Dissemination of the redefined kelvin

Welcome to the first Newsletter of DireK-T

Dear colleagues and partners,

I am pleased to introduce the first edition of our project newsletter. Over the past ten months, our dedicated team has made initial strides towards our overarching goal: establishing a robust framework for the dissemination of thermodynamic temperature from 4 K to approximately 300 K.

Activities accomplished in this first phase are detailed within the following pages. Personally, I would like to dedicate the next lines to briefly highlight the first consortium meeting as well as two eminent upcoming events.

Held in Brussels in June 2024, the first consortium meeting was attended by 32 participants, 16 of whom were in person. We were honoured by the extraordinary engagement of colleagues from the associated project partners and collaborators from extra-European institutes: Canada (NRC), China (NIM, TIPC-CAS), India (NPLI), Korea (KRISS), and Taiwan (ITRI). Discussions on the development of thermodynamic temperature measurements and other state-of-the-art thermometry topics provided valuable technical insights and reinforced future collaborations. I would like to extend a warm thank you to SMD, our diligent host, and to all distinguished guests for their active participation and contributions.

The IMEKO 2024 XXIV World Congress, scheduled for August this year, will be the next opportunity to get direct insight of the project activities by attending the presentation, “European Partnership in metrology project: Dissemination of the redefined kelvin (DireK-T)”. We invite all our stakeholders to join this enriching experience, where we can exchange knowledge, foster collaborations, and drive progress together.

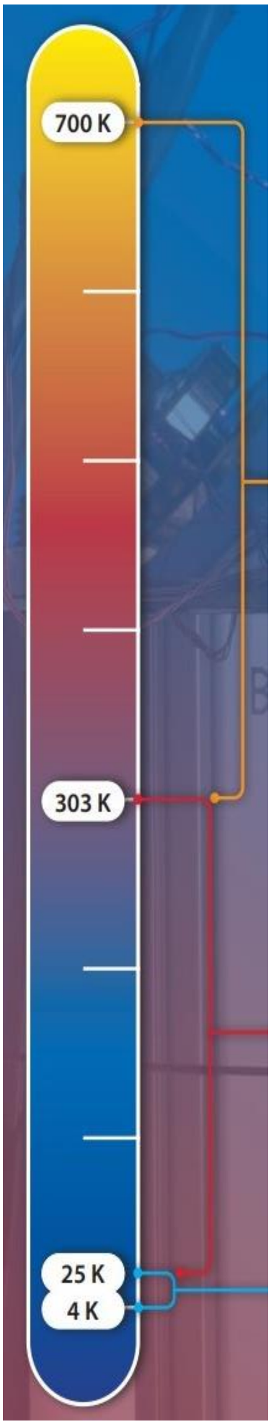
To mark the 200th anniversary of Lord Kelvin’s birth, an international workshop will be organized by the project consortium as part of the prestigious Royal Society Theo Murphy meeting in February 2025. Titled “*The Redefined Kelvin – Progress and Prospects*” the event will focus on the major scientific developments stimulated by the kelvin redefinition in May 2019, provide an opportunity to examine technical progress against the CCT Strategy, and kick-start new developments and avenues for research.

Thank you for your continued dedication and support. I hope you may find the content of this newsletter interesting and inspiring as we continue our journey towards the advancement and innovation of primary thermometry.

Roberto Maria Gavioso,

Project Coordinator

Introduction



The European Metrology Partnership research project 'Dissemination of the redefined kelvin' (DireK-T), started in September 2023 with a duration of three years, brings together a critical mass of several leading primary thermometry experts worldwide. The main aim of the project is to take advantage of the kelvin redefinition to demonstrate the validity of primary thermometry approaches for the direct 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 research work utilises the experience gained over the past EMPIR project 'Realising the redefined kelvin' (Real-K) https://real-k.aalto.fi, which 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.

DireK-T addresses the high-level metrology needs stated by 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 (T90), above 400 K and, in so doing, establish the background capacity for dissemination of thermodynamic temperatures approaching 700 K, ensuring that thermodynamic temperature can be realised and disseminated to room temperature and beyond.

This project will demonstrate dissemination of the kelvin from 4 K to 300 K with defined scale level uncertainties, will develop a robust framework for establishing traceability by primary thermometry and will work towards the next generation primary thermometry to 700 K.

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 objective by using multiple practical primary thermometry approaches to disseminate thermodynamic temperatures. The ultimate goal is 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.).

