Publishable Summary for 15SIB02 InK 2
Implementing the new kelvin 2

Overview

The global measurement system, grounded in the international system of units (the SI), is the essential foundation for reliable measurement. Such a measurement system, is necessary for trade, manufacturing, sustaining and improving quality of life. In November 2018 the International Committee for Weights and Measures (the CIPM) agreed to redefine the SI units in terms of fixed values of fundamental constants, with the implementation date set for World Metrology Day 20 May 2019. This project focused on supporting the redefinition of the SI unit for temperature, the kelvin. This project focused on establishing within EURAMET, the necessary equipment, experimental procedures and expertise for a successful introduction of the redefined kelvin. Low uncertainty determinations of T-T_{90} and also T-T_{2000} were performed, which, when combined with the results of InK 1, covered most of ITS-90 and all of PLTS-2000 ranges.

Need

In November 2018 the CIPM agreed to introduce the most fundamental change to the SI system ever undertaken since its inception. The SI, from that point on, was to be based on defined values of fundamental constants. This project focused on leading the thermometry community to a successful redefinition of the kelvin.

Research was performed focused on delivering the primary thermometry results and capability needed to facilitate an effective kelvin redefinition. In particular; robust T-T_{90} and T-T_{2000} data was determined to provide revised thermodynamic temperature data for the supplementary information for the *MeP*-K-19 (the CCT document that enables the international thermometry community to implement the redefined kelvin). In the medium term the *Me*P-K-19 will promote the use of primary thermometry for realisation and dissemination of temperature, especially at the extremes of temperature >1300 K and <20 K. In the longer-term primary thermometry could be used throughout the whole range for dissemination of temperature or a combination of primary thermometry and a new but range restricted international temperature scale (the so-called ITS202X) could be introduced.

Objectives

The overall aim of the project was to facilitate a successful transition to the redefined kelvin ensuring that the necessary research was completed and necessary structures (e.g. documentation) were in place. To achieve the requirements of the kelvin redefinition the following objectives were pursued:

1. To develop the facilities and methodologies for thermodynamic temperature measurements and to determine T-T90 in the range from ~ 430 K to ~ 1358 K using two different primary methods (acoustic and radiometric) and with a target standard uncertainty of 5 mK.
2. To establish a robust uncertainty budget for Refractive-Index Gas Thermometry. To determine *T-T90* in the range ~5 K to ~200 K using three different methods (acoustic, refractive-index, dielectric constant) and with a target standard uncertainty of 0.5 mK.
3. To investigate three novel thermometry methods (Doppler Broadening Thermometry, Double Wavelength thermometry and Radiation Thermometry Traceable to Synchrotron Radiation). To establish novel primary thermometry approaches to attain uncertainties required to probe the underlying systematic uncertainties in T-T90.
4. To improve primary thermometers (pMFFT, CSNT, CBT) for the ultralow temperature thermometry regime (0.9 mK to around 1 K). To resolve the PLTS-2000 background data discrepancy (6 % at lowest temperatures) including revised *T-T2000* data over the range 0.9 mK to 1 K (target standard uncertainty of 1 %).

5. To contribute to new or improved international standards. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain.

Progress beyond the state of the art

Good progress in this collaborative research was made in the EMRP Joint Research Project SIB01 InK 1 through developing a sophisticated interconnected research infrastructure (equipment and experts) in primary thermometry. InK 1 performed state of the art temperature measurements in the temperature regions 1 K to 0.02 K and ~80 K to ~300 K, and established thermodynamic temperatures for a selection of high temperature fixed points. Many of the results of the InK 1 project were published in a special edition of *Phil Trans A* whose contents can be accessed for free at: http://rsta.royalsocietypublishing.org/content/374/2064. InK 2 built on the achievements of the InK 1 project through further extending the state of the art in primary thermometry capability into temperature areas not explored in InK 1.

