Welcome to the Newsletter of Real-K!

Welcome to the fifth and final Newsletter of Real-K! The research in Real-K is now at an end and final reporting is underway.

I am very pleased to report that the Real-K consortium gave very strong input into the 10th International Temperature Symposium https://its10.msc-conf.com/ (ITS-10) which took place 3-7 April 2023 in Anaheim, California, USA. The ITS-10 Symposia are the premier thermometry conferences and only happen once every 10 years. The coordinator of Real-K had the honour of opening the conference with the James F. Schooley plenary address entitled "Progress with Realising the Redefined Kelvin". This talk showcased some of the excellent results obtained in the Real-K project. The Real-K coordinator also organised a focused conference session dedicated to the results of the Real-K project. Here the work-package leaders reported on research highlights in areas as diverse as high and low temperature primary thermometry, ITS-90 life extension work in, for example, alternative fixed points and research towards making gas based primary thermometry more accessible and practical. In all the Real-K project contributed at least 20 papers to the conference, which made it the biggest single contributor to the event.

On 19th April 2023 in Bratislava, Slovakia the important Euramet Technical Committee for Thermometry (TC-T) Technical workshop "Realising the redefined kelvin: Turning the MeP-K into reality" was held. The workshop provided an outstanding opportunity to disseminate the results of the Real-K project to the more than 50 key experts in thermometry (the Euramet TC-T contact persons) from across the Euramet region as well as to a number of attendees on-line.

The Real-K project will have enduring impact on the global thermometry community. There will be eight briefing/recommendation documents to the body responsible for regulating the SI unit the kelvin (the Consultative Committee for Thermometry [CCT]). There will be more than 30 open access publications related to state-of-the-art thermometry from very low to very high temperatures. The project will have demonstrated, for the first time, that thermodynamic temperature realisation and dissemination is not only feasible but practical below 25 K and above 1300 K. The life of the International Temperature Scale of 1990 (ITS-90) will have been secured at least until the end of the 2020s and *ab initio* calculations of thermometric gas properties have been very significantly advanced facilitating primary thermometry over a broader range of temperatures.

The results of Real-K will directly support the follow-on European Partnership in Metrology project "Dissemination of the Redefined Kelvin" (DireK-T). The project's main aim is to objectively demonstrate that thermodynamic temperature can be robustly disseminated to users in the temperature range from 4 K to 300 K. In addition, it will build primary thermometry capability for dissemination of thermodynamic temperatures up to 700 K. DireK-T will run from September 2023 until August 2026 and will be coordinated by the Italian national metrology institute INRIM.

Finally, as coordinator of the Real-K project, I want to thank my colleagues for the hard work and dedication they have shown. It has been an immense privilege and pleasure leading a group of talented researchers who have advanced the state-of-the-art of thermometry in so many areas.

Professor Graham Machin FREng
Real-K Project Coordinator

EMPIR EURAMET
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Euramet TC-T Technical workshop:

The Euramet TC-T Technical workshop, organized by Prof Graham Machin FREng, was held in Bratislava, Slovakia on the 19th of April, 2023. The event brought together experts in the field of thermometry to discuss the practical implementation of the redefined kelvin, focusing on the theme 'Turning the *MeP*-K into reality'.

The workshop kicked off with a welcome introduction by Peter Pavlasek (local host), Graham Machin and Steffen Rudtsch (chair Euramet TC-T). The first session, chaired by Maria Jose Martin, started with an overview of Real-K project by Prof Machin. This was followed by presentations on high-temperature non-contact primary thermometry, with a special emphasis on high-temperature fixed points and the progress in indirect primary radiometry for thermodynamic temperature realization and dissemination by Frederic Bourson and Mohamed Sadli respectively.

In session two, chaired by Steffen Rudtsch, the focus shifted to acoustic gas thermometry. Roberto Gavioso's presentation on primary gas thermometry sparked a lot of interest. This was followed by Giovanni Garberoglio's intriguing talk on the *ab-initio* calculation of virial coefficients.

Roberto Gavioso chaired the third session, dedicated to low-temperature primary thermometry. Bo Gao (TIPC-CAS, China) and Alexander Kirste gave presentations on realizing and disseminating thermodynamic temperatures below 25 K to 5 K and below 1 K to ~ 5 K respectively.

The fourth session, chaired by Jonathan Pearce, addressed research on the ITS-90. Richard Rusby discussed extending the life of ITS-90 through non-uniqueness studies while Fernando Sparasci focused on alternate fixed points to mercury.

The final session of the day was a discussion forum chaired by Mohamed Sadli. Key topics included an overview of the CCT Strategy 2020-2030+ by Prof Machin, current status and prospects for disseminating *T* rather than ITS-90 orPLTS-2000 by Christof Gaiser, and photonic and quantum-based thermometry sensors by Stephan Briaudeau.

