

FINAL PUBLISHABLE REPORT

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TABLE OF CONTENTS

1	Overview	3
2	Need	3
3	Objectives	3
4	Results	4
5	Impact	19
6	List of publications	22
7	Contact details	23

1 Overview

The global measurement system, grounded in the international system of units (the SI), is the essential foundation for reliable measurement. Such a measurement system, is necessary for trade, manufacturing, sustaining and improving quality of life. In November 2018 the International Committee for Weights and Measures (the CIPM) agreed to redefine the SI units in terms of fixed values of fundamental constants, with the implementation date set for World Metrology Day 20 May 2019. This project focused on supporting the redefinition of the SI unit for temperature, the kelvin. This project focused on establishing within EURAMET, the necessary equipment, experimental procedures and expertise for a successful introduction of the redefined kelvin. Low uncertainty determinations of $T-T_{90}$ and also $T-T_{2000}$ were performed, which, when combined with the results of InK 1, covered most of ITS-90 and all of PLTS-2000 ranges.

2 Need

In November 2018 the CIPM agreed to introduce the most fundamental change to the SI system ever undertaken since its inception. The SI, from that point on, was to be based on defined values of fundamental constants. This project focused on leading the thermometry community to a successful redefinition of the kelvin.

Research was performed focused on delivering the primary thermometry results and capability needed to facilitate an effective kelvin redefinition. In particular; robust $T-T_{90}$ and $T-T_{2000}$ data was determined to provide revised thermodynamic temperature data for the supplementary information for the *MeP-K-19* (the CCT document that enables the international thermometry community to implement the redefined kelvin). In the medium term the *MeP-K-19* will promote the use of primary thermometry for realisation and dissemination of temperature, especially at the extremes of temperature >1300 K and <20 K. In the longer-term primary thermometry could be used throughout the whole range for dissemination of temperature or a combination of primary thermometry and a new but range restricted international temperature scale (the so-called ITS202X) could be introduced.

3 Objectives

The overall aim of the project was to facilitate a successful transition to the redefined kelvin ensuring that the necessary research was completed and necessary structures (e.g. documentation) were in place. To achieve the requirements of the kelvin redefinition the following objectives were pursued:

1. To develop the facilities and methodologies for thermodynamic temperature measurements and to determine $T-T_{90}$ in the range from ~ 430 K to ~ 1358 K using two different primary methods (acoustic and radiometric) and with a target standard uncertainty of 5 mK.
2. To establish a robust uncertainty budget for Refractive-Index Gas Thermometry. To determine $T-T_{90}$ in the range ~ 5 K to ~ 200 K using three different methods (acoustic, refractive-index, dielectric constant) and with a target standard uncertainty of 0.5 mK.
3. To investigate three novel thermometry methods (Doppler Broadening Thermometry, Double Wavelength thermometry and Radiation Thermometry Traceable to Synchrotron Radiation). To establish novel primary thermometry approaches to attain uncertainties required to probe the underlying systematic uncertainties in $T-T_{90}$.
4. To improve primary thermometers (pMFFT, CSNT, CBT) for the ultralow temperature thermometry regime (0.9 mK to around 1 K). To resolve the PLTS-2000 background data discrepancy (6 % at lowest temperatures) including revised $T-T_{2000}$ data over the range 0.9 mK to 1 K (target standard uncertainty of 1 %).
5. To contribute to new or improved international standards. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain.

4 Results

In this section an extended summary of the research and results of the InK 2 project objectives are presented. The overall aim of the project was, to prepare the necessary background text and information to ensure an effective transition to the redefined kelvin, and the initiation of the realisation phase of the redefined kelvin. This section is divided into four sub-sections closely following the project objectives.

4.1 Objective 1: To develop the facilities and methodologies for thermodynamic temperature measurements and to determine $T-T_{90}$ in the range from ~ 430 K to ~ 1358 K using two different primary methods (acoustic and radiometric) and with a target standard uncertainty of 5 mK

This part of the project was to establish low uncertainty values of $T-T_{90}$ in the range from ~ 430 K to ~ 1358 K so as to establish the thermodynamic fitness of the current temperature scale, the ITS-90, in that temperature range. To reduce the overall systematic uncertainty in the results two overlapping, but independent thermometry techniques, were established. In addition, to improve the reliability of the measurements from each method, and to ensure that there was a critical mass of researchers to progress the work, several institutes contributed to each activity. The two primary thermometry methods (with partner institutes in brackets) were:

- Lower temperature primary radiometry (NPL, CEM, IO-CSIC, LNE-Cnam, PTB, NIM)
- Higher temperature acoustic gas thermometry (NPL, NIM)

Both methods needed significant enhancement and progression beyond the previous state of the art to try to meet the uncertainty target for the project. The two methods will now be described in more detail.

4.1a Lower temperature primary radiometry

Primary radiometry techniques determine thermodynamic temperatures by measuring the absolute spectral radiance ($W\ m^{-2}\ sr^{-1}\ nm^{-1}$) of a blackbody source. The method requires the determination of the radiance (radiant flux emitted per unit area and unit solid angle) in a finite wavelength band (nm) with optical power measurements traceable to a cryogenic electrical substitution radiometer. Several different methods based on this principle exist, differing in where the defining geometry (two parallel, circular, collinear apertures of known physical dimensions and separation) is located in the calibration chain and whether an imaging system is used.

For this project several different primary radiation thermometry and radiometry systems, operating at different wavelengths, were used to determine T , either directly or indirectly, and hence infer $T - T_{90}$. Primary radiometric measurements were made of:

- fixed-point blackbody (FPB) sources of tin (505 K), zinc (693 K), aluminium (933 K), silver (1235 K), gold (1337 K) and copper (1358 K)
- variable temperature heat pipe blackbody (VTBB) sources which incorporate contact thermometers which have been calibrated according to the ITS-90.

At NPL a cooperation with the National Institute of Standards and Technology (NIST, US) was established. NIST constructed and calibrated an absolutely calibrated InGaAs detector-based radiation thermometer operating at a wavelength of ~1600 nm, with good optical and linearity characteristics. This is known as the Near Infrared Thermometer 3 (NIRT3). The values of $T - T_{90}$ were determined using both FPBs and heat pipe VTBBs. The former were high emissivity (at least 0.99997) graphite blackbody cells, containing high purity metals of, respectively, tin, zinc, aluminium, silver and copper. The copper cell was installed in an electrical furnace with three heated zones. The other cells were installed within a heat pipe liner within a furnace: a potassium heat pipe for the tin and zinc cells and a sodium heat pipe for the aluminium and silver cells. The heat pipes improve the temperature uniformity of the heated zone in which the cell sits, and hence improves the fixed-point freezing plateau duration and shape.

At CEM $T - T_{90}$ measurements were performed using two absolutely calibrated standard radiation thermometers (RTs) to measure both FPBs (Cu, Ag and Zn) and VTBBs. The standard thermometers were a silicon-detector-based LP4 (650 nm and 900 nm filters) and an InGaAs-detector based LP5 (1550 nm filter). Both are calibrated by comparison with a Si trap radiometer and an InGaAs radiometer, respectively, using the radiance mode. The Si trap radiometer and the InGaAs radiometer are calibrated absolutely at IO-CSIC with

an electrical substitution cryogenic radiometer. There was also a Researcher Mobility Grant from CEM to CNAM to make Al fixed point blackbodies.

The LP4 at 900 nm and LP5 at 1550 nm were also used to estimate T by extrapolation (relative primary radiation thermometry) to lower temperatures from a Ag fixed point whose thermodynamic temperature, T_{AgFP} , has been assigned a value of 1234.90 (± 0.17) K ($k = 2$) using the absolutely calibrated thermometer at 650 nm.

The VTBBs used for measuring $T - T_{90}$ were a Na heat pipe and a Cs heat pipe from KE Technologie (see Figure 1). The temperatures of the two VTBBs are measured using two standard platinum resistance thermometers (SPRTs) one of 25 Ω for $T_{90} \leq 873$ K and another of 0.25 Ω for $T_{90} \geq 873$ K. The SPRTs have been calibrated at fixed points with an uncertainty of 10 mK and 20 mK, respectively. The SPRTs are placed in a thermowell within the heat pipe. For temperatures > 873 K, the SPRT is protected with a platinum sheath and air circulation (ISOTECH 416 system) is used to prevent contamination.