In particular InK 2 established primary thermometry capability, by a range of techniques, for the low uncertainty determination of temperature data in areas not covered by InK 1 from 300 K to ~1300 K and from 0.02 K to 0.0009 K. That capability was used to a) measure new low uncertainty thermodynamic temperature values of both T-T_{90} and T-T_{2000} for the all-important *MeP*-K-19 b) show, for the first time, that PLTS-2000 could be thermodynamically inaccurate by more than 6 % at the lowest temperatures, and c) made available practical thermodynamic temperature sensors at low temperatures below 1 K for use by equipment manufacturers.

Results

Key results are highlighted in this section.

Development of the facilities and methodologies for thermodynamic temperature measurements and determination of T-T_{90} *in the range from ~ 430 K to ~ 1358 K using two different primary methods (acoustic and radiometric) and with a target standard uncertainty of 5 mK.*

Facilities were established by the project for determining T-T_{90} in the temperature range from ~430 K to ~1358 K. The two approaches used were primary acoustic gas thermometry and lower temperature primary radiometry. The techniques covered two different ranges with acoustic gas thermometry covering the range from ~430 K to ~870 K and primary radiometry covering the range from ~500 K to ~1358 K. A paper (McEvoy *et al* (2019) was written and submitted to *Meas. Sci. and Technol.* describing these facilities.

The acoustic thermometry facilities consisted of high temperature quasi-isothermal furnaces and cylindrical resonators. For important technical reasons this approach to acoustic gas thermometry is different from lower temperature approaches which use quasi-spherical resonators. Values of T-T_{90} were determined by acoustic thermometry through determining the speed of sound in a gas. The T_{90} values were determined from standard platinum resistance thermometers (SPRTs) embedded in the resonators. Significant technical difficulties in the establishment of the apparatus mean uncertainties are likely to be larger than the target. It is envisaged that further developments and measurements will be performed after the project is completed.

The primary radiometry facilities in the different partner institutes consisted of radiation thermometers/radiometers calibrated either traceable directly to radiometric standards, or indirectly via a fixed point of known thermodynamic temperature. These radiometers were then used to evaluate the thermodynamic temperature of a range of fixed-point blackbody sources (Cu, Ag, Al, Zn and Sn). In addition, three fixed point blackbody sources (Zn, Al and Ag) were circulated between, and measured by, the participants to ensure linkage and comparability of the measurements being made independently in each of the institutes. In addition, values of T-T_{90} were determined through using variable temperature blackbody sources whose temperature was determined using thermometers (usually SPRTs) calibrated to ITS-90.

Primary radiometry is extremely challenging technically and the uncertainties achieved ranged from a few 10’s to a few 100’s mK depending upon the temperature of the radiance source.

A summary report of the results obtained by both primary thermometry techniques was provided to the Consultative Committee of Thermometry (CCT) for consideration at its next meeting in March 2020. In particular, significant results were obtained by lower temperature primary radiometry from 505 K (Sn freezing point) to 1357 K (Cu freezing point), and which broadly confirmed earlier work but with a far more extensive set of data. Higher temperature acoustic thermometry achieved only preliminary results by the end of the project, but the capability has been established and T-T_{90} values will be determined before CCT in March ‘20.

Establishment of a robust uncertainty budget for Refractive-Index Gas Thermometry. Determination of T-T_{90} in the range ~5 K to ~200 K using three different methods (Dielectric constant gas thermometry, (DCGT), refractive index gas thermometry (RIGT) and acoustic gas thermometry (AGT)) and with a target standard uncertainty of 0.5 mK.

A report on RIGT including a full uncertainty budget was submitted and approved by CCT in May 2017. The bulk of this went on to be incorporated within the *MeP*-K-19 which was issued on 20 May 2019 to coincide with the end of the implementation phase of the SI redefinition.

Lower temperture primary thermometry capability was established by three different methods dielectric constant gas thermometry, (DCGT), refractive index gas thermometry (RIGT) and acoustic gas thermometry (AGT). DCGT covered the range from 40 K to above 100 K whilst the other two approaches covered the range from 5 K to 200 K.

