Implementing the new kelvin 2

Welcome to the fourth and final Newsletter of InK2 project!

It only seems a short while since we started the InK2 project (June 2016) and now we have come to its end (May 2019). The InK2 project has made significant advances in primary thermometry on a broad front and its outcomes will impact the thermometry community for years to come.

The InK2 project will make important contributions to the international conference Tempmeko and Temp-beijing 2019 (http://www.tempmeko2019.cn/) held in Chengdu, China on 10-14 June 2019. There will be a special InK2 themed session, a keynote address by the coordinator reporting the results of the InK1 and InK2 projects. In addition, many of the primary thermometry sessions at the conference will be dominated by the work of InK2.

On 23-27 March 2020 the Consultative Committee on Thermometry (CCT) meets. The CCT is a technical committee of the International Committee on Weights and Measures (CIPM) which is the world body that ensures the international system of units (the SI) is properly implemented and regulated by its member states. The new low uncertainty measurements of T-T90 and T-T2000, made in InK2, will be formally reported to CCT and these are expected to have significant and enduring impact on the technical annexes of the MeP-K-19.

The close of the implementation phase of the redefinition of the SI took place on World Metrology Day 20 May 2019. The Mise en Pratiques of the redefined units were launched the same day. Some of the text associated with the redefined kelvin arose as a direct consequence of the work in InK2, especially the text on low temperature Johnson Noise and Refractive Index Thermometry.

The CCT has produced an important statement concerning the future status of temperature traceability which, among other things, explains the role of the MeP-K-19: "The kelvin has been redefined with no immediate effect on temperature measurement practice or on the traceability of temperature measurements, and for most users, it will pass unnoticed. The redefinition lays the foundation for future improvements. A definition free of material and technological constraints enables the development of new and more accurate techniques for making temperature measurements traceable to the SI, especially at extremes of temperature. The guidance on the practical realization of the kelvin (i.e. the MeP-K) supports its world-wide dissemination by describing primary methods for measurement of thermodynamic temperature and equally through the defined scales ITS-90 and PLTS-2000."

The InK consortium can be proud of its achievements and contribution to the redefinition of the kelvin. But as the implementation phase closes the door opens to the larger and dissemination phase of the redefined kelvin. In this new phase National Measurement Institutes around the world will work to turn the new definition into a reality. Temperature traceability currently based on a defined scale is likely to be increasingly challenged by one based on primary thermometry. This challenge will take place at the extremes of temperature >1300 K and <25 K, but over time at more modest temperatures as well. EURAMET plan to be at the forefront of these developments and has recently funded the EMPIR project Realising the redefined kelvin (Real-K) which will take important decisive steps towards establishing temperature traceability directly to the redefined kelvin by 2025.

Finally, I want to say it has been a great pleasure, indeed an honour, to be coordinator of the InK projects at this momentous time for the international measurement community. I thank you, our stakeholders, for your interest and support. I hope you enjoy this final newsletter and will sign up to receive the Real-K newsletters when the project is launched in September 2019.

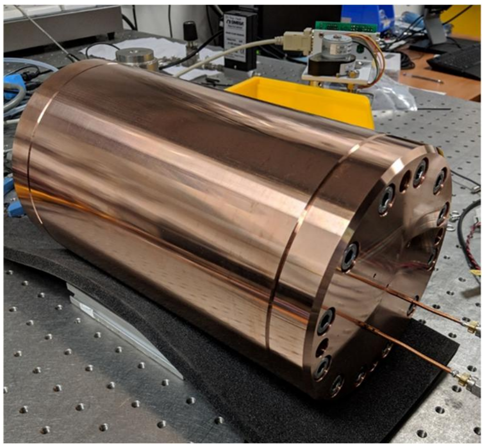
Prof. Graham Machin,
InK2 coordinator

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

Research highlights

T–T_{90} by acoustic gas thermometry

NPL has been carrying out T–T90 measurements using acoustic thermometry and an aluminium resonator up to 156 °C. In order to perform T–T90 measurements up to higher temperatures than are achievable with the aluminium resonator, a cylindrical resonator has now been designed and built. This has been constructed from a copper alloy, namely CuCrZr. This alloy retains its hardness up to 500 °C to 600 °C while still retaining 80 – 90 % of the thermal and electrical conductivity of copper. The resonator was machined using conventional techniques and measurements on a roundness machine showed that the form of the resonator good to a few micrometres.



