Welcome to the first Newsletter of Real-K!

I must first say that we live in extraordinary times and none of us could have anticipated when we started the project just a few months ago that we would be where we are today. I will talk about the impact of Covid-19 on the project near the end of this introduction but first I want to focus on what we have achieved.

The project started with the kick-off meeting, ably hosted by CNAM in Paris, at the end of September 2019. At that meeting we planned the details of the first 9 months of our work together. A website was set up and stakeholder committee established. This newsletter reports some of the technical progress we managed to achieve in the first 5 months of the project before the Covid-19 virus struck and our institutes were, and largely remain, closed.

The Covid-19 crisis has profoundly impacted all of our lives and of course that includes progress with the Real-K project. We have had to cancel the first project meeting planned for June 2020 at CEM in Madrid. Time will tell if we are able to reschedule or if we will have to skip that meeting. In recent days myself, the Project Manager Lucy Lyall, and the Workpackage leaders have been busy re-planning and rescheduling the activities of Real-K and we are working with the MSU to introduce a six month delay into the project which will then be on course to be completed in early 2023. We hope that by introducing a substantial delay we will be able to resume Real-K with fresh vigour in the Autumn of 2020.

I am reminded that what we are doing is of great importance. Fever detection is a critical first line of defence against Covid-19 and that means reliable thermometry, underpinned by the work we do in the NMI thermometry community, remains as vital as ever.

Finally, I pass on my best wishes and regards to friends and colleagues who read this newsletter. Take care, keep in touch and I trust I will have more and better things to report in future editions.

Graham Machin

Real-K coordinator

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Introduction

This is the first newsletter of the EMPIR project ‘Realising the redefined kelvin’ (Real-K). The three-year project started in September 2019 and it brings together a critical mass of leading thermometry practitioners in Europe and selected leading international unfunded partners who will bring key skills to the consortium. The research work utilises the experience gained over the past decade through the projects EMRP and EMPIR projects ‘Implementing the new Kelvin 1 and 2’ and will lead the realisation and dissemination phase of the redefined kelvin into the 2020s.

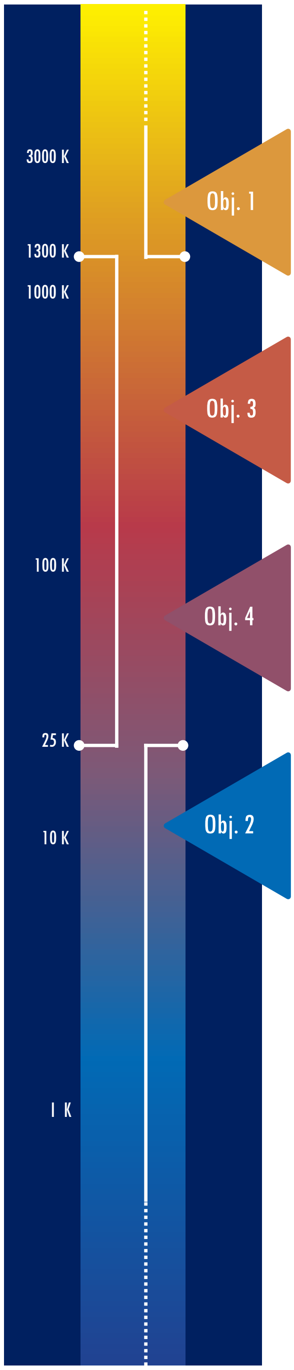
On May 20, 2019, the implementation phase of the redefinition of the international system of units (the SI) was completed and the new unit definitions came into force. For the SI quantity temperature, this means that its unit kelvin is now defined in terms of a fixed value of the Boltzmann constant (k). However, extensive research is still required in order to turn the kelvin redefinition and its associated *Mise en Pratique* into a reality.

Currently nearly all temperature measurements performed around the world are traceable to one of the two defined scales (either the ITS-90 or the specialist low temperature scale, the PLTS-2000). However, with the impetus given by the redefinition there will be a rise in primary thermometry approaches for realising and disseminating temperature, directly linked to the redefined kelvin.

The Real-K project will take the kelvin redefinition and its associated *Mise en Pratique* (*MeP*-K) and begin to turn it into a reality by the following objectives

1. developing primary thermometry approaches at temperatures greater than 1300 K
2. demonstrating practical primary thermometry for temperatures below 25 K
3. extending the life of the currently defined scale to allow time for primary methods to develop and identifying a replacement for the mercury triple point
4. reducing the uncertainty in a number of different primary thermometry methods.