Extensive measurements were performed using DCGT at 10 K intervals for the temperature range between 40 K and 80 K with both Helium and Neon. In addition measurements were undertaken in helium, neon and argon above 100 K. Typical uncertainties in these measurements are of the order of 0.5 mK.

Both RIGT and/or AGT have been used by several partners in this temperature range (LNE-CNAM, INRIM, TIPC-CAS). The measured T-T_{90} values are consistent with those of previous estimates but those evaluated here are of higher quality (lower uncertainty). In fact the data has, in some cases, uncertainties lower than the objectives target of 0.5 mK (k=1).

A report was prepared summarising these results and this was sent to CCT for consideration at the next CCT meeting in March 2020. This objective was fully achieved and in some cases exceeded in terms of the target uncertainty.

Investigation of three novel thermometry methods (Doppler Broadening Thermometry, Double Wavelength thermometry and Radiation Thermometry Traceable to Synchrotron Radiation). Establishment of novel primary thermometry approaches to attain uncertainties required to probe the underlying systematic uncertainties in T-T_{90}.

Doppler broadening thermometry (DBT): A significant step forward in this new primary thermometry technique was achieved during this research. The thermometry is performed by determining the Doppler width of a spectral line in a thermostatted gas. Molecular species were selected (e.g. acetylene) to ensure clean spectral lines could be measured. Capability was established to undertake primary thermometry by the technique in the temperature range from the water triple point and above. The final measurements had uncertainties lower than the target uncertainty, with determinations of the water triple point and the gallium melting point having uncertainties <10 ppm, with values consistent with other measurements. With further development DBT could become a promising additional primary thermometry technique.

Double wavelength thermometry (DWT): Significant advances were made in DWT in this project over a wide range of temperatures from 900 K to ~2750 K. However the approach was more technically challenging to implement than theory suggested, and indeed the uncertainties of the measurements were rather large, certainly larger than conventional single wavelength radiometry.

Radiation Thermometry Traceable to Synchrotron Radiation (RTTSR): This is a highly novel approach to thermometry which is only possible because PTB has access to the Metrology Light Source synchrotron in Berlin. It was pursued in this project primarily to test the reliability of primary filter radiometry which may have several ill-defined systematic uncertainties which could be identified by performing thermometry by this different approach. The optical radiation emitted by the synchrotron is calculable according to the Swinger theory. By comparing the optical output of a blackbody to that of the synchrotron the systematic effects of the techniques are examined. This is a very complex experiment, and large scale, for example the distance between the filter radiometer and the Metrology Light Source window is 22 metres. The results were very good with RTTSR confirming the measurements by single wavelength filter radiometry. The uncertainty of the method was around a factor of two larger than the best filter radiometry.

More than three papers were published from this objective and a recommendation report was prepared for CCT. This objective was fully achieved with Doppler Broadening Thermometry: it was capable of low uncertainty primary thermometry, Double Wavelength Thermometry and it was shown to be more difficult than envisaged especially with Radiation Thermometry Traceable to Synchrotron Radiation, which although not a routine measurement method, provided essential confirmation of HTFP values obtained by single wavelength primary radiometry.

Improvement of primary thermometers (pMFFT, CSNT, CBT) for the ultralow temperature thermometry regime (0.9 mK to around 1 K). Resolving the PLTS 2000 background data discrepancy (6 % at lowest temperatures) including revised T-T_{2000} data over the range 0.9 mK to 1 K (target standard uncertainty of 1 %).

Research was performed to improve the performance of three low temperature thermometers; the Magnetic Field Fluctuation Thermometer (pMFFT), the Coulomb Blockade Thermometer (CBT) and the Current Sensing Noise Thermometer (CSNT). A document outlining Johnson Noise Thermometry (pMFFT & CSNT) was written, submitted and approved by CCT for inclusion in the *MeP*-K-19. The inclusion of CBT is still a matter of debate by CCT and the decision about its inclusion within the *MeP*-K will be deferred until the next revision.