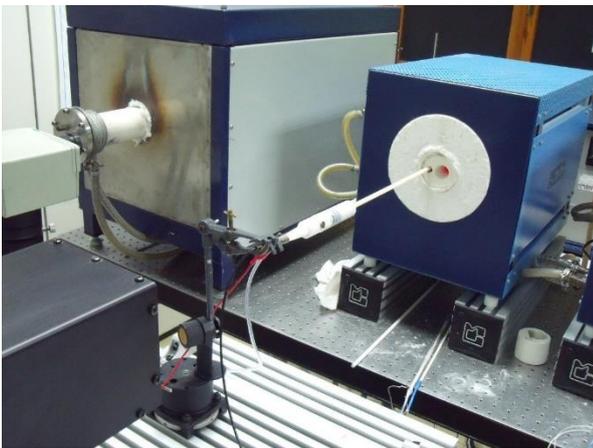
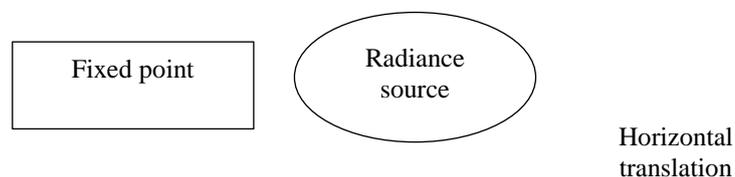


Figure 1: Measurements at CEM of $T - T_{90}$ in heat pipes using a SPRT and a radiation thermometer (RT)

LNE-Cnam used a radiance method to measure the thermodynamic temperature, T , of the Zn, Al and Ag fixed points, as well as a heat pipe VTBB. The measurements were carried out by comparing the radiance of the fixed points to that of a monochromatic source, which is absolutely calibrated using a trap detector which has been calibrated against the LNE-Cnam cryogenic radiometer. The comparison is performed using LNE-Cnam's monochromator-based radiance comparator. This is generally used in the visible range but, for this work, it has been adapted to work in the infrared spectral range (around 1500 nm) using a suitable grating and an InGaAs photodiode detector.

Figure 2 shows an overview of the radiance comparator which, for the fixed point/ monochromatic radiance source comparison, is translated in front of the bench containing the sources. The instrument is comprised of four main parts: A, B, C and D defining respectively the geometrical extent, the spectral range, the shape of the beam and the detection system.



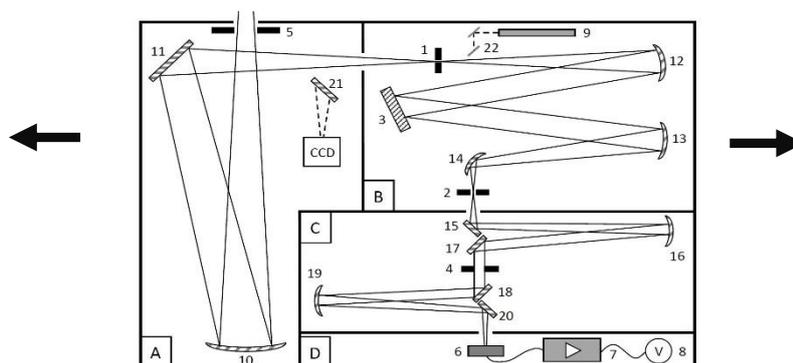


Figure 2: Schematic view of the LNE-Cnam radiance comparator in front of the sources showing the: field stop and entrance slit of the monochromator (1), exit slit (2), grating (3), Lyot pupil (4), entrance pupil (5), signal output (6, 7 and 8), gold coated mirrors (10 to 20)

The comparison between the absolute radiance source and the blackbody is performed by fixing the effective wavelength of the radiance comparator at the wavelength of the laser. The ratio of the two signals is corrected using the optical responsivity of the radiance comparator.

Measurements at PTB were performed using a four-wavelength ratio filter radiometer¹ (FRFR), which operates at four distinct wavelengths between 440 nm and 1550 nm. It is constructed from three silicon photodiodes and one InGaAs photodiode. The arrangement consists of four separate filter radiometers mounted on a linear stage with a common 3 mm diameter aperture, as shown in Figure 3.

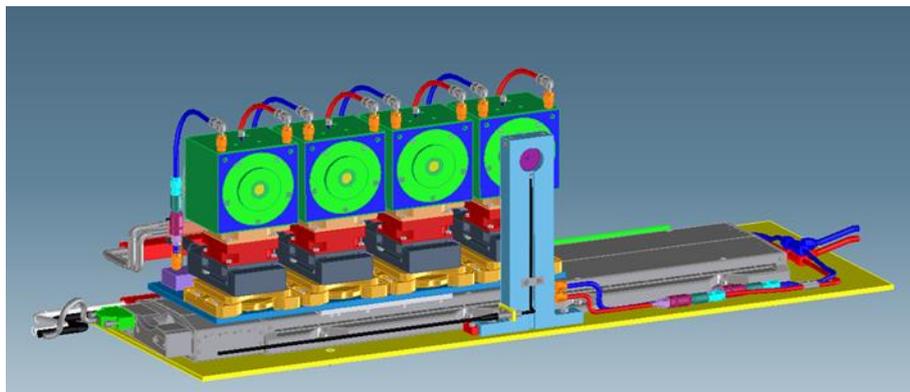


Figure 3: A schematic of the four-wavelength filter radiometer system of PTB

The calibration of the filter radiometer was a two-step process. First, a broadband transfer detector (Si trap detector or InGaAs single photodiode) is calibrated against a cryogenic radiometer at several discrete laser emission lines. Then the transfer detector is used to calibrate the filter radiometers at a spectral comparator.

For thermodynamic temperature measurements, the filter radiometers were used in conjunction with the PTB's large area blackbody (LABB) whose temperature range was 692 K and 1235 K. This blackbody furnace has been developed for accurate realisation of the spectral irradiance in the red and near-infrared spectral ranges. Its temperature is measured by standard platinum resistance thermometers according to the International Temperature Scale of 1990 (ITS-90). The blackbody consists of two concentric sodium heat pipes, the inner one with temperature stability of a few mK forming the radiating cavity. The filter radiometer was used to measure $T - T_{90}$ using the double heat pipe blackbody source (Figure 4).

¹ Note this same system is used in Objective 3 "Radiation Thermometry Traceable to Synchrotron Radiation"

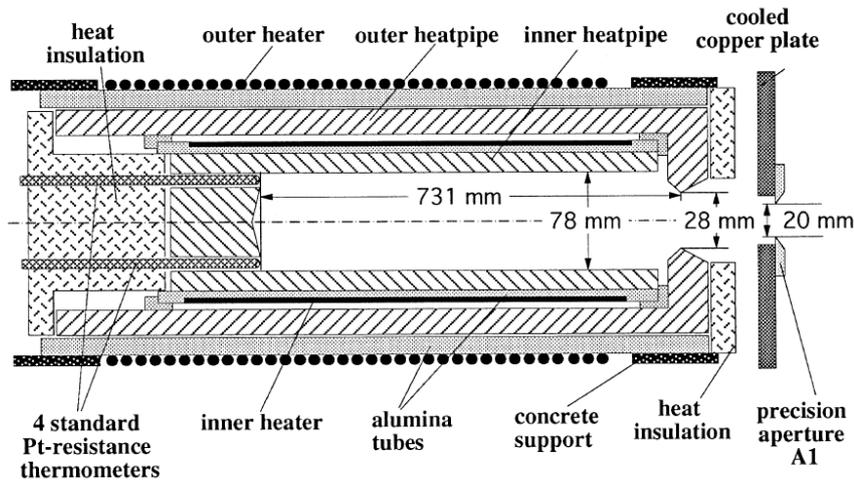


Figure 4: Schematic drawing (not to scale) of the PTB double-heat pipe blackbody

NIM, China also performed absolute radiometric measurements of the Ag point.

Attaining the target uncertainty remained unattainable by the participants (NPL, CEM, IO-CSIC, LNE-Cnam, PTB, NIM) despite many improvements to the system. A Technical Workshop was held in September 2018 (in conjunction with the IMEKO World Congress in Belfast) to share experience and to progress the state of the art, particularly in InGaAs-detector-based lower temperature radiometry. Nevertheless, the projected ($k=2$) uncertainties remained somewhat away from the target; typically for the Zn point this ranged from, ~35 mK - 120 mK rising, at the Ag point, to ~100 mK - 170 mK or higher.

4.1b Acoustic gas thermometry

Acoustic Gas Thermometry (AGT) makes use of the simple relationship between thermodynamic temperature T and the limiting low-density speed of sound, u_0 , in a monatomic gas: $u_0^2 = \gamma_0 k T / m$, where k is the Boltzmann constant, m is the average molecular mass of the gas, and γ_0 is the limiting low-pressure value of the adiabatic index, which is equal to 5/3 exactly in a monatomic gas. In high accuracy AGT, the speed of sound $u(T, p)$ is determined from the acoustic resonance frequencies of a gas-filled cavity. Typically, the shape of this cavity is either cylindrical, spherical or quasi-spherical. For the measurements performed in this project a cylindrical cavity has been used both at NPL and NIM. The resonance frequencies of a subset of acoustic modes are measured at several gas pressures and a single temperature (an isotherm), and a physical model describing the pressure dependence of $u(T, p)$ is fitted to the data to find $u_{0,T}$.

