantilla, J.M., Martin, M.J., McEvoy, H.C., Rougié, B., Sadli, M., Salim, S.G., Sasajima, N., Taubert, D.R., Todd, A., Van den Bossche, R., van der Ham, E., Wang, T., Wei, D., Whittam, A., Wilthan, B., Woods, D., Woodward, J., Yamada, Y., Yamaguchi, Y., Yoon, H., Yuan, Z., *Phil. Trans R. Soc. A.* **374**: 20150044, 2016, <http://dx.doi.org/10.1098/rsta.2015.0044>

[18] Lowe, D.H. & Machin, G., *Metrologia*, **49**, 2012, 189-199, <http://dx.doi.org/10.1088/0026-1394/49/3/189>

[19] Lowe, D., Todd, A., van den Bossche, R., Bloembergen, P., “Definitive temperatures of HTFPs”, *Int. J. Thermophys. In preparation*, 2017

[20] Machin, G., Bloembergen, P., Anhalt, K., Hartmann, J., Sadli, M., Saunders, P., Woolliams, E., Yamada, Y. & Yoon H, *Int. J. Thermophys.*, **31**, 2010, 1779-1788, DOI 10.1007/s10765-010-0834-5

[21] Bloembergen, P., Yamada, Y., *Int. J. Thermophys.*, **32**, 2011, 45-67, doi:10.1007/s10765-011-0936-8

[22] Saunders, P., *Int. J. Thermophys.*, **32**, 2011, 26-44, DOI: 10.1007/s10765-011-0926-x

[23] Sadli, M., Machin, G., Anhalt, K., Bourson, F., Briaudeau, S., del Campo, D., Diril, A., Lowe, D., Mantilla Amor, J. M., Martin, J.M., McEvoy, H., Ojanen, M., Pehlivan, O., Rougié, B., Salim S. G. R., *Phil. Trans R. Soc. A.* **374**: 20150043, 2016, <http://dx.doi.org/10.1098/rsta.2015.0043>

[24] Gavioso, R.M., Madonna Ripa, D., Steur, P.P.M., Gaiser, C., Zandt, T., Fellmuth B., de Podesta, M., Underwood, R., Sutton, G., Pitre, L., Sparasci, F., Risegari, L., Gianfrani, L., Castrillo, A., Machin G., *Phil. Trans. R. Soc. A* **374**: 20150046, 2016, <http://dx.doi.org/10.1098/rsta.2015.0046>

[25] de Podesta, M., Underwood, R., Sutton, G., Morantz, P., Harris, P., Mark, F. D., Stuart, F. M., Vargha, G. & Machin, G., *Metrologia*, **50**, 2013, 354 – 376, doi:10.1088/0026-1394/50/4/354

[26] Lin, H., Feng, X. J., Gillis, K. A., Moldover, M. R., Zhang, J. T., Sun, J. P., Duan, Y. Y., *Metrologia*, **50**, 2013, 417 - 432 doi:10.1088/0026-1394/50/5/417

[27] Gaiser, C., Zandt, T., Fellmuth, B., *Metrologia* **52**, 2015, S217-S226, doi:10.1088/0026-1394/52/5/S217

[28] Qu, J., Benz, S. P., Pollarolo, A., Rogalla, H., Tew, W. L., White, R., Zhou K., *Metrologia* **52**, 2015, S242 –S256, doi:10.1088/0026-1394/52/5/S242

[29] Pitre, L., Risegari, L., Sparasci, F., Plimmer, M.D., Himbert, M.E., Giuliano Albo, P.A., *Metrologia* **52**, 2015, S263-S273, doi:10.1088/0026-1394/52/5/S263

- [30] Gavioso, R. M., Madonna Ripa, D., Steur, P. P. M., Gaiser, C., Truong, D., Guianvarc'h, C., Tarizzo, P., Stuart, F.M., Dematteis, R., *Metrologia*, **52**, 2015, S274- S304, doi:10.1088/0026-1394/52/5/S274
- [31] Fischer, J., de Podesta, M., Hill, K.D., Moldover, M., Pitre, L., Rusby, R., Steur, P., Tamura, O., White, R., Wolber, L., *Int. J. Thermophys.* **32**, 2011, 12 – 25, DOI: 10.1007/s10765-011-0922-1
- [32] Underwood, R., Sutton, G., de Podesta, M., Stanger, L., Rusby, R., Harris, P., Morantz, P., Machin, G., *Phil. Trans R. Soc. A*. **374**: 20150048, 2016, <http://dx.doi.org/10.1098/rsta.2015.0048>
- [33] Moldover, M.R., Gavioso, R. M., Newell, D. B., *Metrologia* **52**, 2015, S376- S384, doi:10.1088/0026-1394/52/5/S376
- [34] Moldover, M.R., Gavioso, R.M., Mehl, J.B., Pitre, L., dePodesta, M., Zhang, J.T., *Metrologia*, **51**, 2014, R1-19, doi:10.1088/0026-1394/51/1/R1
- [35] Gaiser, C., Fellmuth, B., “Method for extrapolating the compressibility data of solids from room to lower temperatures.” *Phys. Status Solidi B.*, 2016, doi: 10.1002/pssb.201552717
- [36] Feng, X. J., Gillis, K. A., Moldover, M. R., Mehl, J. B., *Metrologia* **50**, 2013, 219 – 226, doi:10.1088/0026-1394/50/3/219
- [37] Comité International des Poids et Mesures (CIPM), The Provisional Low Temperature Scale from 0.9 mK to 1 K, PLTS-2000, Appendix to Recommendation C1 (2000), <http://www.bipm.org/utils/en/pdf/PLTS-2000.pdf>, Accessed 14 June 2016
- [38] Shibahara A., Hahtela, O., Engert, J., van der Vliet, H., Levitin, L.V., Casey, A., Lusher, C.P., Saunders, J., Drung, D., Schurig, Th., *Phil. Trans R. Soc. A* **374**, 20150054, 2016, <http://dx.doi.org/10.1098/rsta.2015.0054>
- [39] Kirste A., Engert, J., *Phil. Trans R. Soc. A* **374**, 20150050, 2016, <http://dx.doi.org/10.1098/rsta.2015.0050>
- [40] Hahtela O., Mykkänen, E., Kemppinen, A., Meschke, M., Prunnila, M., Gunnarsson, D., Roschier, L., Penttilä J., Pekola., J., “Traceable Coulomb blockade thermometry”, *Metrologia.*, *In preparation*, 2017
- [41] Engert J., Kirste, A., Shibahara, A., Casey, A., Levitin, L., Saunders, J., Hahtela, O., Meschke, M., Pekola, J., “New evaluation of T -T2000 from 0.02K to 1K by independent thermodynamic methods”, *Int. J. Thermophys.*, *In preparation*, 2017
- [42] <http://www.vtt.fi/sites/ink2>
- [43] Machin, G., McEvoy, H.C, Sparasci, F., Gianfrani, L., Engert, J., “A complete evaluation of the thermodynamic fitness of the defined temperature scales through the EMPIR Implementing the new kelvin projects”, *Meas. Sci. Technol.*, *In preparation*, 2017