Research highlights

Demonstrating dissemination of thermodynamic temperature from 4 K to 25 K

Below 25 K the current temperature scale (ITS-90) is not directly realised anywhere in the world on a routine basis. Dissemination is instead generally reliant on sensors calibrated years - or even decades - ago that still act as "carriers of the scale". Furthermore, the most stable and reliable type of these reference sensors are no longer manufactured and therefore not commercially available. Work in previous projects (EMRP JRP SIB01 InK1, EMPIR JRP 15SIB02 InK2 and EMPIR JRP 18SIB02 Real-K) developed the technical approaches required for disseminating thermodynamic temperature directly without the recourse to any defined scale. This project builds on those developments and demonstrate that low uncertainty realisation and especially dissemination of thermodynamic temperature is possible with uncertainties compatible with the current defined scale approach. Thermodynamic temperature realized using three different methods of primary thermometry (AGT, DCGT and RIGT) will be disseminated to two NMIs without primary thermometry capabilities but who have facilities to calibrate on ITS-90 and/or maintain reliable wire scales between 4 K to 25 K. By using these facilities to directly compare the thermometers calibrated by thermodynamic temperature, these NMIs will prove, for the first time ever, the consistency of the different primary thermometry given in the MeP-K and verify whether the target uncertainty of 0.3 mK for dissemination in this range is achievable.

The initial step is to characterise and hence identify, within a batch of resistance thermometers with different sensing elements by different manufacturers, the sensors which have the capability to reproduce and maintain a wire scale with uncertainties within a few tenths of a millikelvin. The best performing sensors identified by the selection process will subsequently be used for the dissemination of thermodynamic temperature.

By the end of 2023, a total batch of 16 thermometers (Pt, Pt-Co and Rh-Fe) were selected and checked for stability at PTB, LNE-CNAM, INRIM, NPL and TIPC-CAS. The thermometers were then delivered to INTiBS.

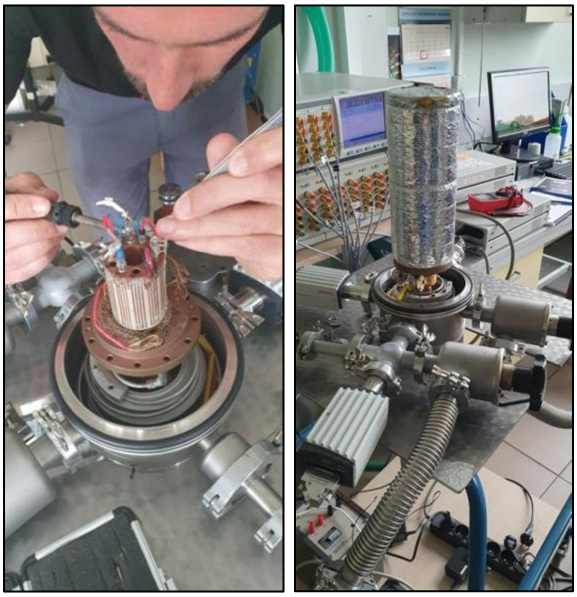


Figure 1. Cryogenic measurement system of INTiBS for ITS-90 calibration of capsule-type resistance thermometers between 9 K and 25 K.

The experimental facilities available at INTiBS comprise a GM cryocooler (Figure 1) covering the temperature range down to 9 K, and a liquid He cryostat for measurements down to 4 K. These apparatus are being used to test the performance of the different types of resistance thermometers in terms of stability, sensitivity, and linearity and ultimately to calibrate them on ITS-90 based on comparison with reference thermometers. These activities started in January 2024 and expected to be completed in October 2024. Meanwhile, PTB, LNE-CNAM, INRIM, and TIPC-CAS are completing the preparation of the RIGT, DCGT and AGT apparatus to be used for thermodynamic calibration in this temperature range.

Demonstrating dissemination of thermodynamic temperature from 25 K to 300 K

The ITS-90 above around 25 K (approximately the triple point of Neon) is more straightforward to realise. However, it has two serious issues: it has significant departures from true thermodynamic temperature around 100 K amounting to around 10 mK and the defined interpolating thermometers (cSPRTs) can be calibrated at different fixed points leading to scale non-uniqueness. If thermometers are calibrated directly to thermodynamic temperature both these problems would be immediately eliminated. This project addresses this need by calibrating practical thermometers directly to thermodynamic temperature using two thermodynamic approaches (Refractive Index Gas Thermometry - RIGT and Acoustic Gas Thermometry AGT) and then, using those thermometers as transfer standards, disseminating thermodynamic temperature to recipient institutes. This would open the way to more routine and practical thermodynamic temperature dissemination in the latter part of the decade and, ultimately, lead to more consistent thermometry as needed for example by the climate science and fundamental materials research communities.