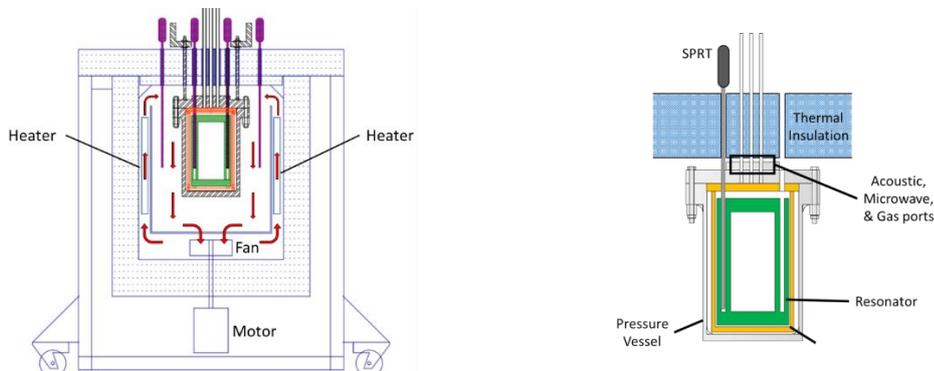


Figure 5: Schematic design of the NPL cylindrical resonator Overview (left) Resonator (right)

Simultaneous microwave and acoustic measurements are performed in the resonator to facilitate compensation of the acoustic measurements for temperature- and pressure-induced dimensional changes. At higher temperatures, dimensional changes in the cylindrical resonator from material creep are also likely to be significant. Initial proof of concept measurements were performed with an aluminium resonator, but for the

higher temperature measurements NPL used a cylindrical resonator constructed out of a copper alloy - CuCrZr. This alloy is known to retain its hardness up to 873 K (and hence reduce the influence of temperature induced shape changes) while still retaining 80 % - 90 % of the thermal and electrical conductivity of copper. Typical uncertainty estimates are around 10 mK for the NPL measurements.

NIM's longer term target is to apply acoustic gas thermometry up to the copper point (1358 K) with cylindrical acoustic gas thermometry. Heat pipes are being used to provide a uniform and stable temperature environment for the cylindrical cavity. Their objective is to achieve uncertainties for the ($T - T_{90}$) measurement near 500 K, 1000 K and 1358 K of 10 mK, 50 mK and 120 mK, respectively.

Unfortunately, due to technical and other challenges only preliminary acoustic gas thermometry results have been obtained and the measurements will continue beyond the end of the project.

4.1c Measurement results and discussion

All of the results of the measurements of all the apparatus developed above have been pooled and a report was prepared for the Consultative Committee for Thermometry (CCT). Some partners (NPL, NIM) will continue measurements, in acoustic gas thermometry, beyond the scope of this project. That data will be incorporated into the final report to the CCT, which will meet in March 2020. A summary of the results are given in Figure 6 and Figure 7 below. Despite best efforts, and the fact that the partners (NPL, CEM, IO-CSIC, LNE-Cnam, PTB, and NIM) went beyond the state of the art in primary radiometry in their institutes, the target uncertainty of 5 mK was not achieved. Nevertheless, this data represents the lowest uncertainty and it was the most comprehensive re-evaluation of $T - T_{90}$ in this temperature range.

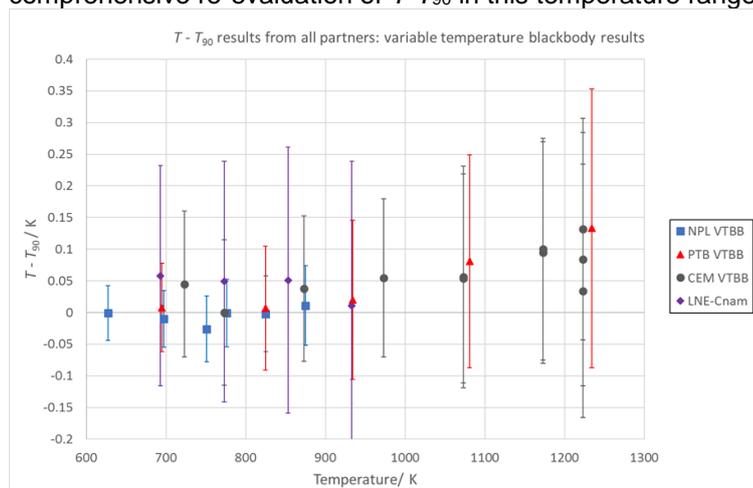


Figure 6: Plot of the $T - T_{90}$ results using the variable temperature blackbody source

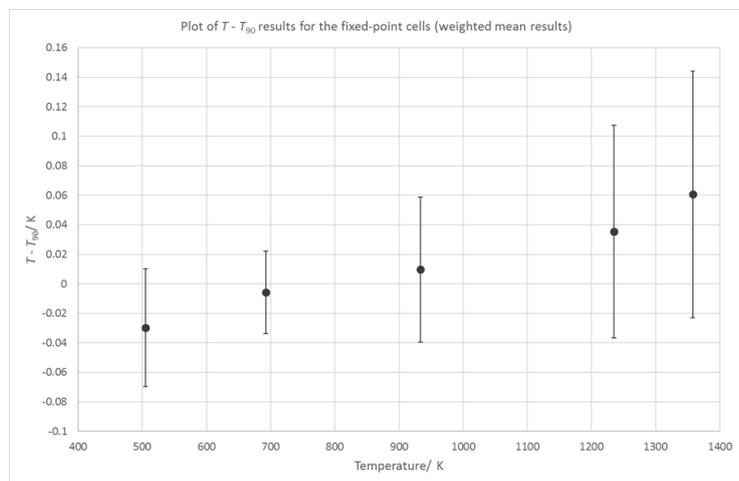


Figure 7: The weighted mean (for the Zn, Al, Ag and Cu fixed points) and the results of the Sn point measurements along with the associated uncertainties

To summarise the findings of this objective:

State of the art facilities for primary radiometric and acoustic gas thermometry determination of $T-T_{90}$ have been established.

Determination of $T-T_{90}$, by primary radiometry, has been made on both fixed-point and variable-temperature blackbody sources.

The results have been pooled and a report submitted to CCT. These are consistent with previous results in the same temperature range but form a much more comprehensive data set.

4.2 Objective 2: To establish a robust uncertainty budget for Refractive-Index Gas Thermometry. To determine $T-T_{90}$ in the range ~5 K to ~200 K using three different methods (acoustic, refractive-index, dielectric constant) and with a target standard uncertainty of 0.5 mK

This part of the project aimed to establish low uncertainty values of $T-T_{90}$ in the range from ~5 K to ~200 K to establish the thermodynamic fitness of the current temperature scale, the ITS-90, in that temperature range. To reduce the overall systematic uncertainty in the results three overlapping but independent thermometry techniques were established. In addition, to improve the reliability of the measurements for each method and to ensure that there was a critical mass of researchers to progress the work, several institutes contributed to each activity. The three primary thermometry methods (with partner institutes in brackets) were:

- Acoustic gas thermometry (AGT) (LNE, CNAM, INRIM)
- Dielectric constant gas thermometry (DCGT) (PTB)
- Refractive Index Gas Thermometry (RIGT) (LNE, CNAM, TIPC-CAS, INRIM)

All three methods needed significant enhancement and progression beyond the previous state of the art with the aim of meeting the uncertainty target for the project. The three methods, and experimental approaches, will be described in more detail below.

4.2a Acoustic gas thermometry

Acoustic gas thermometry is the same approach that is described in Section 4.1b so no general technical details will be given. However, because of the lower temperatures the resonators are made from diamond turned copper and are quasi-spherical in shape. The latter is important to break the degeneracy of the resonances and so improve resonant frequency determination. Figure 8 shows a photograph of an acoustic resonator that could be used for AGT (and RIGT). Additional activity was performed under two RMGs (INTiBS and SMU to CNAM) investigating the thermodynamic temperature of a number of non-ITS-90 cryogenic fixed points (Xe , SF_6 , C_2F_6) and also the use of one of them (SF_6 , by SMU) for calibrating platinum resistance thermometers.



