Publishable Summary for 22IEM02 DireK-T
Dissemination of the redefined kelvin

Overview

The aim of this project is to take advantage of the kelvin redefinition using practical primary thermometry approaches for the dissemination of thermodynamic temperature. The kelvin redefinition in May 2019 initiated a comprehensive research phase for the realisation and dissemination of thermodynamic temperature to replace the ITS-90/PLTS-2000 scales currently in use. This project progresses beyond the state of the art, through: demonstrating dissemination of the kelvin from 4 K to 300 K; developing a robust framework for establishing traceability by primary thermometry; working towards the next generation primary thermometry to 700 K.

Need

The CIPM (International Committee of Weights and Measures) Consultative Committee for Thermometry (CCT) recommendation T1 (2017) stated that member state National Metrology Institutes (NMIs) “take full advantage of the opportunities for the realisation and dissemination of thermodynamic temperature afforded by the kelvin redefinition and *the mise en pratique* for the definition of the kelvin (*MeP*-K)”. In addition, the research needs for temperatures above ambient was highlighted by the CCT recommendation T1 (2021) that NMIs establish capability to determine the difference (T-T_{90}) between the thermodynamic temperature T and its approximation, the defined scale ITS-90 (T_{90}), above 400 K and, in so doing, establish the background capacity for dissemination of thermodynamic temperatures approaching 700 K.

The *MeP*-K allows for the dissemination of temperature either by thermodynamic means or one of the defined scales. However, many issues remain about how the two approaches interrelate and how to demonstrate the degree of equivalence. To facilitate disseminating thermodynamic temperature these issues need addressing.

The EMPIR JRP 18SIB02 Real-K project began the transition away from defined scales by establishing the capabilities to disseminate thermodynamic temperature at high temperatures >1235 K and low temperatures, particularly <5 K. This project’s research, building on the achievements of EMPIR JRP 18SIB02 Real-K, addresses the high-level metrology needs stated by CCT, ensuring that thermodynamic temperature can be realised and disseminated to room temperature and beyond. The project includes a wide range of NMIs ensuring the developed approaches are appropriate for NMIs at different stages of development.

Objectives

The overall objective of this project is to establish the capability to disseminate thermodynamic temperature from 4 K to ~300 K, which requires an internationally agreed framework to demonstrate that thermodynamic temperature dissemination is reliable, as well as to enable thermodynamic temperature dissemination above 300 K.

The specific objectives of this project are:

1. To demonstrate practical thermodynamic temperature realisation and dissemination from 4 K to 25 K with targeted measurement uncertainties of 0.3 mK (k=1) using at least three independent thermodynamic methods (Dielectric Constant Gas Thermometry - DCGT, Refractive Index Gas Thermometry - RIGT and Acoustic Gas Thermometry AGT) to, at least, two NMIs without primary thermometry capabilities in this range, using practical temperature sensors (e.g. capsule-type RhFe or Pt thermometers) as transfer standards.

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2. To demonstrate practical thermodynamic temperature traceability in the range 25 K to 300 K using at least two independent thermodynamic methods (Refractive Index Gas Thermometry - RIGT and Acoustic Gas Thermometry AGT) to, at least, two NMIs without primary thermometry capabilities in this range, using practical temperature sensors (capsule-type platinum resistance thermometers) as transfer standards. Target uncertainty 0.25 mK at 25 K and 0.6 mK at 300 K (k=1).
3. To develop a coherent framework for thermodynamic temperature dissemination to ensure consistency of dissemination of temperature from NMIs to users over the temperature range 4 K to 300 K whether it is by thermodynamic temperature or the defined scale (ITS-90) and develop a recommendation to CCT about the measurement uncertainties and the level of equivalence between these approaches to ensure that users have a clear understanding of the relationship between the two.
4. To establish a capability for the realisation and dissemination of thermodynamic temperature between 300 K and 700 K with T-T_{90} target uncertainty of 0.6 mK at 300 K and 7 mK at 700 K (k=1).
5. To establish an integrated European temperature metrology infrastructure and facilitate the take up of the developed technology and measurement infrastructure by the measurement supply chain (accredited laboratories, instrument manufacturers), CIPM Consultative Committee for Thermometry (CCT), EURAMET and other RMO TC-Ts and relevant end users (industry and academia such as CERN, quantum computing, fundamental materials science communities, etc.).