A total of 12 capsule-type standard platinum resistance thermometers (cSPRTs) have been selected and/or purchased by six project participants (INTiBS, CEM, INRIM, UL, CMI, SMD), who are responsible for their initial calibration over different sub-ranges of ITS-90 in the interval between the Triple point of neon (TPNe) at 25 K and the melting point of gallium (MPGa) at 303 K. Calibration activities are undergoing and expected to be completed by the end of 2024. Following ITS-90 calibration, the cSPRTS will be delivered to the laboratories responsible for their thermodynamic calibration.

Additional to these activities, the project fosters the development of thermodynamic calibration capabilities by two NMIs, namely Tubitak and CMI. In both cases, AGT apparatus suitable for use in the temperature range between the triple point of mercury (TPHg) at 234 K and the melting point of gallium (MPGa) at 303 K have been designed and are currently undergoing realization and test. Figure 2 shows the AGT apparatus developed by Tubitak, which employs a spherical triaxial ellipsoidal copper resonator. Accurate speed of sound measurements with Ar at the triple point of water have already been obtained and reported by Tubitak at the M9 meeting in Bruxelles.

Figure 2. Primary acoustic gas thermometer (AGT) being developed by Tubitak for thermodynamic temperature measurements between 234 K and 303 K.

Two external collaborators to the project will take part in the comparison of thermodynamic calibrations by delivering cSPRTs calibrated using AGT: the National Research Council of Canada (NRC), and the Korean NMI (KRISS). NRC has completed and is currently testing an AGT apparatus suitable for calibration between 25 K and the triple point of water (TPW). The AGT apparatus of KRISS will be used for calibration between 173 K and 303 K.

Development of a coherent framework for thermodynamic temperature dissemination

With no coherent framework for disseminating thermodynamic temperature the current situation is completely inadequate. In fact, although the mise en pratique for the definition of the kelvin (MeP-K-19) states the allowable thermodynamic methods (e.g. in the context of this project AGT, DCGT and RIGT) that could be used to provide temperature traceability, crucially it does not address the many practical issues associated with establishing reliable traceability to thermodynamic temperature. This project aims at 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.

Two protocols describing the procedures for the comparison and the dissemination of thermodynamic temperature, respectively in the ranges 4 K to 25 K and 25 K to 303 K, were drafted by CEM, revised and approved by all the project participants. These documents detail the technical and organizational aspects: timelines and modalities for the delivery, exchange and tests of the cSPRTs used as transfer standards; communication protocols between the participants and the pilot (CEM) of the comparison; mixed delivery-ownership schemes to maintain the comparison rigorously blind; statistical and analytical methods to assess the consistency of the final results. The protocols also define the terms and the procedures for ITS-90 auxiliary calibrations which, combined with the results of thermodynamic calibrations, will provide a relevant number of (T-T_{90}) determinations as an additional important project outcome.