The ultimate goal is that primary thermometry will be the basis of temperature traceability throughout the entire range. Easing the transition to primary thermometry in this way should enable *in-situ* traceability at lower cost, in applications such as remote monitoring in manufacturing and the nuclear power sector, and thus will give operators confidence of safe and efficient operation.



TURNING THE KELVIN REDEFINITION IN TO REALITY

Research highlights

Realisation and dissemination of the redefined kelvin <25 K

The aim of this objective is to extend the working range of primary thermometry to the temperature range from 1 K to 25 K for direct realisation and dissemination of thermodynamic temperatures. This will enable measurements of thermodynamic temperature using only a single device thus avoiding reference the temperature scales ITS-90 and PLTS-2000. We will demonstrate consistency of the developed primary methods and use them to demonstrate a smooth overlap for the PLTS-2000 <1 K.

Coulomb Blockade Thermometer (CBT)

In this project, we aim to extend the metrologically verified temperature range of CBT from 20–200 mK (uncertainty level below 1 %, $k = 2$) up to 25 K.

Two approaches for fabricating new, traceable CBTs are in progress: using sidewall-passivating spacer structure and shadow evaporation method with a thin e-beam patterned germanium film as a mask. By developing the latter fabrication process further, we could decrease the e-beam patterning time by a factor of 20. Figure 1 shows a scanning electron micrograph of the first CBT device fabricated with the new process. The device has 50 parallel chains of 100 series-connected tunnel junctions.

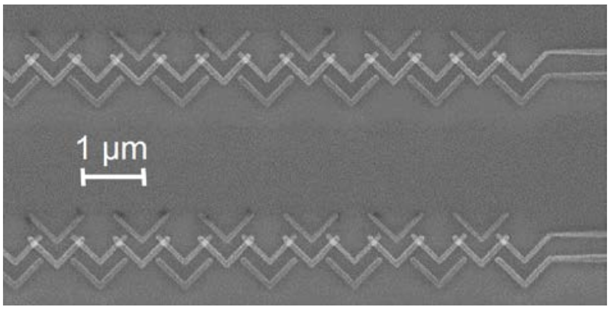


Figure 1. One end of two series-connected chains of tunnel junctions of a CBT for thermometry at 1–25 K.

By connecting a large number of tunnel junctions in series, errors caused by the electromagnetic environment of the CBT are suppressed. Another approach is to use a CBT with only two tunnel junctions in series and to embed it in a very low-impedance environment. We obtained promising results in experiments with a two-junction CBT in a low-impedance environment realized by on-chip capacitors of about 50 pF. The relative deviation between the temperature readings of a conventional CBT with $N = 100$ and a two-junction CBT was within ±5 % at temperatures 25–75 mK.

Refractive-Index Gas Thermometry

Single-Pressure Refractive-Index Gas Thermometry (SPRIGT) is among primary thermometry methods recommended to be used to disseminate the new kelvin. A SPRIGT was implemented for the first time in the range 5 K to 24.5561 K using ^{4}He as the thermometric gas at pressures 30–120 kPa. The purpose of the work was to demonstrate the accuracy of the technique to measure the thermodynamic temperature T and to determine thereby the deviation between T and T_{90} (the International Temperature Scale of 1990 (ITS-90).

Figure 2. A photograph of the (single pressure) RIGT.

The thermodynamic temperature was determined at 17 points with uncertainties from 63 µK near 5 K to 164 µK near 24.5561 K, which are competitive with those of acoustic gas thermometry (AGT).

To determine T–T_{90}, a local temperature scale was established using three calibrated rhodium-iron resistance thermometers (RIRT). During temperature cycles from 5 K to 300 K and back, a repeatability of 10 µK was observed, demonstrating the high quality of the more recently manufactured RIRTs with regard to the conservation of T_{90}.

EMPIR EURAMET The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Facilitating full range primary thermometry

The aim of this objective is to reduce the uncertainty of several primary thermometry methods, which are included in the Mise en Pratique for the definition of the kelvin, namely acoustic gas thermometry (AGT), coupled dielectric constant gas thermometry (DCGT), refractive index gas thermometry (RIGT), and to extend the application range of these methods. These achievements will promote the development of simplified procedures for the direct dissemination of the thermodynamic temperature.