Progress beyond the state of the art and results

Demonstrating dissemination of thermodynamic temperature from 4 K to 25 K (objective 1)

The current state of the art for temperature realisation and dissemination between 4 K and 25 K is through the defined scale (ITS-90). The situation is complex with different technical approaches and overlapping ranges; (0.65 K to 5 K ^{3}He/^{4}He vapour pressure thermometry, 3 K to ~24.6 K interpolating He gas thermometer and above ~13.8 K fixed points and capsule standard platinum resistance thermometer). Because of the complexity there are very few full ITS-90 realisations globally in this temperature range.

This project progresses the state of the art building on the developments of EMPIR JRP 18SIB02 Real-K, where the capability for disseminating the redefined kelvin below 25 K was developed, to demonstrate for the first time, low uncertainty thermodynamic temperature dissemination. Three thermodynamic approaches (Dielectric Constant Gas Thermometry - DCGT, Refractive Index Gas Thermometry - RIGT and Acoustic Gas Thermometry AGT) will be used to perform the thermodynamic temperature calibrations of capsule-type thermometers to be used as transfer standards for dissemination to NMIs without primary thermometry capabilities. Target uncertainty 0.3 mK (k=1) in the range for the dissemination.

Towards demonstrating dissemination of thermodynamic temperature from 25 K to 300 K (objective 2)

The current state of the art for temperature realisation and dissemination in this temperature region is through calibration of platinum resistance thermometers to the defined scale (ITS-90).

This project advances the state of the art by building on the developments of EMPIR JRP 18SIB02 Real-K, where the theoretical and experimental advances needed to demonstrate low uncertainty thermodynamic temperature dissemination were achieved by improved ab initio calculations of the thermophysical properties of monatomic gases and accurate (T-T_{90}) determinations. Two thermodynamic approaches (Refractive Index Gas Thermometry - RIGT and Acoustic Gas Thermometry AGT) will be used to perform direct thermodynamic temperature calibrations without reference to ITS-90. Target uncertainty in temperature dissemination of 0.25 mK at 25 K and 0.6 mK at 300 K (k=1).

Development of a coherent framework for thermodynamic temperature dissemination (objective 3)

The current state of the art is that there is no coherent framework for disseminating thermodynamic temperature. The *mise en pratique* for the definition of the kelvin (*MeP*-K) states the allowable thermodynamic methods that can be used but does not address the many practical issues such traceable dissemination requires.

This project progresses the state of the art by developing a coherent framework that addresses these practical needs, by specifying the procedures for an inter-comparison of thermodynamic methods in order to prove their mutual consistency, ensuring the reliability of the dissemination of thermodynamic temperature to make it accessible in the future to the user community through a recommendation to the CCT.

Establish capability for dissemination of thermodynamic temperature between 300 K and 700 K (objective 4)

The current state of the art is that only a few NMIs have made tentative steps towards developing capability for thermodynamic temperature measurements above 300 K.

This project progresses the state of the art by developing the capability to measure thermodynamic temperature to 700 K and develop values of T-T_{90} with a target uncertainty of 7 mK at 700 K (k=1).

Outcomes and impact

Outcomes for industrial and other user communities

Temperature is one of the most measured parameters in industry and by other users (e.g. climate change research). These developments will therefore have outcomes in almost all industrial sectors as well as more widely. However, most impact will be long-term (discussed below).

European accreditation bodies and calibration laboratories have a long-standing interest in the SI and its development. Links with such bodies have been established and the outcomes of this project with its implications for traceability will be fully communicated.

Temperature sensor manufacturers have signalled their interest in this project both directly and indirectly through trade bodies/learned societies. The outcomes of this project will be communicated to them through an e-newsletter and through the project website. Articles on the project outcomes will be published in trade body journals.

It is known that the introduction of ITS-90 caused significant indirect costs to industry through for example having to update standards, change algorithms and recalibrate reference standards. The consortium anticipates that dissemination of thermodynamic temperature will become widespread, negating the need for a new scale with industry avoiding significant costs.

In summary, because temperature is such a key parameter for industry and over many areas of human endeavour, it is anticipated there will be significant outcomes from this project. There will be stimulation of practical primary thermometry *per se* and the development of practical primary thermometry calibration facilities potentially leading to new products for European companies.

Outcomes for the metrology and scientific communities

The project outcomes for the global thermometry community will be very significant, both through advances in the SI system of units (the kelvin) and contributions to the Consultative Committee of Thermometry.