The workshop concluded with an open discussion forum involving all the session chairs and speakers. Thanks to SMU and the workshop organizers, the event was a great success, serving as an effective platform for sharing knowledge and fostering discussions on turning the *MeP*-K into reality. This newsletter is designed to capture and illuminate the highlights from this insightful workshop.

Overview of Realising the Redefined Kelvin – Professor Graham Machin FREng

The Real-K project ran from Sep 2019 to Apr 2023. It had four main objectives:

- Realise & disseminate thermodynamic temperature above 1300 K
- Realise and disseminate thermodynamic temperature from 0.0009 K to 25 K
- Perform life extension activities of ITS-90
- Undertake background research to facilitate full range primary thermometry

The project was highly successful in all of these advancing the state of the art in thermometry on a broad front. Notable achievements were:

- Assigned definitive low uncertainty thermodynamic temperatures to Fe-C (1426 K), Pd-C (1765 K), Ru-C (2226 K)

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and WC-C (3020 K); (U<0.02%), demonstrated the *MeP*-K-19 by indirect primary radiometry above 1300 K and has undertaken a trial dissemination of thermodynamic temperature using HTFPs.

- Practical primary thermometry has been significantly advanced through developments in Johnson Noise, Coulomb Blockade and gas-based Thermometry. Work was undertaken to show that ITS-90 could be replaced with primary thermometry below 25 K with the possibility that the low temperature defined scale (the PLTS-2000) could be superseded by ~2030
- The mid-term future of the ITS-90 has been secured through undertaking comprehensive type 1 and type 3 non-uniqueness studies and evaluation of possible mercury point replacements namely CO_2 and SF_6. This work will ensure that the ITS-90 could remain fit-for-purpose into 2030s
- Important advances in *ab initio* and measurement of thermodynamic non-ideality of thermometric gases has been performed for He, Ne and Ar. This is an important step towards facilitating full range primary thermometry, at least to 300 K. This will be the subject of the follow-on project Disseminating the redefined kelvin (DireK-T) which will start in September 2023.

High temperature fixed points – introductory overview: Frederic Bourson

This talk gave a comprehensive review on the significant advancements in high-temperature fixed points (HTFPs). It was clear that HTFPs are now ripe for practical application, demonstrating of the significant progress in the research and innovation in this crucial area. The *mise-en-pratique* for the redefinition of the kelvin (*MeP*-K) at high temperatures has provided primary labs with the opportunity to disseminate *T* across a broad temperature range, from about 1300 K and above through the use of HTFPs.
The Real-K project has marked a significant advancement, extending the range of temperature references available with the highest beyond 3000 K.

After more than 20 years of intensive research, HTFPs have achieved maturity: they are now reproducible, robust, and the impact of the thermal conditions in which they are implemented is well understood. HTFPs are now poised to play a critical role for the *MeP*-K in the forthcoming decades.

Progress with indirect primary radiometry for thermodynamic temperature realization and dissemination: Mohamed Sadli

In this presentation an overview of the achievements of the first workpackage of the project was given. In particular, the determination of the thermodynamic temperatures of the solid-liquid phase transitions of four high-temperature fixed points by six participants was highlighted. The agreement among the temperature values determined by the participants was extremely good and all the laboratories agreed in such a way that the final expanded uncertainties on the weighted-mean average thermodynamic temperatures ranged from 0.11 K to 0.22 K. These results include the thermal effects which were analysed to ensure that the uncertainty estimates accounted for the sensitivity of the cells to changing thermal conditions. Overall, this collaborative work complements perfectly the work performed in a former JRP project (InK[1]). It extends the temperature range of HTFPs with assigned thermodynamic temperatures to 3020 K at the high-temperature

[1] Machin, G., Engert, J., Gavioso, R., Sadli, M., Woolliams, E., "**Summary of achievements of the EMRP project implementing the new kelvin (InK)**", *Measurement* **94** 149-156 (2016) doi:10.1016/j.measurement.2016.07.069

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end and to 1426 K at the lowest temperature range above the copper point. A complete set of 7 HTFPs with assigned thermodynamic temperatures, with low uncertainties, are therefore accessible to any laboratory seeking thermodynamic temperature reference points above the copper point up to 3020 K.

Towards primary gas thermometry for thermodynamic temperature dissemination: Roberto Gavioso

where in this presentation the latest progress achieved in the development of primary gas-based thermometry methods, achieved in the course of the Real-K project, were reviewed. The presentation discussed the current and future perspectives of dissemination of the kelvin in the range between 4 K and ambient temperature, with special emphasis on the progress of *ab-initio* calculations and their simplification of primary thermometry methods [Garberoglio *et al*. review paper submitted to *J. Phys. Chem. Ref. Data* 2023, also on ArXiV:, recent determinations of (T–T_{90}) and their analysis for a new, accurate consensus estimate up to 335 K [Gaiser *et al*. *J. Phys. Chem. Ref. Data* 2022], as well as future work towards practical dissemination of the kelvin within a Euramet newly funded project en-titled “Dissemination of the redefined kelvin (DireK-T)” which will start in September 2023.