Figure 8: Acoustic resonator used in this objective for RIGT and AGT

4.2b Dielectric constant gas thermometry

The approach of DCGT is to replace an evaluation of the density usually measured via extensive quantities (e.g. the gas bulb volume in constant volume gas thermometry) by a measurement of the dielectric constant of the thermometric gas. Through using the Clausius-Mossotti equation, temperature can be determined from a permittivity and a pressure measurement in a fluid of known polarisability. For low temperature primary thermometry, this method has been extensively developed by PTB using cylindrical capacitors, determining the difference in capacitance between capacitors in vacuum or filled with a pure gas at the same temperature. Benefit has been taken by progress in the *ab-initio* calculation of the polarisability of helium which has substantially increased the ultimate accuracy of the method. In this project determinations of $(T - T_{90})$ were made in temperature regions where there were particularly sparse data namely between 40 K and 120 K with different gases (He and Ne). A photograph of the PTB Dielectric gas thermometer is shown in Figure 9.



Figure 9: Photograph of the dielectric constant gas thermometer of PTB

4.2c Refractive index gas thermometry

The approach of RIGT is like DCGT where the need to evaluate the gas density is essentially replaced by a determination of the refractive index of the gas. In fact, both are classified in the larger class of temperature measurement known as Polarising Gas Thermometry². It is clear that the two approaches are linked in that the refractive index is proportional to the square-root of the dielectric permittivity of the gas whose temperature is being measured. A photograph of the (single pressure) RIGT established at TIPPC-CAS in China is shown in Figure 10. An RMG (INRiM to CNAM) worked on improving the thermal enclosures for improving pressure measurement. The results of this RMG could improve both RIGT and also AGT (Section 4.2a).



Figure 10: Novel Single Pressure Refractive Index Gas Thermometry (SPRIGT) of LNE-Cnam/TIPC-CAS

4.2d Measurement results and discussion

Significant and extensive new results have been obtained in the temperature range ~ 5 -200 K. In a number of cases the uncertainty is significantly lower than the anticipated target of 0.5 mK. Particularly noteworthy are the low uncertainty DCGT results of PTB (Figure 11), the figure also includes data from InK 1 and also shows the uncertainty assigned to the current best estimate of $T-T_{90}$ by CCT. Figure 12 shows remarkably low uncertainty (SP)RIGT results from LNE-Cnam/TIPC-CAS between ~ 5 and ~ 25 K. New and extended range AGT results from INRIM are shown in Figure 13, confirming previous results and extending the temperature range of the data even beyond 200 K to ~ 450 K.

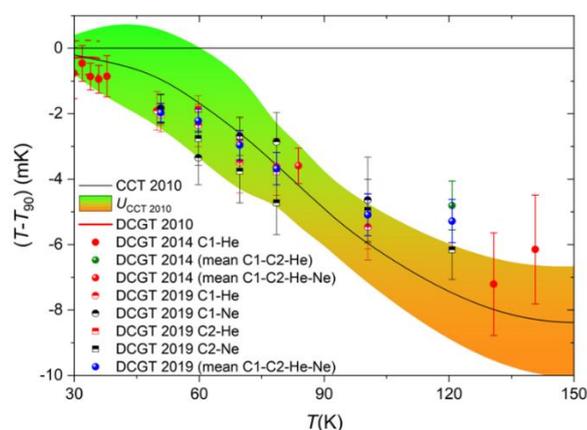


Figure 11: Results of DCGT $T-T_{90}$ at 50 K, 60 K, 70 K, 80 K, 100 K and 120 K with helium and neon gas obtained at PTB. The individual results have been combined to a weighted mean value shown as the blue dots in the graph. The data is unpublished and therefore preliminary. The 2019 results were taken as part of InK 2, 2014 were taken in InK 1

² The interested reader is referred to the *MeP-K-19* Section 4.3 where more details of Polarising Gas Thermometry can be found; along with DCGT and RIGT. <https://www.bipm.org/utis/en/pdf/si-mep/SI-App2-kelvin.pdf>
The RIGT text in the *MeP-K-19* is based on a deliverable (D3) from this project.

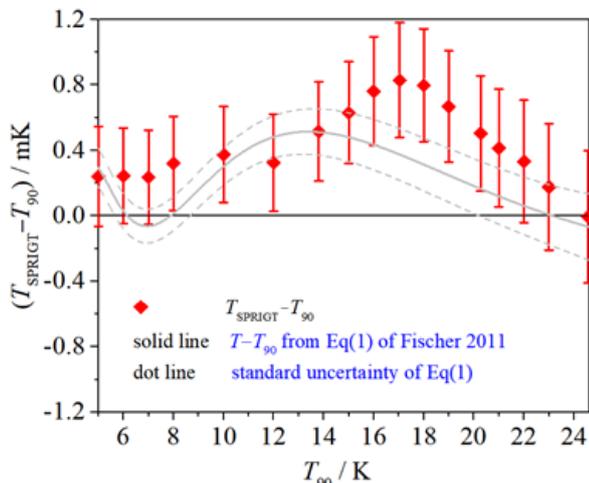


Figure 12: Preliminary $T-T_{90}$ results determined by (SP)RIGT with its standard uncertainty from 5 K to 24.5561 K by LNE-Cnam/TIPC-CAS

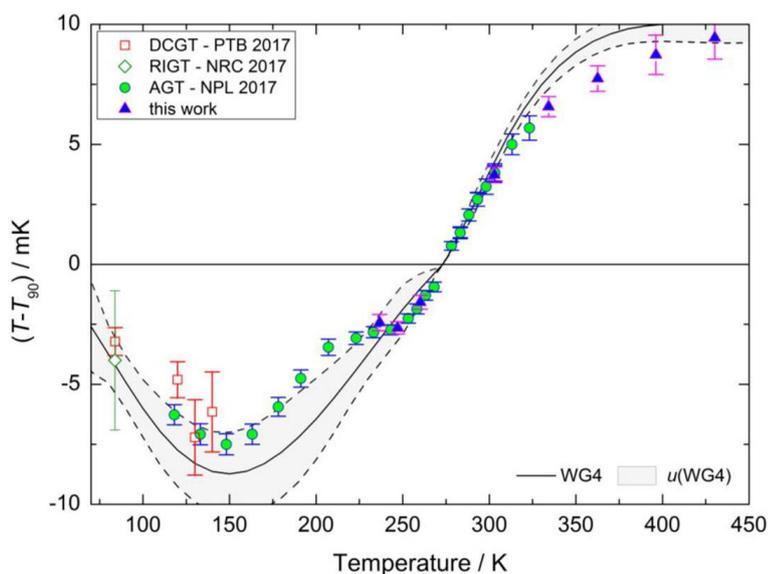


Figure 13: Comparison of $(T - T_{90})$ measured at INRiM by acoustic gas thermometry (blue triangles) in the course of the InK 2 project. This is compared with the AGT measurements performed by NPL and DCGT measurements performed by PTB in InK 1. The RIGT results from collaborator NRC are included for completeness

These results were summarised in a report to CCT³ and will be discussed as part of revising the $T-T_{90}$ consensus data, at the next CCT meeting in March 2020.

To summarise the findings of this objective:

Advances have been made in the state of the art of primary thermometry by all three approaches pursued in this objective, namely; Refractive Index Gas Thermometry (RIGT), Acoustic Gas Thermometry (AGT) and Dielectric constant Gas Thermometry (DCGT).

³ This is deliverable D4 of InK 2

The unfunded partner (TIPC-CAS), in cooperation with CNAM, have established unique primary thermometry capability below the Ne point for single pressure RIGT.

The results obtained in this project represent a significant advance in the knowledge of $T-T_{90}$ in the temperature range covered by this objective. A report has been prepared for CCT detailing the preliminary findings of this objective.

It is anticipated that all partners will continue in their primary thermometry measurement activities in preparation for CCT in March 2020.

