European partnership in metrology project: Dissemination of the redefined kelvin (DireK-T)

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ABSTRACT

Here we give an overview of the European Partnership in Metrology (EPM) project; Dissemination of the redefined kelvin (DireK-T). The background context will be introduced, including the redefinition and progress with realising the redefined kelvin thus far. An overview of the aims and objectives of the DireK-T project will be given and the paper will end with a description of the project outcomes and impact.

1. Introduction

Since the redefinition of the kelvin in May 2019 [1] significant progress has been made in realising the kelvin by thermodynamic approaches, with the tantalising prospect that, within this decade, thermodynamic temperature could be disseminated directly from National Measurement Institutes (NMIs) at high (>1300 K) and possibly low (<4 K) temperatures [2]. Those achievements were made in earlier European projects, especially the EMPIR Realising the Redefined kelvin (Real-K) [3]. However, much work remains to be done to put in place the foundation for disseminating the redefined kelvin at intermediate temperatures, that is from 4 K to 300 K and beyond. Here we present a recently initiated European Partnership in Metrology (EPM) project entitled "Dissemination of the redefined Kelvin" (DireK-T) whose aim is to partially address this need. The project involves collaborative scientific activities by fourteen international partners, including NMIs from outside of the EURAMET region.[1] The main objective of the project is to successfully demonstrate the dissemination of thermodynamic temperature from ~4 K to ~300 K, using different primary thermometry approaches, and put in place the infrastructure to facilitate the dissemination of the kelvin above 300 K beyond the lifetime of the project.

In the range between 4 K and 25 K, three thermodynamic methods, Dielectric Constant Gas Thermometry (DCGT), Refractive Index Gas Thermometry (RIGT) and Acoustic Gas Thermometry (AGT), will be used to calibrate capsule-type resistance thermometers of various kinds (Pt, PtCo, RhFe) with a target standard uncertainty of 0.30 mK ($k = 1$). In the range 25 K–300 K two thermodynamic methods, DCGT and AGT, will be used to calibrate capsule type standard platinum resistance thermometers (cSPRTs) with target uncertainties of 0.25 mK ($k = 1$) at 25 K and 0.6 mK ($k = 1$) at 300 K. In both ranges the thermometers will serve as transfer standards to test the consistency of calibration to *thermodynamic temperature* within a blind international comparison, the first of this kind to be performed.

Additional activities of the project include:

- The creation of a coherent framework for temperature dissemination from NMIs to users, whether it is by thermodynamic temperature or the defined scale (ITS-90), including assessment of the level of equivalence between these alternative dissemination approaches.
- The extension, by four different NMIs, of the useful working range of the AGT primary method, up to 700 K with standard target uncertainty of 7 mK with the ultimate aim of even higher temperatures.
- The development of thermodynamic temperature capability based on AGT in the range between 234 K and 303 K by two NMIs currently without primary thermometry capabilities in this range.

The outcomes of the project will mark a significant advance towards the realisation and dissemination of thermodynamic temperature using multiple primary thermometry approaches, as opposed to using internationally agreed and periodically updated defined scales. This represents significant progress towards the long-term goal of the CIPM Consultative Committee for Thermometry (CCT) to realise and disseminate thermodynamic temperature directly traceable to the kelvin as opposed to mediated through a defined scale [4].

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2. Methods and procedures

In this section we give an overview of the activities in the four technical workpackages (WPX).

2.1. WP1: Practical thermodynamic temperature dissemination between 4 K and 25 K

The aim of this work package is the direct realisation and dissemination of thermodynamic temperature (*T*) in the range from 4 K to 25 K by using three different methods of primary thermometry (AGT, DCGT and RIGT) previously developed in the InK1 [5], InK2 [6] and Real-K [3] EMRP and EMPIR projects. The direct determination of *T* will negate the need to realise the International Temperature Scale ITS-90 (which is complex in this temperature region), thus simplifying direct dissemination of the kelvin via resistance thermometry.