Ab-initio calculation of virial coefficients for metrology: Giovanni Garberoglio

In this talk, the main outcomes for the Real-K project regarding the calculation of virial coefficients were presented. An improved three-body potential energy surface for the helium trimer resulted in a reduction of the theoretical uncertainty on the third virial coefficient by a factor of almost 5 in the temperature range 10 – 1000 K. New *ab-initio* data for improved second virial coefficient values for neon and argon were reported. In the former case, the theoretical uncertainty is comparable to or smaller than the experimental one, but in the second case theoretical calculation are still less accurate than experimental determinations.

Realising and disseminating thermodynamic temperatures below 25 K to 5 K: Bo Gao

Here work within the frame of Real-K on “Realising and disseminating thermodynamic temperatures below 25 K to 5 K”, was presented. These focused on the most recent achievements obtained using a combination of two primary methods, namely acoustic gas thermometry (AGT) and single-pressure refractive-index gas thermometry (sPRIGT), in collaboration with LNE-CNAM. These included some extremely accurate determinations of the thermodynamic temperature, with relative combined standard deviations well within 10 ppm, in the temperature range between 5 K and 25 K [Pan *et al.* *Metrologia* **58** (2021) 045006 and Gao *et al* *Metrologia* **58** (2021) 059501, showing a substantial improvement of the calibration and dissemination capabilities in this temperature range.

Realizing and disseminating thermodynamic temperatures below 1 K to ~ 5 K: Alexander Kirste

Different primary thermometers for low temperatures have been developed and improved in the EURAMET EMRP/EMPIR projects “InK”, “InK2” and “Real-K” as practical thermometers with a relative uncertainty of currently less than one percent. They were evaluated and validated in the temperature range from 800 μK to 20 K, proving that their temperature readings agree well with the International Temperatures Scales ITS-90 and PLTS-2000 within their stated relative uncertainties. While the two implementations of SQUID-based Johnson noise thermometers (JNT) – the current sensing noise thermometer

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(CSNT) and the primary magnetic field fluctuation thermometer (pMFFT) – are both included in the *mise en pratique* for the definition of the kelvin in the SI (*MeP*-K-19), the Coulomb blockade thermometer (CBT) could be included in future. Hence for the dissemination of the kelvin below 4 K, direct thermodynamic temperature measurement using the CSNT or the pMFFT has become possible as an alternative to the dissemination of the PLTS-2000 and ITS-90.

Extending the life of ITS-90 – non-uniqueness studies: Richard Rusby

The current temperature scale is the International Temperature Scale of 1990 (ITS 90). It has been in place since 1990 and has served the global temperature measurement community well, providing reliable, low uncertainty traceability for over 30 years. However, there are various potentially life-limiting issues for the ITS 90, chief among which are the impact of Types 1 and 3 non-uniqueness, which will ultimately limit the uncertainties achievable.

Type 1 non-uniqueness, also known as subrange inconsistency (SRI), is associated with the difference between the interpolations over different, overlapping ITS 90 subranges for the same SPRT. A significant amount of data exists for the assessment of the uncertainty arising from this effect, because the differences can easily be calculated, given the relevant fixed-point data. However, it is now clear that much of what is apparently SRI is likely to be the result of propagated uncertainties in the data. In Real-K a substantial body of new data has been published.

Type 3 non-uniqueness arises from the difference between individual SPRTs over the same subrange because their resistance characteristics are not identical, and the interpolations cannot take the detailed differences fully into account. Its assessment requires SPRT resistances to be compared at several temperatures in the subrange of interest. Because such comparisons are difficult to do with sufficient precision there is a paucity of reliable data, particularly for long-stem SPRTs at elevated temperatures, and the results necessarily overestimate the magnitude because of the effect of the comparison uncertainties. In Real-K the amount of data on Type 3 non-uniqueness has been greatly increased.

It has been suggested that the two types of non-uniqueness are linked, and some inferences on Type 3 non-uniqueness can be drawn from the SPRT-dependent dispersion of data for Type 1 non-uniqueness. Data of both kinds are needed to allow reliable estimates of the intrinsic non-uniqueness of the ITS 90 to be obtained.