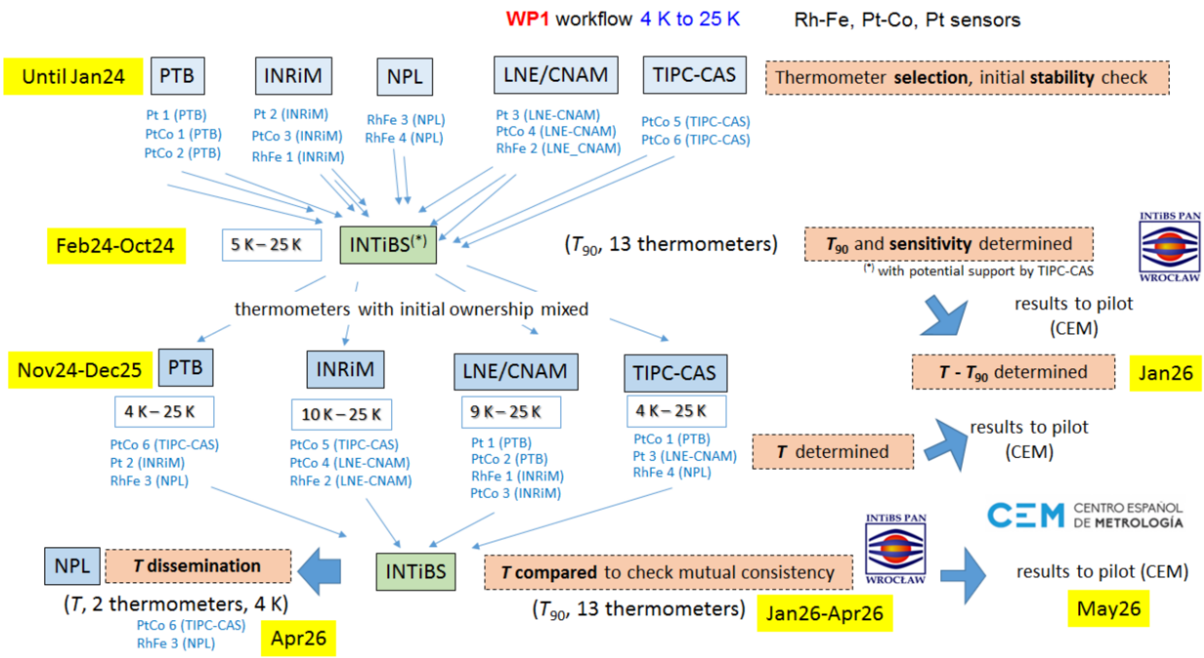


Figure 3. Organization and timeline of the comparison of thermodynamic temperature in the range 4 K to 25 K.

Establishment of capabilities for dissemination of thermodynamic temperature between 300 K and 700

By now, only tentative steps have been made towards the development of accurate primary methods for realising and measuring thermodynamic temperature above 300 K, with just a few reported determinations of (T-T_{90}) obtained using AGT approaches. This project will establish the capability to measure thermodynamic temperature above 300 K with the target of 700 K as the upper limit. Five project participants, including CMI, CMS-ITRI, INRiM, NIM and NPL will undertake thermodynamic temperature measurements in different overlapping ranges between 300 K and 700 K, aiming at (T-T_{90}) determinations with a target uncertainty of 0.6 mK at 300 K and 7 mK at 700 K (k=1). Such elevated temperature range represents a challenge to accurate AGT because of the sensitivity of speed of sound to impurities, likely to significantly degas from the metal wall of the apparatus. Also, condenser microphones traditionally used as sound transducers do not operate in this range, a problem typically addressed using acoustic waveguides. We expect that shared cooperative work of a consortium will ease to find effective solutions to these and other design problems, boosting progress towards the development of high temperature AGT methods and techniques. The apparatus developed in this effort will be capable of use (or modification to be used) in the future for dissemination of thermodynamic temperature through the calibration of long stem thermometers.

Dedicated technical discussion relating to high temperature AGT above 300 K have taken place during the project kick off meeting, followed by an online technical discussion between NIM, INRiM, and NPL. These informal knowledge exchange meetings will continue to be held approximately every 3 months for the duration of the project.

An NPL scientist visited CMS-ITRI during May 2024 to commission a cylindrical resonator AGT system (Figure 4). At CMS-ITRI, validation tests were successfully performed at the maximum operational temperature of 300 °C, with accurate thermodynamic temperature results reported from preliminary speed of sound measurements in argon. Further tests and measurements are ongoing.

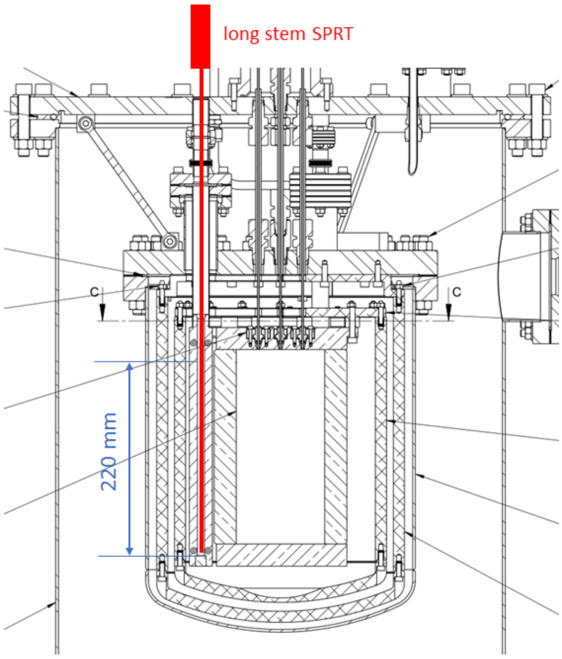


Figure 4. High temperature (up to 300 °C) AGT apparatus set up at CMS-ITRI.