The initial important task in this work package will characterize 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. In the past, this function was performed by Rh-Fe resistance thermometers from a single manufacturer but, these sensors are no longer available, alternatives have to be found. The best performing sensors identified by the selection process will subsequently be used for the dissemination of thermodynamic temperature. The performance of the different types of resistance thermometers will be compared for stability, sensitivity and their deviation from linearity.

Dissemination of thermodynamic temperature will be to two NMIs through the selected and calibrated resistance thermometers. These two NMIs do not have primary thermometry capabilities within the temperature range of this workpackage but have facilities able to calibrate on ITS-90 and/or maintain reliable wire scales between 4 K and 25 K. By using these facilities to directly to compare the thermometers calibrated by thermodynamic temperature, these NMIs will demonstrate, for the first time, the consistency of the different primary thermometry approaches given in the *MeP*-K and verify whether the target standard uncertainty of 0.3 mK for dissemination in this range is achievable.

2.2. WP2: Dissemination of primary thermometry between 25 K and 303 K

The aim of this work package is to demonstrate that in the range between 25 K and 303 K the redefined kelvin may be disseminated by cSPRTs directly calibrated to thermodynamic temperature. The target standard uncertainty of the dissemination in this range spans between 0.25 mK at 25 K and 0.6 mK at 300 K, by two primary thermometry methods (DCGT and AGT), which will be implemented by absolute and/or relative primary thermometry.

Importantly, and for the first time, the low uncertainty claimed by primary methods will be tested by comparing the thermodynamic calibration results obtained by different experiments as a part of a dissemination trial to NMIs without primary thermometry capabilities. These NMIs will initially be responsible for the ITS-90 calibration of the cSPRTs and their delivery to the NMIs performing the primary thermometry experiments. Note the calibration results will not be disclosed so as not to bias the thermodynamic comparison.

Finally, the emerging capabilities of two NMIs in primary acoustic thermometry (AGT) will be boosted by active collaboration with a more experienced partner. Two new AGT apparatus will be completed and used for the realisation of the redefined kelvin over the temperature range between 234 K and 303 K, with the quality of these realizations verified by comparison to ITS-90 calibrations.

2.3. WP3: Assessment of traceability and dissemination of thermodynamic temperature

The aim of this work package is to develop a coherent framework to ensure consistency of the dissemination of temperature from several NMIs over the range 4 K–300 K whether it is by thermodynamic temperature or the defined scale, i.e. the International Temperature Scale of 1990 (ITS-90). This framework will be recognised internationally through a recommendation to the Consultative Committee of Thermometry (CCT) detailing the measurement uncertainties and the level of equivalence between these approaches. This will ensure that users globally have a clear understanding of the relationship between the two approaches.

The dissemination of calibrated cSPRTs to multiple NMIs will ensure that, upon accounting for the consensus estimate of the differences (T-T_{90}), the realizations of T and T_{90} are mutually consistent within their combined uncertainties, and will assess the uncertainty of each scale both in correspondence of the fixed points of ITS-90 and in the intermediate ranges between fixed points, where the uncertainty of ITS-90 is limited by various non-uniqueness [see for e.g. [7,8]] contributions.

The outcome of these comparisons will inform the CCT with regard to the uncertainty which may be achieved by thermodynamic calibrations with different primary methods and will inform a future revision of the *mise en pratique* for the definition of the kelvin *MeP*-K-19 [9,10].

2.4. WP4: Establishing primary thermometry capability from 300 K to 700 K

The aim of this work package is to establish a capability for the 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 ($k = 1$). This will be achieved by developing high-temperature AGT systems. These systems are required for dissemination of thermodynamic temperature in the gap between the well-established techniques of low-temperature AGT, DCGT, and RIGT (∼5 K–∼300 K) and primary radiation thermometry (>700 K).

Research conducted as part of the EURAMET InK2 [6] and Real-K [3] projects advanced the state-of-the-art in high temperature AGT. However, significant challenges remain in attaining low enough uncertainties for AGT, or indeed any primary thermometry approach, to be a viable alternative to ITS-90 for realising and disseminating temperature in this range.