In Real-K, new information on typical uncertainties arising from Type 1 and Type 3 non-uniqueness has been obtained to enable practitioners to improve uncertainty assessment. Some information on improved experimental techniques for assessing these contributions has also been provided. This new information constitutes improved recommendations for the estimation of Type 1 and Type 3 non-uniqueness, to be published in the literature and submitted as a briefing document to the BIPM Consultative Committee for Thermometry.

Extending the life of ITS-90 – alternate fixed points to mercury: Fernando Sparasci

The mercury triple point (TP Hg, -38.8344 °C) is a defining fixed point of the International Temperature Scale of 1990 (ITS-90). It is also a highly toxic heavy metal, and it is conceivable that its use could be banned by an international treaty (under the Minimata Convention), potentially posing an existential threat to the ITS-90. Hence there is a need to identify a possible alternative. The three main candidates for replacing the triple point of Hg are the triple points of Xe (TP Xe, ~161.406 K or -111.744 °C), CO_2 (TP CO_2, ~216.482 K or 56.668 °C) and SF_6 (TP SF_6, ~223.555 K or -49.595 °C). For Xe and SF_6, investigations have so far been mainly for capsule SPRTs, which is a significant limitation as nearly all commercial calibrations are for long-stem SPRTs.

In Real-K, three key factors have been addressed to enable the replacement of the mercury fixed point. These are 1) the consensus fixed-point temperatures of the alternatives, 2) the propagation of uncertainties if these alternatives are introduced into the temperature scale, and 3) alternative interpolating equations. These three factors are discussed below.

The main conclusion arising from this study is that any of the Xe, CO_2 or SF_6 triple points could successfully replace the mercury point, and the choice should be based on their utility, realization uncertainty, and their location in the subrange. The realization uncertainties of the alternative fixed points are likely to be larger than those for the mercury point (mainly due to the lower heat capacity and available purity), but the propagation of the uncertainties would in all cases be somewhat lower. The effect of removing the Hg triple point, and replacing it with the MP Ga, results in a non-uniqueness error which is significantly increased in comparison with the ITS-90 prescription, but which is still small for many practical purposes. Full-range interpolations, from TP Ar to FP Sn, Zn or Al, also omitting TP Hg, have been presented and show good properties and avoid the incompatibilities of the ITS-90 with respect to the TP Hg and also the FP In. This approach will be beneficial for some users, but it is anticipated that many laboratories will want to retain a fixed-point to replace the TP Hg in this frequently used temperature range.

Information and data to influence decision making around the improvement of the temperature scale, as well as uncertainty assessment in the current paradigm, have been submitted as a briefing document to the BIPM Consultative Committee for Thermometry and will appear in the literature.

CCT Strategy 2020-2030+ overview: Professor Graham Machin FREng

During 2021 CCT renewed its Strategy to cover the period 2021-2030+. The Strategy update led from CCT WG Strategy Planning and was driven by stakeholders' needs identified in "CIPM strategy 2030+: responding to evolving needs in metrology". There seven key priority areas are identified: 1) climate change and environment, 2) health and life sciences , 3) food safety, 4) energy, 5) advanced manufacturing, 6) digital transformation and 7) "new" metrology. The CCT Strategy 2021 to 2030+ can be found here. The main part of the document consists of a review of achievements of the CCT (2017-2020) and two future scans covering the periods 2021-2025 and 2025-2030+. Required key comparisons and pilot studies are also listed. The key takeaway regarding the development of the *MeP*-K is that the CCT envisages no changes to the *MeP*-K-19 until after 2027 and then only if new primary thermometry approaches (e.g. Coulomb Blockade Thermometry [CBT]) need to be incorporated. The key takeaway regarding the development of the defined temperature scales is that the CCT has no formal plans to change the defined temperature scales until after 2030.
In summary; CCT envisages a slow evolutionary approach to change in temperature realisation and dissemination with defined scales and thermodynamic temperature approaches as co-equal co-traceability providers into 2030s.

MeP-K-19 current status and prospects for T vs ITS-90, PLTS-2000: Christof Gaiser

In this contribution, the background, and the content of the current version of the *Mise en pratique* for the definition of the kelvin (*MeP*-K) was presented. The focus was on a recent paper that updated the ($T - T_{90}$) estimates by combining and analyzing the data used for the 2011 estimates and data from more recent primary thermometry. The new data was obtained from four types of gas thermometry: acoustic, dielectric constant, refractive index, and constant volume. Their uncertainty estimates are now comparable with the uncertainties in the best measurements of thermodynamic temperature values and the uncertainties in ITS-90 realizations. The results presented were the basis for a planned

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updating of the *MeP*-K annex "Estimates of the differences $T - T_{90}$. For users without primary thermometry capability, it is now possible to access thermodynamic temperature values T below 335 K with comparably low uncertainties via an ITS-90 calibration and then applying ($T - T_{90}$). This is a way to bridge the existing gap between enormous effort required for T measurements and comparably good access to T_{90}.

