Final Publishable JRP Summary Report for JRP SIB01 InK Implementing the new kelvin

Overview

This project addressed outstanding high-priority issues in temperature measurement for the international metrology (measurement science) community. In particular the methods and data generated here are being used to prepare the international measurement community for the forthcoming redefinition of the kelvin in 2018. The project developed National Measurement Institute capabilities for making and disseminating high-temperature (> 1000 °C) and low-temperature measurements (< 1 K) directly linked to the forthcoming new kelvin definition, and in addition, generated the lowest-uncertainty data ever achieved for the international temperature scale of 1990 (ITS-90).

Need for the project

The kelvin (K), the SI unit of temperature in the International System of Units, will be redefined in 2018 as part of the Committee for Weights and Measures (CIPM) program to redefine all SI base units in terms of fundamental physical constants. The kelvin will be redefined in terms of a fixed value of the Boltzmann's constant.

To ensure the redefinition is successful, the transition must be supported by accurate primary thermometry methods and a robust and documented *mise en pratique* (*MeP*-K) that allows the new definition to be realised in practice at National Measurement Institutes (NMIs). Ahead of the redefinition the BIPM's Consultative Committee for Thermometry (CCT) identified the following high-priority requirements in primary thermometry:

- The determination of transition temperatures for the high temperature fixed points to be used for realising and disseminating high-temperatures.
- A trial of the methods proposed in the *mise en pratique* for the dissemination of high-temperatures.
- More reliable, low-uncertainty values of the differences between the ITS-90 and thermodynamic temperature for the *MeP*-K, and potential future temperature scale.
- New measurements of the differences between PLTS-2000 and thermodynamic temperature for the *MeP*-K and improved calibration of temperature sensors below 1 K.

From the outset of the project it was realised these steps were a long-term process and would require a follow-on project. The InK 2 project was started in June 2016 to complete the work begun in InK 1.

Scientific and technical objectives

The goal of this project was to address current issues in temperature measurement to help develop a robust *mise en pratique* to disseminate the redefined kelvin from 2018 onwards. To achieve this, four objectives were set: Objective 1 used primary thermometry to determine the transition temperatures of high temperature fixed points to be used for realising and disseminating high-temperatures. Objective 2 developed methods to disseminate high-temperatures. Objective 3 developed more reliable, low-uncertainty values of the differences between the ITS-90 and thermodynamic temperature for the *MeP*-K and potential future temperature scale. Objective 4 performed new measurements of the differences between PLTS-2000 and thermodynamic temperature for the *MeP*-K and improved calibration of temperature sensors below 1 K. In summary the four objectives were:

1) Assign thermodynamic temperatures to high-temperature fixed-points above 1000 °C (>1300 K).
2) Realisation and dissemination of T instead of ITS-90 at high temperatures.
3) Determination of $T - T_{90}$ with lowest ever uncertainties.
4) Develop primary methods of realising and disseminating T below 1 K and resolve the long standing discrepancy in the low temperature part of PLTS-2000.

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Results

1) <u>Assign thermodynamic temperatures to high-temperature fixed-points above 1000 °C (>1300 K).</u>

The International Temperature Scale of 1990 (ITS-90) is used to calibrate temperature sensors by comparing their readings against fixed points that undergo phase changes (such as freezing) at precise temperatures. The scale has 16 fixed points that span temperatures from 13.8 K (-259.3 °C) to 1084.6 °C (1357.8 K). However, temperatures well above 1000 °C are now routinely used in science and industry, and additional high-temperature fixed points (HTFPs), from outside the ITS-90 scale, are already used to calibrate instruments to these temperatures. However, the exact temperatures at which these HTFPs undergo phase changes had not previously been determined by primary thermometry – and thus their uncertainty was greater than it could be.

To address this, the project used primary thermometry methods to measure phase change temperatures of four HTFPs, copper (Cu), and three metal-carbon alloys, cobalt-carbon (Co-C), platinum-carbon (Pt-C), and rhenium-carbon (Re-C). The copper point was investigated as it is the highest fixed point in ITS-90 and thus provides a reference point to the scale, but also because the value has been recognised as requiring further evaluation to refine its accuracy.