When combined with the data taken in the InK 1 project a full evaluation of the PLTS-2000, through T-T_{2000} measurements, with the three primary thermometer types has been performed. For over 99 % of its range (~0.01 K to 1 K) the PLTS-2000 is thermodynamically correct within 1 %. However there appears to be, particularly below 0.003 K, an increasing departure from PLTS-2000 from thermodynamic measurements. This is observed for both CSNT and pMFFT measurements and the departure is larger than the measurement uncertainties. While the cause of the discrepancy in the original background data of the PLTS-2000 has not been definitively identified the new measurements tend to support the PTB-2006 evaluation. A report describing these findings has been prepared for CCT to consider at its meeting in Mar 2020. This objective was fully achieved with new low uncertainty results over the range 0.01 K to 0.0009 K.

Impact

Dissemination has been through papers, talks at meetings/conferences (UK, Finland, Italy, Spain, France, China) and the publication of semi-popular articles in trade and special interest magazines/newsletters. Annual progress reports were submitted to CCT and the RMO TCTs, in addition an annual oral progress report was given to the EURAMET TCT. The website has been updated and the final newsletter sent to the stakeholder community. Presentations were given in NMIs, to CCT, to conferences for e.g. the Spanish Metrology Congress 17 (San Fernando), NEWRAD 17 (Japan), Metrologie 17 (Paris), at the Chinese Academy of Sciences, Beijing (Nov 17) as well as NIM, China. In 2018, presentations were given to French optics, spectroscopy and acoustics conferences, the IMEKO World Congress and the European Association of Thermology. One special event was the EURAMET Summer School of Thermometry held in Thessaloniki, Greece in September 2018. There new researchers to the discipline were trained in a wide range of thermal measurement techniques and there were presentations on the redefined kelvin, including the contribution of InK 2. In 2019 a redefined kelvin workshop was organised at the EURAMET TCT with all the input arising from the InK 2 project. The final version of the *MeP*-K-19 was launched to coincide with World Metrology Day 2019 and the launch of the redefined SI. The text included significant input from InK 2 including the parts describing low temperature Johnson Noise Thermometry and Refractive Index Gas Thermometry. A statement was issued to accreditation bodies, disseminated through EURAMET TCT contact persons, concerning the impact of the kelvin redefinition. Finally, in 2019, a special session, dedicated to InK 2, chaired by the InK 2 coordinator, was held at the important Tempmeko 2019 conference (Chengdu, China). In addition, the coordinator gave an invited keynote address at the same conference which was largely based on the InK projects.

Impact on industrial and other user communities

The main industrial impact of this project will not be felt until well after the kelvin redefinition and the approaches to primary thermometry described in the *MeP*-K-19 start to take effect in the 2020s.

Early impact in the lifetime of the project will be particularly in the ultra-low temperature regime. The EU is the world's largest supplier of cryogenic equipment, dilution refrigerators and cryogen free ultra-low temperature systems. Practical primary low temperature thermometers for use below 20 K to ~1 mK are now more widely available and reliable because of this project

More widely industry will be impacted through the redefined kelvin and more direct traceability to the kelvin definition. This will be in the years following the kelvin redefinition (2019) as the realisation and dissemination phase of the redefined kelvin becomes increasingly operative in the 2020s.

Impact on metrology and other scientific communities

The main impact of the InK 2 project will be on the whole international thermometry community through performing the necessary research required to ensure an effective and trouble-free implementation of the kelvin redefinition in May 2019. This has now been achieved with the kelvin being redefined in Nov 2018 and the implementation phase being complete in 20 May 2019.

The main immediate beneficiary of this research was the CIPM as the work performed in this project strongly facilitates a sound and reliable introduction of the redefined kelvin. The CCT has been and will continue to be strongly impacted by the outcomes of this project, with direct input into the text of the *MeP*-K-19 and through new evaluations of reliable low uncertainty thermodynamic temperature values, T-T_{90} and T-T_{2000}. In addition, the practice primary thermometry methods were advanced sufficiently to admit them into the *MeP*-K, for example Refractive Index Gas Thermometry and low temperature Johnson Noise Thermometry.