4.3 Objective 3: To investigate three novel thermometry methods (Doppler Broadening Thermometry, Double Wavelength thermometry and Radiation Thermometry Traceable to Synchrotron Radiation). To establish novel primary thermometry approaches to attain uncertainties required to probe the underlying systematic uncertainties in $T-T_{90}$

The aim of this part of the project was to establish, for the first time, novel primary thermometry approaches, based upon measurement of electromagnetic radiation, to measure T and $T-T_{90}$. If these methods could be shown to be able to achieve lower uncertainties, they could be effective methods for probing the unknown systematic uncertainties that current methods may have. A variety of novel primary thermometry methods were developed, optimised and tested; these were:

- Doppler Broadening Thermometry (DBT) (SUN, INRIM, UP13, CNAM)
- Double Wavelength Thermometry (DWT) (TUBITAK, CNAM, LNE)
- Radiation Thermometry Traceable to Synchrotron Radiation (RTTTSR) (PTB, VNIIOFI)

The aim was, depending on the method, to explore the following different temperature ranges:

- from the Hg triple point (234 K) to In freezing point (430 K) for DBT;
- from Sn freezing point (505 K) to the Re-C eutectic melting point (2747 K) for DWT;
- from the Cu freezing point (1358 K) to the Re-C eutectic melting point (2747 K) for RTST

4.3a Doppler Broadening Thermometry

Doppler Broadening Thermometry relies on the fact that at low gas pressures the main form of broadening of spectral lines is the Doppler effect. This arises from the thermal motion of the atoms in a gas; the Doppler width being proportional to the central line frequency and the square root of the quotient of thermodynamic temperature and molecular mass. So, in principle primary thermometry using this technique should be relatively straightforward; have a laser whose wavelength is fixed at a molecular or atomic spectral line, hold a quantity of gas of that atomic species at a uniform temperature and the thermodynamic temperature of the gas is directly proportional to the square of the Doppler width. In practice DBT is a very complex technique, partly due to the complexity of the experimental set ups that need to be established and partly, or even largely, due to the perturbing effects of other line broadening and narrowing effects which need to be accounted for in the spectral analysis.

Two different research groups worked in separate institutes but on a strong cooperative basis to establish for the first time DBT with low uncertainties. Figure 14 shows a schematic diagram of the apparatus used for DBT.

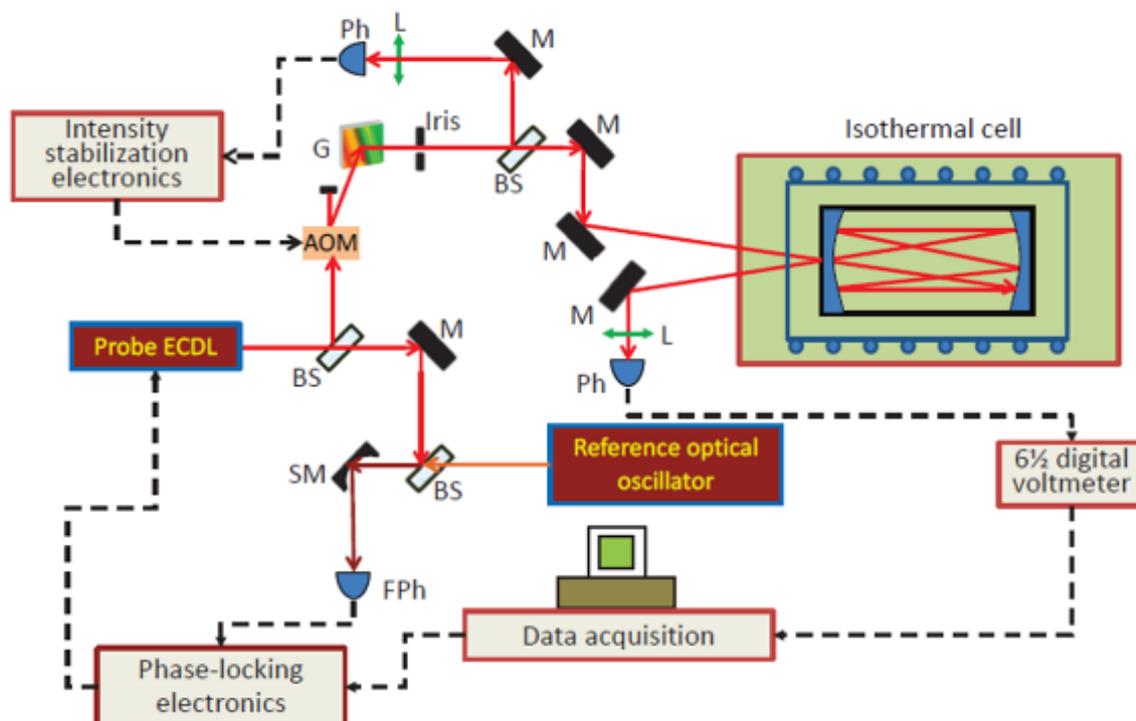


Figure 14: Schematic diagram of DBT apparatus

One of the keys to ensuring a good signal is to get a long enough path in the isothermal gas cell. This is achieved by establishing multiple reflection paths within the cell as indicatively shown in Figure 15. Traceability to ITS-90 is assured through calibrated contact thermometers integrated within the isothermal gas cell.

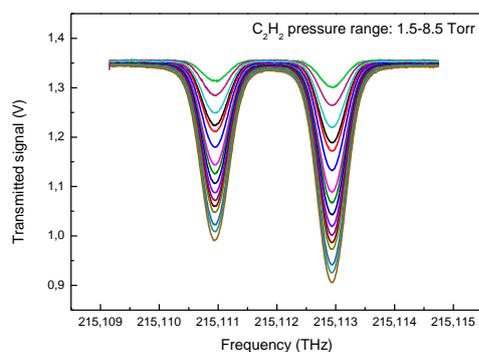


Figure 15: A typical spectrum of a target gas used for DBT, the one shown being acetylene

Individual temperatures are retrieved from fitting the line shape with a specified spectral line shape model. Then many measurements are performed both at one pressure and a number of pressures, both to allow averaging to reduce signal noise and also to separate Doppler broadening from other perturbing effects whose quantity is pressure dependent.

4.3b Double Wavelength Thermometry

The Double Wavelength Thermometry approach has long been suggested as an alternative way of performing thermodynamic thermometry for checking the veracity of single wavelength filter radiometry⁴. The latter requires an absolute calibration, traceable to optical power, and accurate geometric measurements, whereas

⁴ See for e.g. Woolliams *et. al. Int. J. Thermophys.* (2009) **30**:144-154 and references therein

the former is a relative technique requiring only wavelengths to be known accurately. In principle the experimental approach is straightforward; two radiometers at two different wavelengths and two blackbodies at different temperatures are required. Two ratios of spectral radiance *at the same wavelength* are determined with the two unknown blackbody temperatures in each. These can be solved to extract the unknown temperatures. The motivation of including DWT in this project was to test whether it could realise its potential as a way of checking the outcomes of single wavelength filter radiometry and so identify any possible unknown systematic uncertainty effects.

Research was performed in three institutes; TUBITAK, CNAM and PTB. However, it was clear as the experimental work progressed that the technique is in practice very difficult to implement. The major issue comes from the calibration over a broad spectral range, which is far from easy. In fact, the only available photodetectors with a flat spectral response are thermal detectors, which exhibit a poor signal to noise ratio. As a result, DWT shows a poor reproducibility (few %). In addition, DWT appears to be more sensitive to systematic effects than absolute radiometric method. The main limiting factors are: i) the optimisation algorithm of the numerical solver used for temperature computations; ii) the sensitivity to any small signal deviation; iii) any uncontrolled systematic spectral effect such as out of band stray light. If these effects are not quantified and corrected for very precisely the technique can lead to large temperature errors (>10 K).

By using the four-wavelength device at PTB (described in sub-section 4.1a) additional optimisation was possible and this allowed the reduction of uncertainties with the DWT technique to be larger but of the same order of magnitude as single wavelength radiometry. These are shown in sub-section 4.3d.

4.3c Radiation Thermometry Traceable to Synchrotron Radiation

Filter radiometry, based on a well-known blackbody source and a filter radiometer calibrated to optical power, is a well and long-established primary thermometry technique. However, it is also very challenging to do reliably and could be beset with a number of ill-defined systematic effects. To test the reliability of primary filter radiometry a very novel approach has been followed in this objective. The Metrology Light Source (MLS), a synchrotron, at PTB, Berlin has been used. The optical radiation emitted by the synchrotron is calculable according to the Swinger theory. By comparing the optical output of a blackbody to that of the synchrotron the systematic effects of the techniques are examined. This is a very complex experiment, and large scale, note in Figure 16 below that the distance between the filter radiometer and the MLS is 22 metres.