AGT techniques above 430 K are substantially different from those at lower temperatures. For example: standard microphones have an upper temperature limit of 430 K, and above this temperature acoustic waveguides must be employed; outgassing of impurities from the resonator walls can be a major issue; capsule thermometers cannot be used above 505 K; and controlling temperature gradients becomes increasingly difficult.

Currently, none of the participant NMIs possess the capability to disseminate thermodynamic temperature between 430 K and 700 K. Some of the partners have been researching high temperature AGT for several years, while for others this is a relatively new endeavour. Extensive collaboration between the partners is essential to accelerate development of the high temperature AGT, especially for those partners at an early stage of research.

Each participant will develop their apparatus and make independent determinations of $T - T_{90}$ by comparing acoustic temperatures with measurements from SPRTs calibrated according to ITS-90, this data will be pooled at the end of the project to determine new consensus values of $T - T_{90}$ at these elevated temperatures.

3. Discussion and projected outcomes

The DireK-T project has only been running a few months at the time of writing this paper and as such there are no substantial results.

However the project outcomes and impact of the work is potentially far reaching in that it will promote primary thermometry approaches as a means of disseminating thermodynamic temperature, that is providing direct linkage to the kelvin definition [11]. In this section we describe how the project will advance the state of the art regarding thermodynamic temperature dissemination and, in addition, how the impact of the project will be maximised through cooperation with the CCT.

3.1. Progress beyond state of the art

Around five years have elapsed since the redefinition of the kelvin. Immediately after the redefinition not much changed regarding temperature dissemination. Traceability was still almost exclusively delivered through the defined scales ITS-90 and PLTS-2000. However, through the EMPIR Project Real-K (2019–2023) [2,3] remarkable progress was made in providing the means, or at least developing the platform, for *thermodynamic* temperature dissemination by a direct link to the Boltzmann constant through primary thermometry. Specifically, that project will have achieved the following: 1) Laid the framework for realisation and dissemination at high temperatures above 1300 K; 2) developed the capability for realising and disseminating the redefined kelvin below 25 K (the effectiveness of those developments and the framework for performing that dissemination will be demonstrated in this project); 3) performed background theoretical and experimental activities to determine the thermophysical properties of gases as required to facilitate realisation and dissemination of the kelvin [12] (we take advantage of the results of that modelling and those measurements). The gas thermometry progress in the Real-K project, both advanced primary thermometry capability and modelling, will allow us in this project to demonstrate *for the first-time* practical realisation and dissemination of primary thermometry up to at least 300 K. To do that will require us to advance the state of the art regarding primary thermometry in a number of areas these are identified below. For clarities sake we will look at each workpackage in turn, identify the current state of the art and then describe how we will progress it in this project.

3.1.1. Dissemination of thermodynamic temperature from 4 K to 25 K

The current state of the art regarding temperature dissemination in the range between 0.65 K and 25 K is complex. Traceable temperature measurements currently require reference to the ITS-90. To realise ITS-90, sophisticated experimental methods are required, including ^{3}He and ^{4}He vapour-pressure thermometry (ITS-90 from 0.65 K to 5 K), constant volume gas thermometry using ^{3}He and/or ^{4}He (ITS-90 from 3 K to 24.5561 K) and platinum resistance thermometry (ITS-90 above 13.8033 K). The application of these different methods leads to non-uniqueness (type 2) within overlapping temperature ranges. In addition, the direct realisation of the temperature scales is expensive, significantly time-consuming and, as a result, not fully available in hardly any NMI. To circumvent this problem, often so-called wire scales are used below 25 K, which are based on resistance thermometers, mostly rhodium iron thermometers (Rh-Fe), carrying copies of the temperature scales. These require periodic recalibration against realizations of the ITS-90 to maintain veracity. Unfortunately, this is generally not done because of lack of primary realizations of ITS-90 below 25 K, leading to an over reliance on wire scales, sometimes 10 or more years old, to provide traceability to ITS-90 indirectly. Matters are additionally complicated by the fact that these Rh-Fe thermometers are no longer commercially available.