This impact was assured because partners chaired and participated in key CCT working groups and task groups, responsible for both the *MeP*-K-19 and also the validation of thermodynamic temperature values.

Scientific impact has been made through advancing the state of the art in primary thermometry in the partners' laboratories. A significant number of refereed scientific papers in leading relevant journals and presentations at appropriate workshops, symposia and conferences have been published and submitted. Of particular note is the impact InK 2 had at the major Tempmeko/Tempbeijing 2019 conference. The vast majority of the world experts in thermometry attended that meeting, and besides the special session highlighting InK 2 outcomes, there was a keynote address and in total 30 papers/posters derived from the work of InK 2.

Development of an EU cohort of primary thermometry experts was greatly facilitated through this project with 19 staff exchanges having taking place in the InK 2 project with more planned, including through the Researcher Mobility Grant mechanism. This will prove invaluable to the success of the realisation phase of the redefined kelvin which will take place over the coming decade.

Impact on relevant standards

This project has and will continue to have great impact on the thermometry community around the world. It has produced definitive technical data and results and recommendation documents for the CCT. Importantly, it has produced a complete re-evaluation of the PLTS-2000 over its entire range, and the ITS-90 up to the Cu freezing point (1358 K). In addition, definitive text for the *MeP*-K-19 has been written and supplied for, refractive index thermometry (including principles, practice and uncertainties) and the various forms of Johnson Noise Thermometry for ultralow temperature thermometry namely CSNT and pMFFT. Text for CBT has also been prepared in anticipation of its incorporation into a future version of the *MeP*-K, the latter will be considered at the March 2020 CCT meeting.

It is very important that the relevant international bodies are kept informed of the progress and outcomes of the project. An annual oral progress report was given to the EURAMET TC-T in April 2017, April 2018 and April 2019. The RMO Thermometry Technical Committees were sent a written annual progress report in May 2017, April 2018 and July 2019. The global NMI community was kept up to date through annual reports from the InK 2 coordinator to the CCT, issued through the president.

The outcomes of InK 2 will enduringly support all standards that requires reliable temperature measurement, including humidity and moisture and related thermal quantities. InK 2 and the previous InK 1 project have put in place the foundational framework for reliable thermometry, post the kelvin redefinition, throughout the world.

Longer-term economic, social and environmental impacts

The InK 2 project will have wide ranging economic, social and environmental impact over the next decade and beyond. This is because the project's objective is to facilitate and provide ongoing reliable fit-for-purpose temperature measurement which is required in all these domains.

The first long term impact will be through the key stakeholder the CCT (and more generally the CIPM). The research outcomes of InK 2 (in combination with the previous InK 1 project) have supported an effective introduction of the *mise en pratique* for the definition of the kelvin (*MeP*-K-19). In addition, through new evaluations of low uncertainty values for T-T_{90} and T-T_{2000} the InK 1 and InK 2 projects will provide, for any user who needs them, thermodynamic temperature values from the defined scales. It is envisaged that these will become definitively available after the next CCT (Mar 2020). In the long term (late 2020s/2030s) this data may provide the platform for a possible future temperature scale ITS-20XX if required. Or, alternatively, the measurement approaches stimulated by the InK projects may lead to a rise in practical primary thermometry for the realisation and dissemination of thermodynamic temperature directly linked to the redefined kelvin. (See the *Impact on metrology and other scientific communities* section above for more details).

The redefinition of the kelvin, in May 2019, has led to a situation that was akin to that when the metre was redefined in the 1980s. After the metre redefinition there was a rapid expansion of new optically based dimensional measurement approaches leading to large new industries today (Renishaw for e.g.). It is very likely that something similar will happen in the decades following the kelvin redefinition. NMIs will increasingly use primary thermometry for dissemination of temperature (for e.g. by the mid-2020s this is likely to have happened for high temperatures above 1300 K and for low temperatures below 20 K. These are two of the objectives of the soon to start EMPIR Real-K project). In the longer term (2030s and beyond) it is envisaged that there will be an increasing use of *practical* primary thermometry directly in industry to facilitate "always on always traceable" temperature sensing, where traceability is built directly into the sensor itself. These new sensing methods may even give rise to new sensor manufacturers in the future.