Calculation of thermometric gas properties

Progress towards the development of novel primary thermometry methods requires a relevant uncertainty reduction of the theoretical *ab initio* calculation of several thermophysical properties of the monatomic gases (He, Ne and Ar), which are used as thermometric substances. Accordingly, the second virial coefficient $B(T)$ and second acoustic virial coefficient $\beta_a(T)$ for helium-3 and helium-4 between 1 K and 400 K were computed using a highly accurate pair interaction potential involving a new representation of the relativistic and quantum-electrodynamics (QED) components. Also, the non-additive three-body interaction energy for helium has been calculated by UW adiabatic and relativistic contributions and corrections. The results of all these calculations will likely lead to a significant, about six-fold improvement in accuracy compared to previous ab initio calculations.

Phase shift and path-integral approaches were developed and cross-validated to improve the calculation of the second density virial B(T) and the third density virial $C(T)$ of atomic gases.

Several papers describing all these theoretical results are being completed and will soon be submitted for publication.

Measurement of thermodynamic properties

Among thermodynamic properties, speed of sound and density have a special importance, as they allow to determine directly the temperature-dependent deviations from ideality and can be determined experimentally with low uncertainties. The experiments can validate the theoretical results and drive the selection of appropriate alternative computational tools.

Speed-of-sound measurements in supercritical Ne gas were carried out with a double-path-length pulse-echo technique. A total of 145 measurements were taken along twelve supercritical isotherms between 200 K and 420 K in steps of 20 K at pressures between 20 MPa and 100 MPa (Figure 3). The combined expanded uncertainty (at the 0.95 confidence level) of the speed of sound amounts to 0.007 %, including the contributions of the uncertainty of the temperature and pressure measurements. Publication of these results is underway.

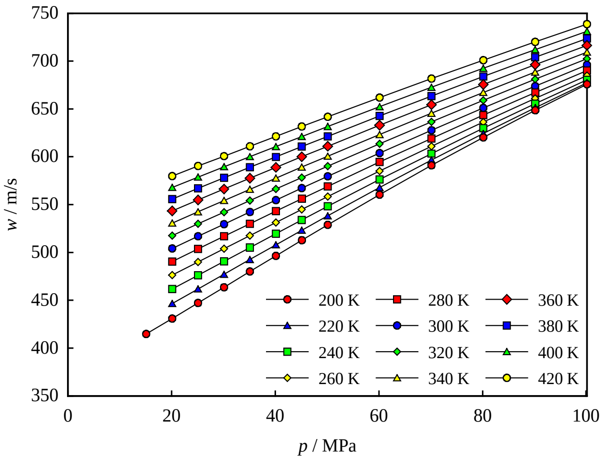


Figure 3. Experimental speed of sound in neon along isotherms between 200 K and 420 K up to 100 MPa.

Coupled dielectric constant gas thermometry and Burnett expansion experiments with Helium have started. Promising results were retrieved from preliminary measurements indicating that relative uncertainties in the low percent region for the second density virial coefficient of helium will be achieved. Coupled DCGT and expansion measurements with Argon were carried out for the temperatures 253 K, 273 K, 296 K and 303 K. Relative uncertainties of the second density virial coefficient of Argon are typically in the order of a few percent but can most likely be reduced to the level of one percent.

Modification and adaptation for acoustic gas thermometry of a cryogenic apparatus, previously used for RIGT measurements have started. Tests of the acoustic transduction systems between 12 K and ambient temperature with a simplified acoustic resonator are underway.

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Dissemination of project results

Scientific articles

- B. Gao, H. Zhang, D. Han, C. Pan, H. Chen, Y. Song, W. Liu, J. Hu, X. Kong, F. Sparasci, M. Plimmer, E. Luo, and L. Pitre, "Measurement of thermodynamic temperature between 5 K and 24.5 K with Single-Pressure Refractive-Index Gas Thermometry", *Metrologia* (accepted for publications), DOI: https://doi.org/10.1088/1681-7575/ab84ca.

Presentations

- O. M. Hahtela, A. Kemppinen, J. Lehtinen, A. J. Manninen, E. Mykkänen, M. Prunnila, N. Yurttagül, F. Blanchet, M. Gramich, B. Karimi, E. T. Mannila, J. Muhojoki, J. T. Peltonen, and J. P. Pekola, "Coulomb Blockade Thermometry on a Wide Temperature Range", (summary paper submitted to the CPEM 2020).

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.

Project coordinator: Graham Machin (graham.machin@npl.co.uk).

Project website: https://real-k.aalto.fi.

Newsletter: Every nine months an e-Newsletter will be available via the project website.

To register as a project stakeholder, contact Kaj Nyholm (kaj.nyholm@vtt.fi).