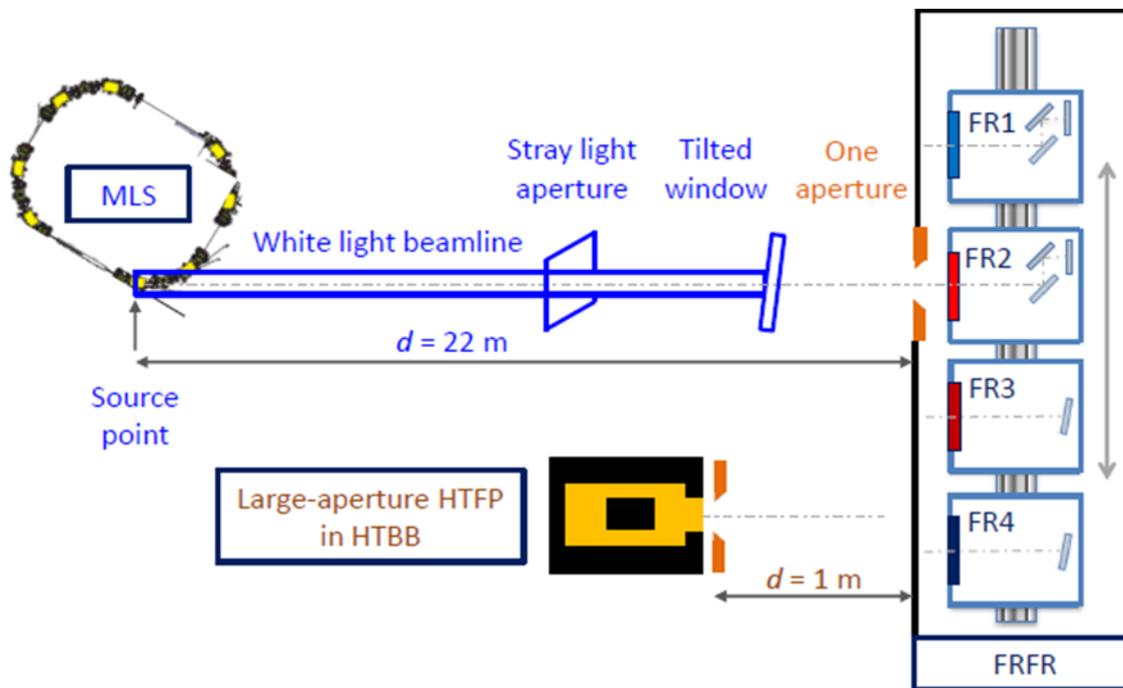


Figure 16: Schematic experimental set up for primary thermometry at the metrology light source in Berlin (this used the same radiometer as that given in Figure 3) [HTFP = high temperature fixed point, in this case Re-C nominally 2747 K, and HTBB = high temperature blackbody used as a high temperature radiance source and for melting the HTFP]

4.3d Measurement results and discussion

As the three techniques are so different the results will be discussed separately.

Firstly, in Figure 17 below typical results for DBT at the water triple point and at the Gallium point are given. Unfortunately, measurements were not made at the mercury point as anticipated due to the difficulty of thermostating the gas cells at that low temperature. However very important results were obtained. In particular it has been shown that DBT is a potentially competitive primary thermometry technique. In just three years primary thermometry by DBT, at two different temperatures, has been demonstrated with global full uncertainty analysis of <10 ppm. With further development this uncertainty may be able to be lowered further and at higher temperatures the technique could be better than with the more established technique of lower temperature primary radiometry.

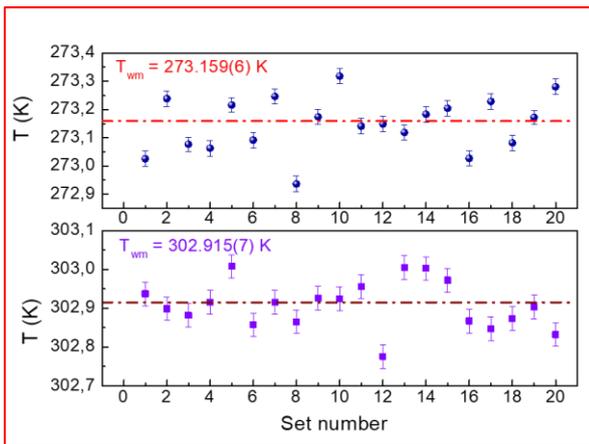
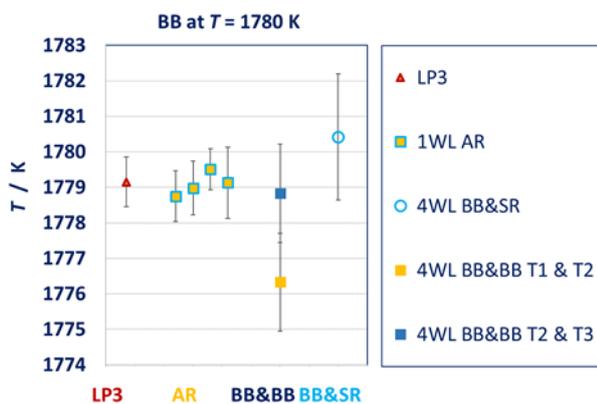


Figure 17: Results for DBT at the water triple point and the gallium melting point obtained by SUN

Secondly the results for Double Wavelength Thermometry were decidedly mixed with some participants (CNAM, TUBITAK) being unable to get meaningful results with temperature offsets amounting to 10 K or more. However, by optimising the DWT through using four wavelengths instead of two it was possible to extract temperature values with uncertainties of the same order (though still larger than) filter radiometry. Results are shown in Figure 18 below.



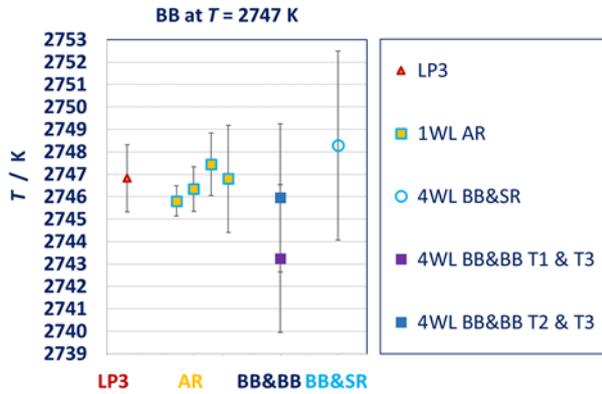


Figure 18: Results from DWT by PTB at 1780 K (upper) and 2747 K (lower) (note these figures compare the results of single wavelength (LP3, 1WL AR), and DWT (BB&BB) the data points labelled BB&SR relate to RTTSR [see below])

In this project the results of PTB showed that DWT can provide useful confirmation of the veracity of single wavelength primary radiometry. However, it is not the panacea that some have suggested, and the technique is beset with formidable experimental challenges, especially dealing with the stray light in a satisfactory manner.

Thirdly, remarkable results were obtained with Radiation Thermometry Traceable to Synchrotron Radiation. Despite the great complexity of the measurement technique for thermodynamic temperature measurements, remarkably good results were obtained. Both measurements of a variable temperature blackbody at various temperatures (see Figure 18 above) and also a Re-C point (see Figure 19) have been shown, within uncertainties, to be in agreement with the measurements of primary radiometry. This very important result shows that, at least as far as probing the synchrotron radiation allows, there are no unidentified sources of systematic uncertainties associated with filter radiometry. The reliability of filter radiometry as a primary thermometry technique is significantly strengthened because of the findings of these measurements.

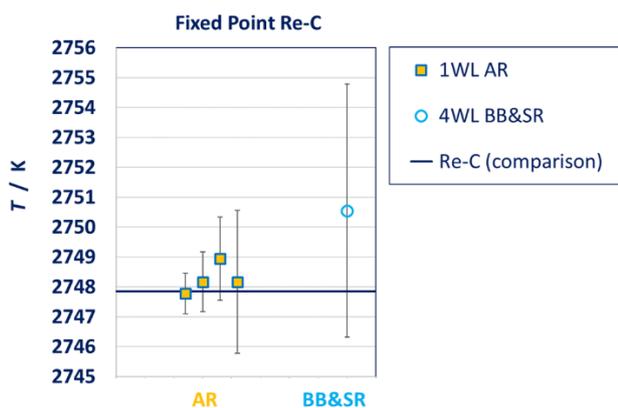


Figure 19: Comparison of thermometry of a Re-C fixed point, based on primary radiometry (AR) and RTTSR (BB&SR), good agreement is demonstrated between the two fully independent techniques

To summarise the findings of this objective:

Doppler Broadening Thermometry (DBT). The state of the art of DBT has been significantly advanced to the point where it is likely that the technique will become a competitive primary thermometry approach in the future. The preliminary results with uncertainties of <10 ppm lend veracity to this conclusion.

Double Wavelength Radiation Thermometry (DWT) was attempted to be implemented by a number of partners. However, its utility was severely hampered due to a number of limiting factors such as; extreme sensitivity to stray light and any small signal deviation and in finding a unique solution to the temperature algorithm proved challenging. Although it was possible in one case (PTB) to get reasonable results the experimental overhead in achieving low uncertainties render it uncompetitive with single wavelength absolute radiometry.