Here we will progress the state of the art and address the issue of old wire scales. We will establish a sound basis for modern resistance thermometry by assessing the performance, in terms of stability, of different types of temperature sensors (Pt-Co, Rh-Fe, Pt) to broaden the possibilities for use in this specific temperature range. Furthermore, by taking advantage of the outputs of the EMPIR project Real-K, we will practically realise the redefined kelvin (by primary thermometry) and perform a trial dissemination of thermodynamic temperature using three primary methods, acoustic gas thermometry (AGT), refractive index gas thermometry (RIGT) and dielectric constant gas thermometry (DCGT). *This will be the first ever* full realisation and dissemination of the redefined kelvin in this temperature range through the approved *MeP*-K-19 methods.

Specifically we will:

- Identify and select resistance thermometers that are sufficiently stable and assess their performance in terms of sensitivity as required for the establishment of a future reliable wire scale with an uncertainty of a few tenths of a mK.
- Establish a new wire scale using direct calibration to thermodynamic temperature to significantly reduce the complexity for the realisation of the kelvin below 25 K.
- Compare the results obtained using different primary thermometers to identify and increase understanding of possible systematic sources of uncertainty, which would not otherwise be possible to assess by one thermodynamic method alone.

The target uncertainty over the full range of the dissemination is set at the challenging 0.3 mK ($k = 1$).

3.1.2. Towards demonstrating dissemination of thermodynamic temperature from 25 K to 300 K

The current state of the art regarding temperature realisation and dissemination in this temperature region is through calibrations of capsule (and above the Argon triple point at ~83.8 K) capsule or long-stem platinum resistance thermometers to the defined scale of ITS-90. This approach is subject to type 1 non-uniqueness (which arises from the application of different equations in overlapping ranges, using the same thermometer) sources of uncertainty, and crucially is thermodynamically inconsistent to around 1 part in 10^4 at around 100 K. This means that anyone requiring thermodynamic temperatures must apply significant corrections to their ITS-90 temperatures in parts of this temperature region.

We will progress beyond the state of the art through use of the low-uncertainty modelling results of thermophysical and electromagnetic properties of gases and the measurement capabilities developed in the Real-K project, we will demonstrate, *for the first time*, low uncertainty thermodynamic temperature calibration and dissemination. The sensors being calibrated are the same as for ITS-90 dissemination (capsule and standard platinum resistance thermometers) but the calibration will be to thermodynamic temperatures, without the restriction to adhere to the fixed point temperatures, as prescribed in the ITS-90. This will both: a) eliminate the type 1 non-uniqueness uncertainty sources by directly providing thermodynamic temperature values and b) negate the issue of thermodynamic inconsistency with the ITS-90 at around 100 K. In addition, to identify and, either eliminate or at least quantify method specific uncertainty sources, we will use two independent thermodynamic approaches (DCGT and AGT) to perform the thermodynamic temperature calibrations.

Target uncertainties for thermodynamic temperature dissemination in this range vary between 0.25 mK at 25 K and 0.6 mK at 300 K ($k = 1$).

3.1.3. Development of a coherent framework for thermodynamic temperature dissemination

The current state of the art is that there is **no coherent framework for disseminating thermodynamic temperature.** As practical primary thermometry becomes accessible for providing traceability directly to the kelvin this situation is completely unacceptable. 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.

Here we aim to address this issue establishing the state of the art by organizing traceability trials for the work in the first two workpackages, analysing their results and develop a coherent framework for disseminating thermodynamic temperature. We will also document achievable uncertainties and levels of equivalence with the current defined scale (ITS-90). This will make accessible dissemination of thermodynamic temperature to the widest possible range of users. The framework will be documented as a recommendation to CCT and will become the first globally accepted *de facto* approach to thermodynamic temperature dissemination.

3.1.4. Establish capability for dissemination of thermodynamic temperature to approximately 700 K

In essence there is not current state of the art in this temperature range. Only preliminary, tentative steps have been made by a few NMIs towards the development of accurate primary methods for realising and measuring thermodynamic temperature above 300 K with a variety of AGT approaches.