The objective was achieved as the temperature of the Cu point was re-determined with greater accuracy, and the temperatures of the Co-C, Pt-C and Re-C points were also determined (see Table 1). A calculation of the overall uncertainties of the metal-carbon fixed point measurements will be determined post project (mainly taking into account uncertainty introduced by alloy impurities and variations in internal furnace temperature). After this additional step (expected by end 2016), all the values will be recommended to the BIPM's Consultative Committee for Thermometry (CCT) for incorporation within the *mise en pratique* for the new kelvin definition.

HTFP	**Temperature (K)**
Re-C	2747.84 (0.35)
Pt-C	2011.43 (0.18)
Co-C	1597.39 (0.13)
Cu	1357.80 (0.08)

Table 1: Phase change temperatures and uncertainties for the four HTFPs studied.

2) <u>Realisation and dissemination of *T* instead of ITS-90 at high temperatures.</u>

The aim of this objective was to perform a detailed evaluation of two potential methods for the realisation and dissemination of thermodynamic temperatures above 1000 °C directly, without using temperature scales. This has never been widely attempted before, but has the advantage that users, principally in industry, will have continuous access to reliable temperatures, and any concerns about future scale changes will be eliminated. In addition, future technological improvements in temperature dissemination could be implemented without the need of a scale change, because the kelvin is being directly realised and disseminated and hence not limited to any scale. Results of this research will be used to provide recommendations for high-temperature dissemination to the CCT.

The project investigated two alternative methods; dissemination through known temperature references, such as HTFPs; or dissemination by absolutely calibrated radiation thermometers. Both methods were evaluated, for the first time, by all European NMIs capable of making such measurements. The following draft recommendations have been proposed to the CCT Working Group for Non-Contact Thermometry:

(i) HTFPs can be used to disseminate either the ITS-90 scale or direct temperature from NMIs to users, with uncertainties at least comparable with current approaches.

However, considering that this study (along with others) has shown that there are still some ill-understood effects due to the interplay of the furnace and HTFP cell, namely thermal inertia and non-uniformity of temperatures within furnaces, 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 quantification.

(ii) Filter radiometers and radiation thermometers, traceable to the radiant watt, can be used to disseminate temperature to users directly, with uncertainties comparable to current methods.

However, it should be noted that unknown radiometer drift remains a problem. If this approach is adopted it is recommended an HTFP be used to periodically assess the stability of the radiometer, or that at least two radiometers be used as the basis of the transfer, and that periodic cross comparisons are 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 draft recommendations were presented and discussed at the CCT Working Group for Non-Contact Thermometry (CCT WG NCTherm) meeting in July 2016, and will form the basis of a formal declaration of CCT WG NCTherm on the optimum use of these HTFPs, and the remaining research that needs to be conducted to achieve their maximum performance.

3) Determination of $T - T_{90}$ with lowest ever uncertainties.

The ITS-90 scale is used globally to disseminate temperature and to calibrate temperature sensors. However it is known that certain parts of the scale are different from thermodynamic temperature, and these areas required new measurements, particularly from the triple point of neon to the triple point of water (~24.5 K to 273.16 K), and between 550 K and the freezing point of zinc (~693 K).

To address this, the project determined the difference between ITS-90 and thermodynamic temperature values derived via primary thermometry, with the aim of reducing uncertainties by a factor of two for temperatures between 2.5 K to ~650 K. Two primary methods were used, acoustic and dielectric constant thermometry – the use of two independent methods allowed systematic errors to be identified and quantified in each.

The objective was partially achieved, as measurements were made between 25 K to ~303 K with the lowest levels of uncertainty ever recorded. Ultra-low uncertainty measurement above ~303 K were not achieved, due to greater technical challenges experienced with primary thermometry than were originally envisaged. However, the capability to make ultra-low uncertainty measurements up to 1300 K was developed during the InK 1 project, and will be utilised by the InK 2 project. These results from InK 1 and InK 2 will cover the entire ITS-90 range and will be ready for the final evaluation of ITS-90 for the *mise en pratique* annex. When taken together these results will represent the most comprehensive and low-uncertainty evaluation of ITS-90 ever undertaken, and will lay a firm foundation for any possible future successor scale.