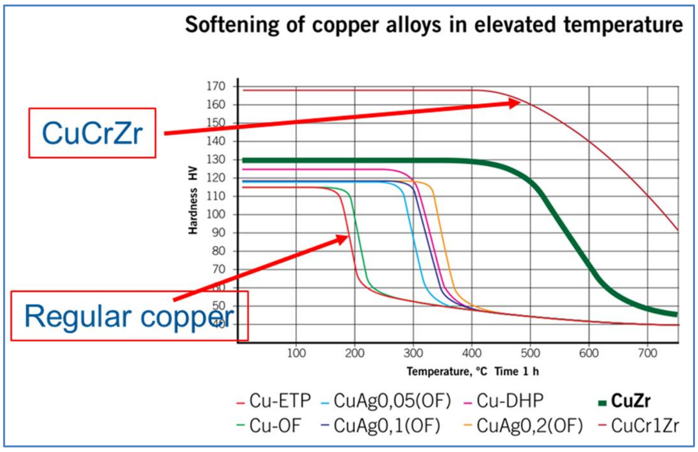


Figure 1. Left: The NPL cylindrical resonator, right: hardness properties of copper alloy vs. temperature.

It has been observed that the shape and size of the resonator changes with heating. In order to compensate for this a theoretical method has been developed which uses multiple microwave modes to calculate the required corrections to the acoustic modes to allow for the distorted shape. This should improve the results obtainable with the resonator

At VNIIFTRI a difference was determined between temperature defined by International Temperature Scale (ITS-90) and thermodynamic temperature measured by relative acoustic gas thermometry at 79 K and at 83.8058 K. Measurement were carried out using quasi-spherical acoustic resonator filled with helium at different pressures. The isotherms were fitted for four different acoustic modes simultaneously assuming the same thermal accommodation coefficient and third acoustic virial coefficient for all modes. Obtained values of the difference between temperature measured by thermometers realizing ITS-90 and thermodynamic temperature are listed in the table below.

Table 1. Values of T, $u_C(T)$, $u_C(T_{90})$, T-T_{90} and $u_C(T-T_{90})$

T_{90}, K	$u_C(T_{90})$, mK	T, K	$u_C(T)$, mK	T–T_{90}, mK	$u_C(T–T_{90})$, mK
83.80580	0.28	83.80099	0.93	-4.81	0.97
79.00000	0.32	78.99548	0.87	-4.47	0.93

The values agree with previously published data within estimates of combined standard uncertainty. Results are submitted to the *International Journal of Thermophysics*.

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Single Pressure Refractive Index Gas Thermometry (SPRIGT)

At the Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences (TIPC-CAS) in China breakthroughs in the three key technologies of Single Pressure Refractive Index Gas Thermometry (SPRIGT), high-stability temperature regulation, high-stability pressure control and high-accuracy microwave frequency measurement, have been realized with the help from LNE-Cnam, namely temperature stability of 2 mK, pressure stability of 0.1 ppm, and microwave frequency stability of 0.01 ppb with integration times of 33 s, 0.7 s, and 3 h, respectively.

TIPC-CAS has got preliminary results in the determinations of thermodynamic temperatures. The measurements have been carried out with high-purity Helium 4 at temperatures from 5 K to 24.5561 K with TM11, TE11, TM12, TE13 microwave modes on three single pressures of 30 kPa, 60 kPa, and 90 kPa, respectively. A detailed uncertainty budget has been developed for the three single pressures, where the uncertainty of reference temperature and that of the 2nd virial coefficient are the main uncertainty components for relative higher and lower temperatures, respectively. Good repeatability and consistency of thermodynamic temperatures are realized among the three different pressures. Following the weighted mean method commonly used internationally, total uncertainties less than 0.19 mK (k=1) for thermodynamic temperatures from 5 K to 24.5561 K are determined in SPRIGT (see figure 2).