Radiation Thermometry traceable to Synchrotron Radiation (RTSR), has, for the first time, been implemented. Great progress has been made and results obtained with uncertainties that were able to provide confirmatory measurements for single wavelength primary radiometry. However, it is clear that the approach is technically very complex, requiring access to a metrology synchrotron source and so it is not suitable for routine use.

4.4 Objective 4: To improve primary thermometers (pMFFT, CSNT, CBT) for the ultralow temperature thermometry regime (0.9 mK to around 1 K). To resolve the PLTS-2000 background data discrepancy (6 % at lowest temperatures) including revised $T-T_{2000}$ data over the range 0.9 mK to 1 K (target standard uncertainty of 1 %)

The focus of this activity was to examine $T-T_{2000}$ in the lowest part of the range from <20 mK to 0.9 mK by several primary thermometry methods. The overall objective, by joining these results with those of the InK 1 project, was to develop a completely new data set of PLTS-2000 from 1 K to 0.9 mK with an uncertainty of 1 %. In addition, practical primary thermometers were developed for use by equipment manufacturers and guidelines for their use written and made available as part of the *MeP-K-19*. In the event low temperature Johnson Noise thermometry, the foundation of two of the methods investigated in this project, was added to the *MeP-K-19*.

The three different primary thermometers used in this project were the CSNT (Current sensing noise thermometer) developed by RHUL, the pMFFT (primary magnetic field fluctuation thermometer) developed by PTB and the CBT (Coulomb blockade thermometer) developed by VTT/Aalto. The former two are essentially practical, but variant, versions of Johnson Noise Thermometers where the mean square noise signal in a resistor is proportional to its temperature. The latter works on a different principle utilising the temperature-dependent conductance (G) of tunnel array junctions where the full width at half maximum of the conductance dip is a direct function of the array temperature. Figure 20 shows practical incarnations of the three thermometers.

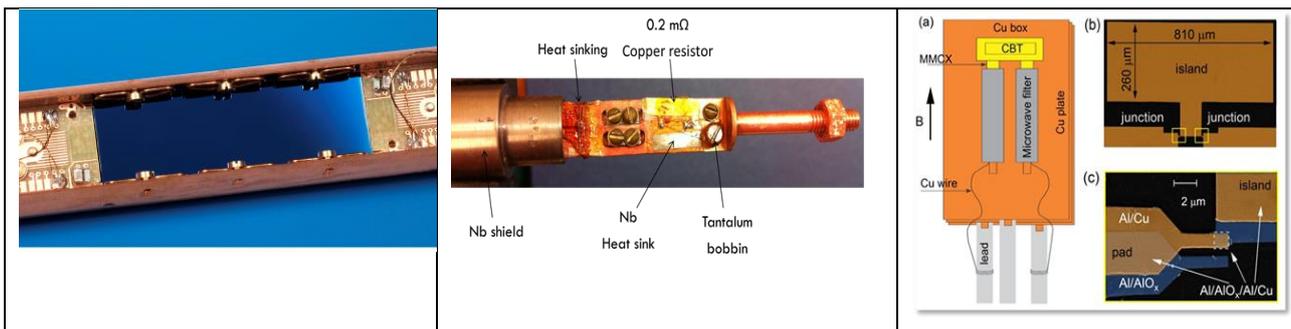


Figure 20: Photographs of the three types of low temperature primary thermometers (pMFFT (left), CSNT (centre) and CBT (right)) used in this project

The state of the PLTS-2000 before the inception of the InK 1 and 2 projects was that shown in Figure 21 (left). Essentially all the background data agreed to within about 1 % down to ~20 mK thereafter there was a sharp departure amounting to some 6 % at the lowest temperatures. A full re-evaluation of this curve has been possible in this project using the three different primary thermometers. The PLTS-2000 was disseminated by PTB through the use of calibrated super conducting reference devices – or a primary realisation was established directly to the ^3He melting curve in the facilities of RHUL and PTB. In the InK 1 project measurements were performed to ~20 mK and in this project the data was completed to 0.9 mK (Figure 21 (right)).

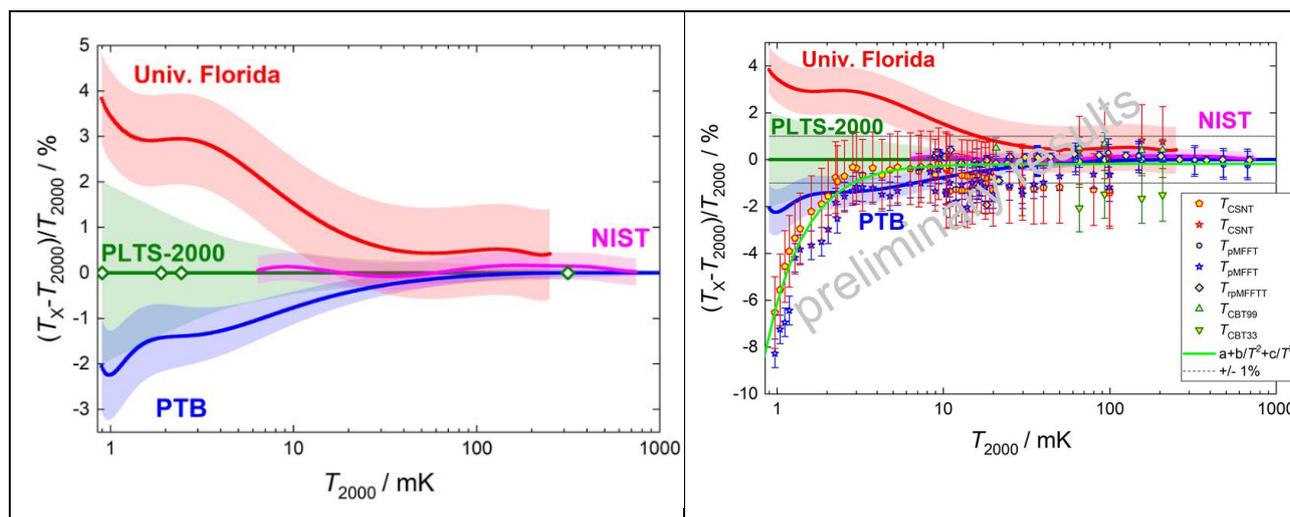


Figure 21: The status of PLTS-2000 prior to the InK projects (left), and after the InK projects (right)

Below 10 mK there seems to be a growing departure from PLTS-2000 for both types of primary thermometer. The exact source of this departure is as yet unclear hence these results are labelled preliminary until more investigation into the cause of the discrepancy can be undertaken. However, what is clear is that the new data confirms that *the PLTS-2000 is correct over 99 % of its range to within 1 %.*

A validation report discussing the three thermometer types was submitted to CCT. However, this project showed that the three thermometer types agree within their uncertainties and can in principle be used to measure thermodynamic temperature directly without recourse to the defined scale. This has been acknowledged by the CCT for the two Johnson Noise based thermometers by allowing them to become part of the *MeP-K* released in conjunction with the unit redefinition. The position and acceptance of the CBT will form part of the discussions at the forthcoming CCT in March 2020.

To summarise the findings of this objective:

All new thermodynamic temperature determinations with three different primary thermometers (CSNT, pMFFT, CBT) agree very well within their combined standard uncertainties.

In the temperature range from 0.01 K to 1 K, i.e. over 99 % of its definition range, the PLTS 2000 is thermodynamically correct to better than 1 %.

Below about 3 mK, the new data obtained with noise thermometry (CSNT and pMFFT) indicates a deviation of the PLTS 2000 from thermodynamic temperature growing to lower temperatures.

The new thermodynamic low-temperature data lends some support to the PTB-96 scale though the deviation ($T-T_{90}$) is more extreme in the measurements taken here.

4.5 Summary of results

In the above section an overview of the results of the research undertaken in InK 2 has been presented. The facilities developed/enhanced, as well as the experimental results determined in this project will be of long-term enduring value to the temperature community. However, given the size of the project it has been impossible to present all the details and the interested reader is referred to the extensive publication record for more information.