To progress this unsatisfactory situation the project will establish the capability to measure thermodynamic temperature above 300 K with the target of 700 K as the upper limit. At least three different NMIs will undertake thermodynamic temperature measurements. The results will be pooled values of $T - T_{90}$ with a target uncertainty of 0.6 mK at 300 K and rising to 7 mK at 700 K ($k = 1$). Systematic uncertainties in the experiments will be probed as different approaches to AGT will be performed by a number of the participating institutes. Our longer term aim is that the apparatus developed here will be capable of use (or modification to be used) in the future for dissemination of thermodynamic temperature through the calibration of practical temperature sensors, including long-stem SPRTs.

3.2. Maximising project impact through cooperation with the CCT

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

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 aim as it would be a complete realisation of the redefined kelvin (see for e.g. Ref. [13] where the 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)”. The outcomes of this project will mark a significant advance towards that long-term aim 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 would be a complete change from the well-established 100+ year approach to temperature dissemination whereby a mediating defined scale was always used to provide temperature traceability.

Specific outcomes by the end of the project or shortly after will be:

- Capabilities will have been developed and dissemination of thermodynamic temperatures demonstrated from 4 K to 25 K and from 25 K to around 300 K. This will have been performed with uncertainties on a par with, or even smaller than, those of the defined scales.
- Thermodynamic thermometry dissemination will have been shown to be a practical reality and therefore could, in the following years, supersede the defined scale for temperature traceability in these ranges. The advantage of doing is that direct traceability to the redefined kelvin will not suffer from the shortcomings of defined scale temperatures.
- The possibility of thermodynamic temperature dissemination at higher temperatures will hopefully also have been demonstrated to temperatures as high as 700 K

The project members are well represented on the CCT and will provide a ready conduit to provide up to date thermometry practice emerging from the outcomes of this project. Specifically, there will be three reports to the CCT:

- Performance report submitted to CCT discussing the stability and sensitivity of different types of resistance thermometers for use in the range below 25 K
- Report to CCT indicating next steps and limitations on disseminating thermodynamic temperature above 300 K
- Report to CCT giving the framework for thermodynamic temperature dissemination

The latter is particularly significant as it will be the first such framework to be put in place. Such a framework, endorsed by the CCT, is essential to give confidence to the wider thermometry community that thermodynamic temperature dissemination is on a par, or superior, to that of the defined scales. Indeed, such a document may well widen the uptake of thermodynamic temperature dissemination.

Another outcome of this project after it is completed is that it may lead to a revision of the *MeP*-K [9]. The purpose of the *MeP*-K, which was put in place at the time of the kelvin redefinition (May 2019), is to guide the user from the definition of the unit to a practical realisation. This project will be the first notable use of the *MeP*-K prescribed methods for thermodynamic temperature dissemination between 4 K and 300 K. It is very likely that its findings will cause a review of the recommended methods within the *MeP*-K.

The CCT Strategy [4] was revised in 2021. The outcomes of this project are likely to have an impact on the CCT Strategy, potentially triggering a revision in the latter half of the decade, at least of the areas relevant to the temperature range encompassed within this project.

Besides the CCT there will be wider engagement with the metrology and scientific community and we will specifically run a dissemination workshop for EURAMET TC-T members. Of particular scientific importance will be the high-level summer school on “Contemporary issues in primary thermometry” for academics and metrologists.

4. Conclusions

A detailed description of the aims and objectives of the EPM project Dissemination of the Redefined Kelvin (DireK-T) has been given. Trial dissemination of thermodynamic temperature from around 4 K–300 K will be performed, a framework for thermodynamic temperature dissemination developed and approaches for disseminating thermodynamic temperature above 300 K will have been researched. The project will have significant impact in the global temperature metrology community in the coming years and decades as growing capability to disseminate thermodynamic temperature over increasing range of temperatures will become available as a result of the research performed in the DireK-T project.

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