Photonic and quantum-based thermometry sensors: Prof Stephan Briaudeau

In this talk the advances were described in photonic and optomechanical thermometers achieved through the 17FUN05 PhotOQuanT consortium. The project successfully developed photonic sensors that utilize light-matter interaction for temperature measurements, and optomechanical sensors that could potentially produce quantum primary standards. These devices are designed to measure temperature at a micrometer scale with optimized sensitivity and robustness against mechanical, chemical strains and electromagnetic disturbances. Among the notable achievements, the consortium designed photonic silicon resonators with improved microscale sensor design and materials with enhanced stiffness and thermal conductivity. They also fabricated optomechanical sensors capable of quantum measurements up to room temperature. The ultimate goal was to push the boundaries of state-of-the-art photonic and optomechanical sensors, paving the way for more accurate, reliable, and adaptable temperature sensors in the future.

Report on the researcher mobility grants:

Our project has profoundly benefited from the Researcher Mobility Grant (RMG) sheme. This initiative, aimed at amplifying the capability of the European metrology research community, has played a pivotal role in supporting our consortium members in their research pursuits. The RMG has offered our researchers the financial means to partake in research activities that align with the JRP objectives, significantly enhancing their individual capacities in metrology. Furthermore, the cross-border collaboration enabled by the grant, through research at a guestworking organisation, has fostered a rich exchange of ideas and methodologies, greatly contributing to the progress of our project. In total there were 4 RMGs. We had planned more but unfortunately the COVID-19 pandemic prevented a number from taking place. The outcomes of the RMG projects are summarized below:

1. The objective of this RMG was the implementation of software libraries suitable to be included in already developed control systems of primary acoustic gas thermometers. To this end, in the He4 library, thermophysical properties of helium-4 were implemented using up-to-date available scientific publications of *ab-initio* calculations. Furthermore, the algorithms to apply the corrections to the experimental measurements were compiled in the Gfer library. Software is available in the form of Fortran 2008 source code and compiler libraries both for Windows and Linux on the Real-K website and on Zenodo. To simplify the adoption of the implemented platform, interfaces for LabView and Maple were provided together with html-fomat reference manuals. Compiled code can be linked to any proprietary or free software able to call C-format compiled libraries (almost all). Developed software could be easily extended to

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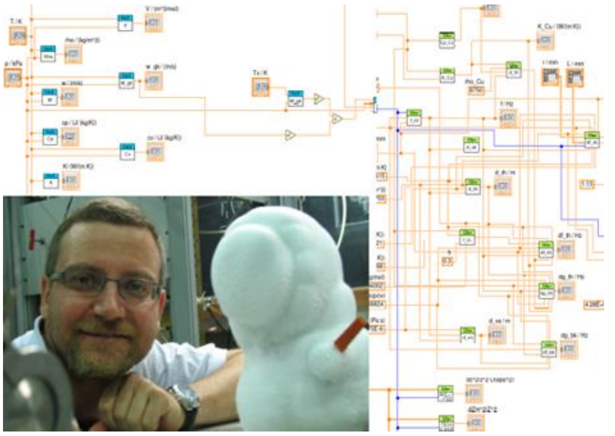
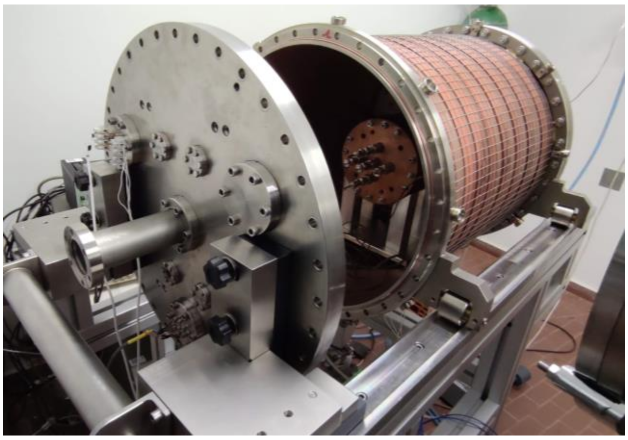
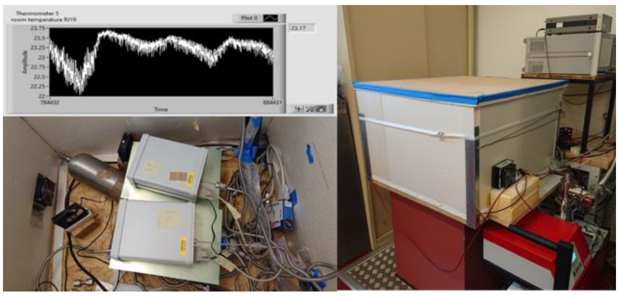
provide properties of other gases like neon or argon, if necessary.