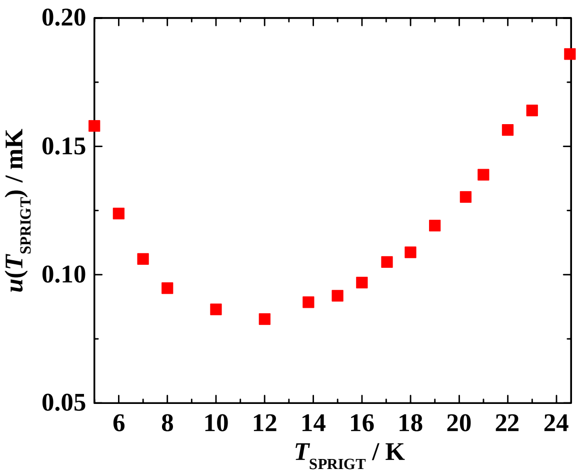

Figure 2. Left: Single Pressure Refractive Index Gas Thermometry at TIPC-CAS in China. Right: Total uncertainties (k=1) for thermodynamic temperatures T_{SPRIGT} *from 5 K to 24.5561 K.*

Refractive index gas thermometry

Determinations of $T-T_{90}$ at the fixed points of Oxygen and Neon were obtained at INRiM by measuring the refractive index of He as a function of pressure in the range between 65 kPa and 350 kPa (see figure) using a copper microwave resonator. These determinations of $T-T_{90}$, namely (–1.55 ± 1.32) mK at 54.3584 K and (–0.47 ± 0.43) mK at 24.5561 K are consistent with previously published refractive index-, acoustic- ,and dielectric constant gas thermometry results. Measurements will continue until the end of the project aiming to achieve additional determinations near the fixed points of hydrogen and argon. This work will be presented at Tempmeko 2019.

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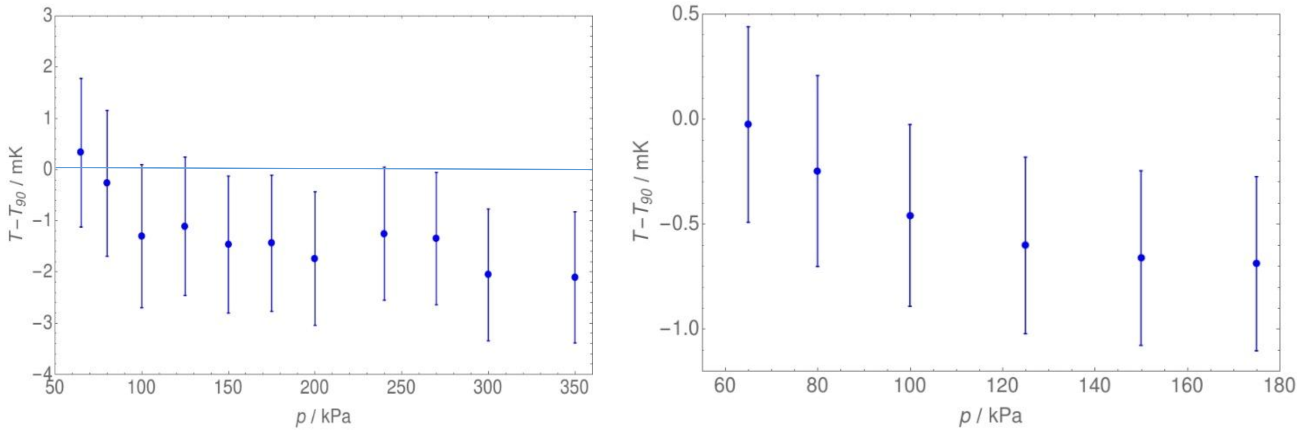