For the global thermometry community. The realisation and dissemination of thermodynamic temperature, as opposed to defined scales, is a long-term objective. The project's outcomes will mark a significant advance towards that long-term objective by using multiple practical primary thermometry approaches to disseminate thermodynamic temperatures.

Specific outcomes will be:

- Capabilities for the dissemination of thermodynamic temperature demonstrated from 4 K to 25 K and from 25 K to ~300 K, with defined scale level uncertainties
- Thermodynamic temperature dissemination practicality demonstrated including the possibility to supersede the defined scale in these ranges
- A coherent framework for dissemination of thermodynamic temperature (4 K - 300 K) developed and recommended to the CCT
- The practicality of thermodynamic temperature dissemination at higher temperatures will have been investigated to ~700 K The outcomes of DireK-T will also be incorporated into the Consultative Committee of Thermometry (CCT) advice and recommendations for use by the global thermometry community at the earliest opportunity. Possible outcomes are: revision of the *MeP*-K, revision of the CCT Strategy and revised consensus values of T-T_{90}. Last, the outcomes of this project will be disseminated to the wider scientific community through peer-reviewed publications, international conferences presentations, workshops and summer schools on "Contemporary issues in primary thermometry" for academics and metrologists.

Outcomes for relevant standards

This project will have a very significant outcomes for the whole thermometry community. This will be put into effect chiefly through the CCT, the global authority on temperature, and the relevant standards body for this work.

Key inputs into the CCT, influencing its guides and recommendations are:

1. Evaluation report on sensors for disseminating thermodynamic temperature from 4 K to 25 K
2. Practical demonstration of practical thermodynamic temperature dissemination from 4 K to 25 K
3. Practical demonstration of practical thermodynamic temperature dissemination from 25 K to 300 K
4. Recommendation report to CCT with framework for thermodynamic temperature dissemination to 300 K
5. New determinations of T-T_{90} in the entire range 4 K to 303 K
6. New determinations of T-T_{90} in the range 303 K to ~700 K
7. Report to CCT on approach to disseminating thermodynamic temperature >300 K

In addition, the key international stakeholders, chiefly the RMO TC-Ts, will be kept informed of the progress of DireK-T by annual written reports. There will also be an annual oral report to EURAMET TC-T.

Longer-term economic, social and environmental impacts

Thermometry is the most widely measured physical parameter so any change will have far reaching impact. This project will accelerate the paradigm shift in the practice of thermometry begun in the EMPIR JRP 18SIB02 Real-K project. There will be an increase in the use of primary thermometry, most appropriate for the needs of the user, to derive traceability to the redefined kelvin.

From an economic perspective. This change will first occur at the NMI level, but over time will be established in accredited laboratories. This will reduce the dependency on NMIs, providing traceability at reduced cost to the user. In the very long-term practical primary thermometry may be used to bring *in-situ* traceability at the point-of-measurement, through the deployment of thermometers with *in-built* traceability. Such innovations are necessary as fully autonomous production and reliable sensor networks are not possible without them.

From a social perspective. These developments may stimulate new industries/products/services, protecting high-value manufacturing employment. The kelvin definition has parallels with the metre redefinition. After the metre redefinition there was an expansion of optically based dimensional measurement approaches. Similar innovations could take place in thermometry with practical primary thermometry supplanting current approaches.

From an environmental perspective. As practical primary thermometry becomes a reality, *any* industrial process requiring reliable temperature measurement will, through the deployment of such sensors, always run optimally, minimising energy use and harmful emissions whilst delivering a consistent quality product with zero waste. Reliable thermodynamic thermometry is essential to improve the reliability of global temperature monitoring and hence monitoring climate change. In addition, the issue of primary temperature measurement and thermometer calibration at liquid hydrogen temperatures will become highly relevant for the optimisation of processes and for custody transfer, once liquid hydrogen is introduced at large scale as part of a global hydrogen economy. Hydrogen is one of the technology pillars on which hopes to abate climate change rest.

Any user requiring long term reliable thermometry will benefit from *in-situ* practical primary thermometry having significant *social and environmental impact*. Practical primary *in-situ* thermometry will give nuclear power plant operators confidence of safe and efficient operation over the >30-year life. Long term nuclear waste repositories require reliable thermometry over decades.

List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 September 2023, 36 months	
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Associated Partners: 11. ITRI, Taiwan 12. NIM, China 13. NPL, United Kingdom 14. TIPC-CAS, China		