2. The RMG researcher initially received basic education into the theory of physical acoustics and the laboratory methods needed to conduct tests with an apparatus designed to implement acoustic gas thermometry (AGT) by measuring speed of sound in gases up to moderately high temperatures and pressures (700 K, 1 MPa). Following initial training, the RMG researcher assembled and tested several components of the experiment, including vacuum and pressure tests of the tightness of a furnace and a pressure vessel, and the performance of different types of acoustic transducers and waveguides. These preliminary tests used argon as the thermometric gas at temperatures up to 340 K. The RMG researcher also developed novel software tools used for the analysis and correction of acoustic data. A second experimental test with Ar was later conducted up to 550 K, intended to record acoustic data at several pressures along an isotherm between 100 kPa and 800 kPa. During this test, a major gas leak from the internal vessel to the furnace cut-short the experimental run causing an electrical short-circuit which damaged microphonics and pressure measuring instrumentation. Despite these issues, which compromised the full completion of the research initially scheduled in the RMG, the analysis of acoustic data at 550 K up to 230 kPa showed, by comparison of speed of sound data from three different radial modes, that the acoustic performance of the AGT was satisfactory. Considering the significant experimental challenges encountered by the RMG researcher, the research activities during the RMG met their target.



3. The goal achieved by the 18SIB02-RMG3 project pertained to the implementation of an improved acoustic gas thermometer (AGT), based on a previous version developed during the parent project Real-K, able to perform prolonged measurements of thermodynamic temperature still with high accuracy, but in considerably less time and, from an experimental point of view, more easily. These outcomes were achieved by not measuring each time a set of data at several gas pressures but at a single one. This method, known as fast-AGT, required the single pressure value to be determined with higher precision and accuracy than previously. This has been accomplished by improving both the environmental enclosure holding the pressure standards and on an active pressure control system, which enabled the pressure oscillations due to ambient temperature issues to be reduced by a factor of 10, i.e. from 1 Pa to 0.1 Pa.



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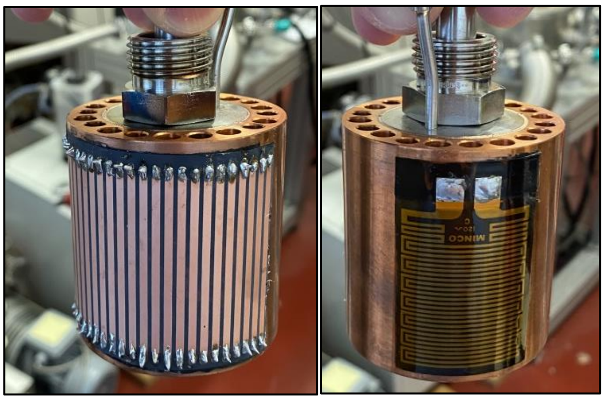
4. The goal of this RMG was focused on the design, testing and characterisation of the triple point fixed point cell of CO_2 that would be capable of calibrating simultaneously capsule and long stem type PRTs. The cell designed used a copper block design with stainless steel components.

After the cell was manufactured it was cleaned and evacuated in order to be filled with pure (in this specific case 99,9995% purity) CO_2 gas. The cell used thermal anchoring on its outer walls to reduce undesired heating and heat pulses generate by a heater to control the triple point state.

The results have shown the potential of the cell designed filled with CO_2 to be used as a calibration point alternative for the Hg point for both capsule and long stem PRTs.

The performance of the tested CO_2 fixed point cell had a consistent level of repeatability which can be documented by a realization repeatability on the level of 0.30 mK. The realized plateaux have shown high level of stability that can be demonstrated by an increase of 1.03 mK after a period of 22 hours. This work also confirmed that it is very important to address the issues that can arise from heat flux effects which can be significant when calibrating long stem platinum resistance thermometers against such low temperature fixed points.

The RMG results were presented at the Congres International de Metrologie 2023, Lyon, FRA and at the 10th International Temperature Symposium, Anaheim, USA.