Figure 3. ($T-T_{90}$) *results along isotherms at the triple point of oxygen (left plot) and neon (right plot). Uncertainty bars include contributions from mode inconsistency, isothermal compressibility, pressure measurements and thermal gradients across the apparatus.*

Doppler Broadening Thermometry by line absorbance analysis

In the framework of the InK2 project, Doppler broadening gas thermometry made a significant step forward for the aims of low uncertainty thermodynamic temperature determinations. Thousands of high-quality absorption spectra were recorded in coincidence with a line-doublet of the C_2H_2 near-infrared spectrum, by using the 3rd generation DBT spectrometer developed at Università della Campania "Luigi Vanvitelli", in Caserta, Italy. A very refined multispectrum fitting procedure (with some relevant physical constrains) was developed and applied to the spectra in order to retrieve the absorbance at the line center (*α*) as well as the integrated absorbance (*A*) for each of the two acetylene lines. Proposed by Livio Gianfrani and co-workers in 2011 (https://doi.org/10.1103/PhysRevA.84.032510), the line absorbance analysis exploits the relationship between *α* and *A* to retrieve the Doppler width of a spectral line from a set of profiles at different gas pressures. In the so-called Doppler regime (namely, at low pressures), this relationship can be modeled by means of a polynomial function in the variable *A*, whose order depends on how large is the explored pressure interval.

The two plots in Figure 4 result from the application of the line absorbance analysis for the R(15) and P(17) lines of a given vibrational band of acetylene at the wavelength of about 1.4 µm. Spectroscopic measurements were performed nearby the temperature of the gallium melting point. The thermodynamic temperature is retrieved from a 4th-order polynomial fit. The weighted mean of the two values shows a statistical uncertainty of about 4 parts per million, which is a quite remarkable result for Doppler broadening thermometry (A. Castrillo, E. Fasci, H. Dinesan, S. Gravina, L. Moretti, and L. Gianfrani, "Optical determination of thermodynamic temperatures from a C_2H_2 line-doublet in the near infrared", *Phys. Rev. Appl.*, in press).

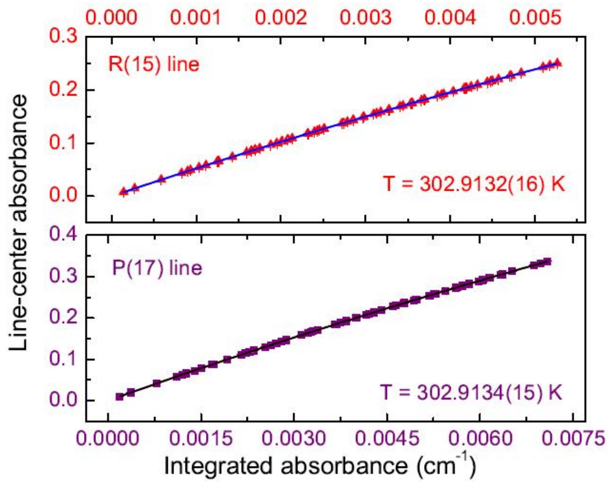

Figure 4. Examples of the line absorbance analysis.

New T–T2000 data from comparison measurements between PLTS-2000 and primary thermometers in the temperature range from 100 mK to 1 mK

The current sensing noise thermometer and the primary magnetic field fluctuation thermometer, two primary thermometers developed in the InK2 project by the Royal Holloway University of London (RHUL) and by PTB, have been compared with a realisation of the Provisional Low Temperature Scale 2000 (PLTS-2000) over more than two decades in temperature. A preliminary evaluation of the data shows good agreement between the thermodynamic temperature values of both thermometers and the PLTS-2000 temperatures. This new data obtained during experiments at RHUL will allow a final conclusion to be drawn regarding the thermodynamic correctness of the PLTS-2000.