5 Impact

Dissemination has been through papers, talks at meetings/conferences (UK, Finland, Italy, Spain, France, China) and the publication of semi-popular articles in trade and special interest magazines/newsletters. Annual progress reports were submitted to CCT and the RMO TCTs, in addition an annual oral progress report was given to the EURAMET TCT. The website has been updated and the final newsletter sent to the stakeholder community. Presentations were given in NMIs, to CCT, to conferences for e.g. the Spanish Metrology

Congress 17 (San Fernando), NEWRAD 17 (Japan), Metrologie 17 (Paris), at the Chinese Academy of Sciences, Beijing (Nov 17) as well as NIM, China. In 2018, presentations were given to French optics, spectroscopy and acoustics conferences, the IMEKO World Congress and the European Association of Thermology. One special event was the EURAMET Summer School of Thermometry held in Thessaloniki, Greece in September 2018. There new researchers to the discipline were trained in a wide range of thermal measurement techniques and there were presentations on the redefined kelvin, including the contribution of InK 2. In 2019 a redefined kelvin workshop was organised at the EURAMET TCT with all the input arising from the InK 2 project. The final version of the *MeP-K-19* was launched to coincide with World Metrology Day 2019 and the launch of the redefined SI. The text included significant input from InK 2 including the parts describing low temperature Johnson Noise Thermometry and Refractive Index Gas Thermometry. A statement was issued to accreditation bodies, disseminated through EURAMET TCT contact persons, concerning the impact of the kelvin redefinition. Finally, in 2019, a special session, dedicated to InK 2, chaired by the InK 2 coordinator, was held at the important Tempmeko 2019 conference (Chengdu, China). In addition, the coordinator gave an invited keynote address at the same conference which was largely based on the InK projects.

Impact on industrial and other user communities

The main industrial impact of this project will not be felt until well after the kelvin redefinition and the approaches to primary thermometry described in the *MeP-K-19* start to take effect in the 2020s.

Early impact in the lifetime of the project will be particularly in the ultra-low temperature regime. The EU is the world's largest supplier of cryogenic equipment, dilution refrigerators and cryogen free ultra-low temperature systems. Practical primary low temperature thermometers for use below 20 K to ~1 mK are now more widely available and reliable because of this project

More widely industry will be impacted through the redefined kelvin and more direct traceability to the kelvin definition. This will be in the years following the kelvin redefinition (2019) as the realisation and dissemination phase of the redefined kelvin becomes increasingly operative in the 2020s.

Impact on metrology and other scientific communities

The main impact of the InK 2 project will be on the whole international thermometry community through performing the necessary research required to ensure an effective and trouble-free implementation of the kelvin redefinition in May 2019. This has now been achieved with the kelvin being redefined in Nov 2018 and the implementation phase being complete in 20 May 2019.

The main immediate beneficiary of this research was the CIPM as the work performed in this project strongly facilitates a sound and reliable introduction of the redefined kelvin. The CCT has been and will continue to be strongly impacted by the outcomes of this project, with direct input into the text of the *MeP-K-19* and through new evaluations of reliable low uncertainty thermodynamic temperature values, $T-T_{90}$ and $T-T_{2000}$. In addition, the practice primary thermometry methods were advanced sufficiently to admit them into the *MeP-K*, for example Refractive Index Gas Thermometry and low temperature Johnson Noise Thermometry.

This impact was assured because partners chaired and participated in key CCT working groups and task groups, responsible for both the *MeP-K-19* and also the validation of thermodynamic temperature values.

Scientific impact has been made through advancing the state of the art in primary thermometry in the partners' laboratories. A significant number of refereed scientific papers in leading relevant journals and presentations at appropriate workshops, symposia and conferences have been published and submitted. Of particular note is the impact InK 2 had at the major Tempmeko/Tempbeijing 2019 conference. The vast majority of the world experts in thermometry attended that meeting, and besides the special session highlighting InK 2 outcomes, there was a keynote address and in total 30 papers/posters derived from the work of InK 2.

Development of an EU cohort of primary thermometry experts was greatly facilitated through this project with 19 staff exchanges having taking place in the InK 2 project with more planned, including through the Researcher Mobility Grant mechanism. This will prove invaluable to the success of the realisation phase of the redefined kelvin which will take place over the coming decade.

Impact on relevant standards

This project has and will continue to have great impact on the thermometry community around the world. It has produced definitive technical data and results and recommendation documents for the CCT. Importantly, it has produced a complete re-evaluation of the PLTS-2000 over its entire range, and the ITS-90 up to the Cu freezing point (1358 K). In addition, definitive text for the *MeP-K-19* has been written and supplied for, refractive

index thermometry (including principles, practice and uncertainties) and the various forms of Johnson Noise Thermometry for ultralow temperature thermometry namely CSNT and pMFFT. Text for CBT has also been prepared in anticipation of its incorporation into a future version of the *MeP-K*, the latter will be considered at the March 2020 CCT meeting.

It is very important that the relevant international bodies are kept informed of the progress and outcomes of the project. An annual oral progress report was given to the EURAMET TC-T in April 2017, April 2018 and April 2019. The RMO Thermometry Technical Committees were sent a written annual progress report in May 2017, April 2018 and July 2019. The global NMI community was kept up to date through annual reports from the InK 2 coordinator to the CCT, issued through the president.

The outcomes of InK 2 will enduringly support all standards that requires reliable temperature measurement, including humidity and moisture and related thermal quantities. InK 2 and the previous InK 1 project have put in place the foundational framework for reliable thermometry, post the kelvin redefinition, throughout the world.

Longer-term economic, social and environmental impacts

The InK 2 project will have wide ranging economic, social and environmental impact over the next decade and beyond. This is because the project's objective is to facilitate and provide ongoing reliable fit-for-purpose temperature measurement which is required in all these domains.

The first long term impact will be through the key stakeholder the CCT (and more generally the CIPM). The research outcomes of InK 2 (in combination with the previous InK 1 project) have supported an effective introduction of the *mise en pratique* for the definition of the kelvin (*MeP-K-19*). In addition, through new evaluations of low uncertainty values for $T-T_{90}$ and $T-T_{2000}$ the InK 1 and InK 2 projects will provide, for any user who needs them, thermodynamic temperature values from the defined scales. It is envisaged that these will become definitively available after the next CCT (Mar 2020). In the long term (late 2020s/2030s) this data may provide the platform for a possible future temperature scale ITS-20XX if required. Or, alternatively, the measurement approaches stimulated by the InK projects may lead to a rise in practical primary thermometry for the realisation and dissemination of thermodynamic temperature directly linked to the redefined kelvin. (See the *Impact on metrology and other scientific communities* section above for more details).

The redefinition of the kelvin, in May 2019, has led to a situation that was akin to that when the metre was redefined in the 1980s. After the metre redefinition there was a rapid expansion of new optically based dimensional measurement approaches leading to large new industries today (Renishaw for e.g.). It is very likely that something similar will happen in the decades following the kelvin redefinition. NMIs will increasingly use primary thermometry for dissemination of temperature (for e.g. by the mid-2020s this is likely to have happened for high temperatures above 1300 K and for low temperatures below 20 K. These are two of the objectives of the soon to start EMPIR Real-K project). In the longer term (2030s and beyond) it is envisaged that there will be an increasing use of *practical* primary thermometry directly in industry to facilitate "always on always traceable" temperature sensing, where traceability is built directly into the sensor itself. These new sensing methods may even give rise to new sensor manufacturers in the future.

The rise in dissemination of thermodynamic temperature by NMIs, and also the rise of practical primary thermometry could well lead to a decreasing role for the defined scales in the 2020s, with PLTS-2000 being completely superseded by primary thermometry approaches and ITS-90 dissemination increasingly curtailed to the mid-range temperatures. Ultimately in the very long-term thermodynamic temperature may be all that is disseminated by NMIs, obviating the need for a defined scale. This would negate cost to industry because it would avoid the introduction (and associated costs) of any future temperature scale and reduce or even eliminate the need for sensor retrieval and recalibration.

From an environmental point of view traceability to thermodynamic temperature would be welcomed. For example, when monitoring global temperatures, corrections for changes in temperature scales have to be made to data. Besides introducing unfortunate step changes in the data record it is not always clear which temperature scale was used for the measurements leading to additional uncertainties. If traceability to thermodynamic temperature is achieved, then no new temperature scale will be needed, and all environmental temperatures will then be founded on fundamental physics and no correction from a defined scale will be required in the future – simplifying the interpretation of data sequences and reducing the contingent uncertainty. In addition, temperature monitoring of long-term hazardous waste (e.g. nuclear waste) requires "fit and forget" technology – practical primary thermometry is potentially an important solution for this currently intractable problem.

So, in summary the economic and social impact of this project in the longer term will be significant through facilitating traceability to thermodynamic temperature and practical primary thermometry. This will have contingent industry benefits through optimising energy use and ensuring the lowest possible carbon emissions (which is also good for the environment). In addition, the rise and introduction of practical primary thermometry will facilitate autonomous production which requires completely reliable and traceable sensors. Finally, totally new high technology sensor manufacturing industries could arise because of the development of practical primary thermometry approaches.

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7 Contact details

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