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Dissemination of project results

Scientific articles

1. GAISER, Christof; FELLMUTH, Bernd; HAFT, Norbert. Thermodynamic-temperature data from 30 K to 200 K. *Metrologia*, 2020.
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3. WANG, Yanfei, et al. A method for spectral irradiance measurement based on a large area WC-C fixed point blackbody. *Optics Express*, 2020, 28.19: 28430-28440.
4. PAN, Changzhao, et al. Active suppression of temperature oscillation from a pulse-tube cryocooler in a cryogen-free cryostat: Part 1. Simulation modeling from thermal response characteristics. *arXiv preprint arXiv:2002.03177*, 2020.
5. PAN, Changzhao, et al. Active suppression of temperature oscillation from a pulse-tube cryocooler in a cryogen-free cryostat: Part 2. Experimental realization. arXiv preprint arXiv:2002.03178, 2020.
6. IMBRAGUGLIO, Dario; STEUR, Petrus Paulus Maria; SPARASCI, Fernando. Comparison of ITS-90 realizations from 13 K to 273 K between LNE-CNAM and INRIM. Measurement, 2020, 166: 108225.
7. HAHTELA, O. M., et al. Coulomb Blockade Thermometry on a Wide Temperature Range. In: 2020 Conference on Precision Electromagnetic Measurements (CPEM). IEEE, 2020. p. 1-2.
8. G. Garberoglio and A. Harvey, Path-integral calculation of the fourth virial coefficient of helium isotopes, The Journal of Chemical Physics
9. A. Peruzzi, et al. Survey of Subrange Inconsistency of Long-Stem Standard Platinum Resistance Thermometers, Metrologia.
10. D. Madonna Ripa, at al. Refractive index gas thermometry between 13.8 K and 161.4 K, Metrologia.
11. P. Changzhao, *et al*. Acoustic measurement of the triple point of neon TNe and thermodynamic calibration of a transfer standard for accurate cryogenic thermometry, Metrologia.
12. Martín, M.J., Mantilla, *et al*. Construction, Characterization and Measurement of Fe–C and Pd–C HTFPs at CEM. *Int J Thermophys*43**,** 57 (2022).
13. Czachorowski P., et al. Second virial coefficients for 4He and 3He from an accurate relativistic interaction potential. Phys. Rev. A 102, 042810 (2020).
14. Madonna Ripa D. et al. Corrigendum: Refractive index gas thermometry between 13.8 K and 161.4 K (2021 Metrologia 58 025008)
15. Pekola, Jukka P., et al. Influence of device non-uniformities on the accuracy of Coulomb blockade thermometry. Metrologia 59.4 (2022): 045009. ttps://doi.org/10.1088/1681-7575/ac79e8
16. Machin G. et al., Towards realising the redefined kelvin, Measurement 201 111725 (2022) https://doi.org/10.1016/j.measurement.2022.111725
17. Machin, G. (2023). The Kelvin Redefinition and Practical Primary Thermometry: Implications for temperature traceability and sensing. *Johnson Matthey Technology Review*, *67*(1), 77-84.
18. KIRSTE, A. Comparison of Different Johnson Noise Thermometers From Millikelvin Down to Microkelvin Temperatures. JPS Conference Proceedings.

19. MACHIN, G. Progress with realizing the redefined kelvin. *ITS-10 proceedings submitted (2023)*
20. LOWE, D. High-Temperature Fixed-Point Furnace Uncertainty. *ITS-10 proceedings submitted (2023)*
21. LOWE, D. Low uncertainty thermodynamic temperature measurement using relative primary radiometry setting up n=2 scale using copper and rhenium-carbon with uncertainties. *ITS-10 proceedings submitted (2023)*ZUZEK, V. Least squares approach to standard platinum resistance thermometer subrange inconsistency reduction with redundant gallium and indium fixed points. ITS-10 proceeding.
22. PEARCE, J. Realizing the redefined kelvin: Extending the life of the ITS-90. *ITS-10 proceedings submitted (2023)*
23. RUSBY, R. Sensitivity of Type 1 Non-uniqueness (Subrange Inconsistency) to Propagated Measurement Error in SPRT Interpolations above 273.16. *ITS-10 proceedings submitted (2023)*
24. GAVIOSO, R. Facilitating primary gas thermometry. *ITS-10 proceedings submitted (2023)*
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27. CAN, M. Realizing of Fe-C, Pd-C, Ru-C and WC-C eutectic fixed-points at UME. ITS-10 proceeding.
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Presentations and other disseminations

1. "Progress in Realising the Redefined Kelvin" at the Sensor and Measurement Science International (SMSI 2021) conference held in May 2021 in Germany.
2. "Towards realising the redefined kelvin" presented at the International Congress on Metrology (CIM 2021) in September 2021 in France.