4) Develop primary methods of realising and disseminating *T* below 1 K and resolve the long standing discrepancy in the low temperature part of PLTS-2000.

The Provisional Low Temperature Scale of 2000 (PLTS-2000) is realised using the melting pressure curve of helium-3, for temperatures from 1 K down to 0.0009 K (0.9 mK). The scale is provisional because it was based on inherently discrepant results, particularly at temperatures below 0.02 K. New measurements are required to identify and overcome this discrepancy and so reduce the inherent uncertainty in the scale. To address this, primary thermometers were developed with the necessary performance to make measurements below 1 K. The measurements performed represent a significant advance from the original PLTS-2000 measurements, as they have been derived using three different, independent thermometry methods.

The overall objective was partially achieved, as primary methods for realising and disseminating temperature measurements were developed between 1 K to 0.02 K. However, the technical challenges of performing ultra-low temperature measurements meant that measurements were not achieved at the lowest end of the PLTS-2000 scale, from 0.02 K to 0.9 mK. The background techniques were put in place and this range will be measured in the follow-up InK 2 project. The combined results from InK 1 and InK 2 will represent a complete re-evaluation of PLTS-2000, and will be a powerful demonstration of the new practical primary thermometers developed by this project. In fact their effectiveness as primary thermometers may ultimately lead one or more of them being used as a means of directly disseminating the redefined kelvin below <1 K.

The results from this project were discussed at the Consultative Committee for Thermometry (CCT) Working Group for Contact Thermometry in July 2016, and will form the basis of recommendations for primary methods for low-temperature measurement.

Actual and potential impact

The project has made advances in temperature measurement which will be particularly important in supporting the international thermometry community in the transition to the new definition of the kelvin in 2018.

Dissemination of results

The results of the project have been shared widely throught the thermometry community. 63 papers have been published in journals (listed in the next section), and it is likely that further papers will be published incorporating work from this project with the InK 2 project. A Royal Society workshop, *Towards implementing the new kelvin*, was held in May 2015 and proved a fitting climax to the project, with many new and important results presented. All presentations, linked to InK 1, from the event have been published in a special edition of the *Philosophical Transactions of the Royal Society A.,* Vol. 374, March 2016. This volume will serve as the most important method of dissemination and will prove to be an enduring record of the InK 1 project. Other dissemination activities include annual reports to the CCT and Regional Metrology Organisation's Technical Committees for Thermometry, and invited presentations at international conferences.

Immediate impact

The project has achieved immediate impact in four technical areas:

1. For the first time, definitive transition temperatures for a set of high-temperature fixed points have been determined, and the Cu freezing point has been re-determined. These new values have been published and will, when further work to assign final uncertainty components for furnace and impurity effects, be recommended to the CCT for inclusion in the next version of the *mise en pratique* (*MeP*-K).
2. For the first time, a comparison of two *MeP*-K recommended approaches for disseminating high-temperatures have been trialled and compared. The work has been published, and the outcomes have been discussed at the CCT Working Group for non-contact thermometry. Recommendations to the CCT have been made on the basis of these findings, and will help the thermometry community to objectively decide which is the most appropriate dissemination approach for high-temperatures.
3. The world's lowest uncertainty determination of ITS-90 has been undertaken in the range of 25 K to 303 K, some of which was performed by two independent temperature measurement methods. This data has been considered by the CCT Working Group for Contact Thermometry for inclusion in a revision of the thermodynamic temperature data annex of the *MeP*-K.
4. For the first time since its inception, PLTS-2000 has been comprehensively investigated using independent methods in the temperature range of 0.02 K to 1 K. The approaches developed here will be used in the follow-on InK 2 project to evaluate PLTS-2000 over its complete range (i.e. down to 0.9 mK above absolute zero).

Potential future impact

The results of this project, when combined with those of the InK 2 project, will make a major and enduring contribution to the thermometry community through the recommendations made to the CCT, and through the provision of new and more accurate temperature data to refine the current temperature scales. The methods and data developed here will support the successful realisation of the redefined kelvin through the development of an effective *mise en pratique*, and in the longer term potentially inform a future temperature scale.

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