NIM has reported microwave measurements from 335 K to 493 K, the results of which show isotropic thermal expansion of the cylindrical resonator. The design of the high temperature AGT system of NIM has been completed, and a preliminary test from 473 K to 623 K has been performed. INRiM have designed and ordered a novel high temperature pressure vessel for their high temperature AGT system; delivery by the manufacturer is expected in late 2024.

Dissemination and communication activities

For the global thermometry community, the realisation and dissemination of thermodynamic temperatures, as opposed to defined scales, such as the ITS-90, is a long-term objective as it would be a complete realisation of the redefined kelvin. The outcomes of this project will mark a significant advance towards that long-term objective by in effect using multiple practical primary thermometry approaches to realise and disseminate thermodynamic temperatures (through calibrated sensors). To help understand how significant these developments are, it must be kept in mind that this is a complete change from the well-established 100+ year approach to temperature dissemination whereby a mediating defined scale was always used.

Therefore the key international stakeholders, chiefly the RMO TC-Ts, are kept informed of the progress of DireK-T by annual written reports. There is also an annual oral report to EURAMET TC-T. This will brief the global thermometry community on the important developments underway in DireK-T and how they will impact the practice of thermometry in the future.

In this framework, the project coordinator, Roberto Gavioso (INRiM) gave a talk on “Perspectives for the dissemination of thermodynamic temperature in contact thermometry” at the CCT Technical Workshop on “Traceability and Dissemination” held on 16th May, 2024. At the annual Euramet TC-T meeting Graham Machin (NPL) presented the project and the expected outcomes.

A DireK-T focused conference session will be arranged in 2025 at the Tempmeko 2025 Conference in France.

In 2026, the Campus de Las Llamas will serve as the venue for a summer school focused on primary thermometry, set to take place in May. Organized with the support of the UIMP (Universidad Internacional Menéndez Pelayo), the event will offer the possibility to update about the progress of thermodynamic temperature measurements and discuss the remaining technical and practical issues towards the adoption of its practical dissemination. The summer school initiative aims to facilitate knowledge sharing in a collaborative atmosphere, and will equally welcome attendance of experienced metrologists in the field, as well as those interested in starting thermodynamic measurement methods with various methods. It represents an opportunity for participants to engage with current topics in thermometry and to enhance their understanding through dialogue and study.

The workshop titled "The Redefined Kelvin – Progress and Prospects," organized under the auspices of the Royal Society Theo Murphy meeting, is scheduled for 24-25 February 2025 in Glasgow. This event, aligning with the 200th anniversary of Lord Kelvin's birth, aims to review the advancements since the kelvin was redefined in 2019. The proposal for this workshop was submitted in November 2023 and received approval in February 2024. Preparations are well underway, with a draft agenda set and speakers confirmed, promising a focused and collaborative environment for experts in thermometry to convene and exchange insights.

UL has launched DireK-T project website, a straightforward and efficient platform for sharing updates on the project's progress. It will feature essential information such as event notifications, recent publications, and news. The website aims to provide a clear and concise resource for those interested in the project's developments, ensuring easy access to the latest information without overwhelming visitors.

Dissemination of project results

Conference presentations

- G. Machin, M. Dobre, R. Gavioso, C. Gaiser, M-J. Martin, R. Underwood, "Dissemination of the redefined kelvin", poster presented at 26th IIR International Congress of Refrigeration: Paris , France, August 21-25, 2023.
- R. Gavioso, M. Dobre, C. Gaiser, R. Underwood and G. Machin, "Dissemination of the redefined kelvin", poster presented at 22nd Symposium on Thermophysical Properties, Boulder, CO, USA, June 23–28, 2024
- G. Machin, R. Gavioso, M. Dobre, C. Gaiser, M-J. Martin, R. Underwood, "European Partnership in metrology project: Dissemination of the redefined kelvin (DireK-T)", paper accepted for presentation at XXIV IMEKO World Congress "Think Metrology" August 26 - 29, 2024, Hamburg, Germany

Consortium and contact information

The consortium consisting of national metrology, research institutes and universities brings together a critical mass of recognised world leaders in the field.

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To register as a project stakeholder, contact Miruna Dobre (miruna.dobre@economie.fgov.be). An updated edition of this newsletter will be distributed every nine months until the project conclusion in August 2025.

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