The rise in dissemination of thermodynamic temperature by NMIs, and also the rise of practical primary thermometry could well lead to a decreasing role for the defined scales in the 2020s, with PLTS-2000 being completely superseded by primary thermometry approaches and ITS-90 dissemination increasingly curtailed to the mid-range temperatures. Ultimately in the very long-term thermodynamic temperature may be all that is disseminated by NMIs, obviating the need for a defined scale. This would negate cost to industry because it would avoid the introduction (and associated costs) of any future temperature scale and reduce or even eliminate the need for sensor retrieval and recalibration.

From an environmental point of view traceability to thermodynamic temperature would be welcomed. For example, when monitoring global temperatures, corrections for changes in temperature scales have to be made to data. Besides introducing unfortunate step changes in the data record it is not always clear which temperature scale was used for the measurements leading to additional uncertainties. If traceability to thermodynamic temperature is achieved, then no new temperature scale will be needed, and all environmental temperatures will then be founded on fundamental physics and no correction from a defined scale will be required in the future – simplifying the interpretation of data sequences and reducing the contingent uncertainty. In addition, temperature monitoring of long-term hazardous waste (e.g. nuclear waste) requires "fit and forget" technology – practical primary thermometry is potentially an important solution for this currently intractable problem.

So, in summary the economic and social impact of this project in the longer term will be significant through facilitating traceability to thermodynamic temperature and practical primary thermometry. This will have contingent industry benefits through optimising energy use and ensuring the lowest possible carbon emissions (which is also good for the environment). In addition, the rise and introduction of practical primary thermometry will facilitate autonomous production which requires completely reliable and traceable sensors. Finally, totally new high technology sensor manufacturing industries could arise because of the development of practical primary thermometry approaches.

List of publications

O. Hahtela, E. Mykkänen, A. Kemppinen, M. Meschke, M. Prunnila, D. Gunnarsson, L. Roschier, J. Penttilä & J. Pekola "Traceable Coulomb Blockade Thermometry", *Metrologia* (2017) **54** 69-76 https://doi.org/10.1088/1681-7575/aa4f84

D. I. Bradley, A. M. Guénault, D. Gunnarsson, R. P. Haley, S. Holt, A. T. Jones, Yu. A. Pashkin, J. Penttilä, J. R. Prance, M. Prunnila, L. Roschier "On-chip magnetic cooling of a nanoelectronic device", *Scientific Reports* ***7**,* Article number: 45566 (2017) https://doi.org/10.1038/srep45566

J. Engert, A. Kirste, A. Shibahara, A. Casey, L. Levitin, J. Saunders, O. Hahtela, A. Kemppinen, E. Mykkänen, M. Prunnila, D. Gunnarsson, L. Roschier, M. Meschke and J.P. Pekola New evaluation of $T - T_{2000}$ from 0.02 K to 1 K by independent thermodynamic methods, *J. Int. Thermophys.* **37**:125, 2016, https://pure.royalholloway.ac.uk/portal/en/publications/new-evaluation-of-t-t2000-from-002k-to-1k-by-independent-thermodynamic-methods(dc393a64-8d59-4083-9435-f2bd70eea8ed).html

M. Palma, C. P. Scheller, D. Maradan, A. V. Feshchenko, M. Meschke & D. M. Zumbühl, On-and-off chip cooling of a Coulomb blockade thermometer down to 2.8mK, *Applied Phys Lett* https://doi.org/10.1063/1.5002565

A. Kirste, J. Engert, Cross-correlation limit of a SQUID-based noise thermometer of the pMFFT type, *IOP Conference Series*, https://doi.org/10.1088/1742-6596/969/1/012083

B. Khlevnoy, I. Grigoryeva, K. Anhalt, M. Waehmer, E. Ivashin, D. Otryaskin, M. Solodilov, V. Sapritsky, Development of Large-area High-Temperature Fixed-Point Blackbodies for Photometry and Radiometry, *Metrologia*, https://doi.org/10.1088/1681-7575/aaa16a