3. "Coulomb Blockade Thermometry on a Wide Temperature Range" showcased at IEEE Precision Electromagnetic Measurements, CPEM 2020 in August 2020 in the United States.
4. "Construction of high temperature fixed points of Fe-C and Pd-C at CEM" discussed at CIM 2021 in September 2021 in France.
5. "New thermodynamic temperature references up to 3020 K" at CIM 2021, held in September 2021 in France.
6. "Characterisation and selection of high-temperature fixed point cells at the WC-C peritectic point (3022 K)" at CIM 2021 in September 2021, France.
7. "Comparison of Different Johnson Noise Thermometers From Millikelvin Down to Microkelvin Temperatures" at the 29th International Conference on Low Temperature Physics (LT29) in August 2022, Japan.
8. "Progress with realizing the redefined kelvin" at the ITS-10 conference in April 2023, United States.
9. "High-Temperature Fixed-Point Furnace Uncertainty" presented at ITS-10 in April 2023, United States.
10. "Low uncertainty thermodynamic temperature measurement using relative primary radiometry setting up n=2 scale using copper and rhenium-carbon with uncertainties" at ITS-10, April 2023, United States.
11. "Realizing the redefined kelvin: Extending the life of the ITS-90" at ITS-10 in April 2023, United States.
12. "Sensitivity of Type 1 Non-uniqueness (Subrange Inconsistency) to Propagated Measurement Error in SPRT Interpolations above 273.16 K" presented at ITS-10 in April 2023, United States.
13. "Full-range Interpolations for Long-Stem Standard Platinum Resistance Thermometers down to the Triple Point of Argon" at ITS-10 in April 2023, United States.
14. "Facilitating primary gas thermometry" at ITS-10 in April 2023, United States.
15. "Assigning thermodynamic temperatures to a set high-temperature fixed points in the range 1400 K to 3000 K" at ITS-10 in April 2023, United States.
16. "Realising the redefined kelvin: Realisation and dissemination of the kelvin below 25 K" at ITS-10 in April 2023, United States.
17. "Realization of Fe-C Eutectic Point at UME" at the 21st International Metrology Congress (CIM2023) in March 2023, France.
18. "Realizing of Fe-C, Pd-C, Ru-C and WC-C eutectic fixed-points at UME" at ITS-10 in April 2023, United States.
19. "Type 3 Non-Uniqueness in Standard Platinum Resistance Thermometers in the Temperature Range from 83 K to 353 K" at ITS-10 in April 2023, United States.
20. "Least squares approach to standard platinum resistance thermometer subrange inconsistency reduction with redundant gallium and indium fixed points" at ITS-10 in April 2023, United States.
21. "Overview of Realising the Redefined Kelvin" at Euramet Tc-T in April 2023, Slovakia.
22. "High temperature fixed points – introductory overview" at Euramet Tc-T in April 2023, Slovakia.
23. "Progress with indirect primary radiometry for thermodynamic temperature realisation and dissemination" at Euramet Tc-T in April 2023, Slovakia.

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24. "Towards primary gas thermometry for thermodynamic temperature dissemination" at Euramet Tc-T in April 2023, Slovakia.
25. "Ab-initio calculation of virial coefficients for metrology" at Euramet Tc-T in April 2023, Slovakia.
26. "Realising and disseminating thermodynamic temperatures below 25 K to 5 K" at Euramet Tc-T in April 2023, Slovakia.
27. "Realising and disseminating thermodynamic temperatures below 1 K to ~ 5 K" at Euramet Tc-T in April 2023, Slovakia.
28. "Extending the life of ITS-90 – non-uniqueness studies" at Euramet Tc-T in April 2023, Slovakia.
29. "Extending the life of ITS-90 – alternate fixed points to mercury" at Euramet Tc-T in April 2023, Slovakia.
30. "CCT Strategy 2020-2030+ overview" at Euramet Tc-T in April 2023, Slovakia.
31. "MeP-K-19 current status and prospects for T vs ITS-90, PLTS-2000" at Euramet Tc-T in April 2023, Slovakia.
32. "Photonic and quantum-based thermometry sensors" at Euramet Tc-T in April 2023, Slovakia.
33. "Acoustic thermodynamic calibration of capsule-type standard resistance thermometers between 10 K and 25 K" at ITS-10 in April 2023, United States.
34. "From ITS-90 to Thermodynamic Temperature: Hybrid SPRT Calibrations with LNE-Cnam Acoustic Gas Thermometry" at ITS-10 in April 2023, United States.
35. "Relative thermodynamic temperature over the whole temperature range" at ITS-10 in April 2023, United States.
36. "New T-T90 data from 5 K to 24.5 K by single-pressure refractive-index gas thermometry" at ITS-10 in April 2023, United States.
37. "New T-T90 data from 6 K to 24.5 K by fast acoustic gas thermometry" at ITS-10 in April 2023, United States.
38. "Thermometry below 1 K, a comparison of several reference sensors based on different physics principles at LNE-Cnam" at ITS-10 in April 2023, United States.
39. "Realization of new fixed point cells at the LNE-Cnam" at CIM 2023 in March 2023, France.Progress in Realising the Redefined Kelvin, Invited oral presentation at SMSI – Sensor and Measurement Science International 2021, May 2021

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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Newsletter: Every nine months an e-Newsletter will be available via the project **website**. This is the 5th and final Newsletter of the Real-K project.
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