Haiyang Zhang, Wenjing Liu, Bo Gao, Yanyan Chen, Changzhao Pan, Yaonan Song, Hui Chen, Dongxu Han, Jiangfeng Hu, Ercang Luo, Laurent Pitre. A high-stability quasi-spherical resonator in SPRIGT for microwave frequency measurements at low temperatures. *Science Bulletin.* 2019, **64(5),** 286-288. https://doi.org/10.1016/j.scib.2019.01.018

YanYan Chen, Haiyang Zhang, Yaonan Song, Pan Changzhao, Bo Gao, Wenjing Liu, Hui Chen, Dongxu Han, Ercung Luo*, Mark Plimmer, Fernando Sparasci and Laurent Pitre. Thermal response characteristics of a SPRIGT primary thermometry system. *Cryogenics*, 2019, **97**, 1-6 https://doi.org/10.1016/j.cryogenics.2018.10.015

Bo Gao, Changzhao Pan, L. Pitre, *et al*. Chinese SPRIGT realizes high temperature stability in the range of 5-25 K. *Science Bulletin*. 2018, **63(12),** 733-734. https://doi.org/10.1016/j.scib.2018.05.023

Dongxu Han, Bo Gao, Hui Chen, Pascal Gambette, HaiyangZhang, Changzhao Pan, Yaonan Song, Wenjing Liu, Jiangfeng Hu, Bo Yu, Yingwen Liu, Ercang Luo, Laurent Pitre. Ultra-stable pressure is realized for Chinese Single Pressure Refractive Index Gas Thermometry in the range 30 kPa to 90 kPa. *Science Bulletin.* 2018, **63(12),** 1601-1603. https://doi.org/10.1016/j.scib.2018.12.001

M. Wähmer, K. Anhalt, J. Hollandt, R. Klein, R. D. Taubert, R. Thornagel, G. Ulm, V. Gavrilov, I. Grigoryeva, B. Khlevnoy, V. Sapritsky Thermodynamic Temperature of High-Temperature Fixed Points Traceable to Blackbody Radiation and Synchrotron Radiation. *International Journal of Thermophysics* https://doi.org/10.1007/s10765-017-2273-z

Gavioso R. M. G. Determination of the thermodynamic temperature between 236 K and430 K from speed of sound measurements in helium. *Metrologia* https://doi.org/10.1088/1681-7575/ab29a2

Laurent Pitre, Mark D. Plimmer, Fernando Sparasci, Marc E. Himbert Determinations of the Boltzmann constant. *Comptes Rendus Physique* https://doi.org/10.1016/j.crhy.2018.11.007

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2016, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Prof. Graham Machin, NPL   Tel: +44 208 943 6742   E-mail: graham.machin@npl.co.uk
Project website address: http://www.vtt.fi/sites/InK2/</td></tr>
<tr><td>Internal Funded Partners:
1 NPL, United Kingdom
2 CEM, Spain
3 CNAM, France
4 CSIC, Spain
5 INRIM, Italy
6 LNE, France
7 PTB, Germany
8 TUBITAK, Turkey
9 VTT, Finland</td><td>External Funded Partners:
10 Aalto, Finland
11 RHUL, United Kingdom
12 SUN, Italy
13 UP13, France</td><td>Unfunded Partners:
14 NIM, China
15 TIPC-CAS, China
16 VNIIOFI, Russian Federation</td></tr>
<tr><td colspan="3">RMG1: CEM, Spain (Employing organisation); CNAM, France (Guestworking organisation)
RMG2: INTiBS, Poland (Employing organisation); CNAM, France (Guestworking organisation)
RMG3: TUBITAK, Turkey (Employing organisation); INRIM, Italy (Guestworking organisation)
RMG4: SMU, Slovakia (Employing organisation); CNAM, France (Guestworking organisation)
RMG5: INRIM, Italy (Employing organisation); CNAM, France (Guestworking organisation)</td></tr>
</table>