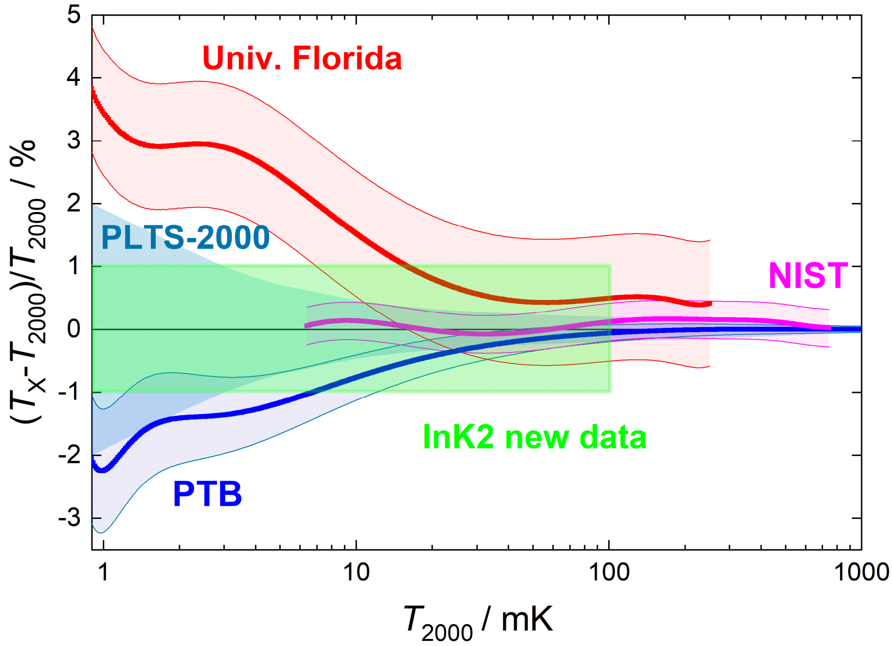

Figure 5. Relative deviations of the background data of the PLTS-2000 (data from NIST, University of Florida and PTB, Rusby R. L. et al., 2002, J. Low Temp. Phys. 126, 633) from the PLTS-2000. Shadowed areas mark the corresponding uncertainties of the data with coverage factor k = 1. The green shadowed rectangle represents the temperature interval of the current measurements where new thermodynamic temperature data are obtained with an expected uncertainty of about 1 %.

Investigation of the SF_6 fixed point cell

The Research Mobility Grant (RMG) that is part of the InK2 project was dedicated to the investigation and characterisation of a new type of fixed point cell (FPC) of SF_6 that is a candidate for replacing the calibration point within the ITS-90 in the temperature range previously covered by the FPC of Hg. The replacement of the Hg FPC is motivated by the EU mercury regulation 2017/852 that restricts the usage of Hg. Based on these future restrictions it is of high importance to have a suitable and well defined fixed point (FP) for the temperature around –50 °C. The research has measured several capsule type platinum resistance thermometers in the SF_6 FPC by an adiabatic technique. A series of repeated realizations have been performed with an average stability of 0.07 mK. This triple point state lasted in average for 39 h. It has been observed that the SF_6 FPC performance is comparable to other ITS-90 cells when used with capsule type SPRTs. Further evaluation of data is being conducted together with the direct comparison with Hg FPC.

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Contact and further information

InK2 project is carried out by the following partners and institutions.

	NPL	NPL Management Limited	UK
	CEM	Centro Español de Metrología	Spain
	CNAM	Conservatoire national des arts et metiers	France
	INRIM	Istituto Nazionale di Ricerca Metrologica	Italy
	LNE	Laboratoire national de métrologie et d'essais	France
	PTB	Physikalisch-Technische Bundesanstalt	Germany
	TUBITAK	Turkiye Bilimsel ve Teknolojik Arastirma Kurumu	Turkey
	VTT	Teknologian tutkimuskeskus VTT Oy	Finland
	Aalto	Aalto-korkeakoulusäätiö	Finland
	CSIC	Agencia Estatal Consejo Superior de Investigaciones Cientificas	Spain
	UP13	Université Paris 13	France
	RHUL	Royal Holloway and Bedford New College	UK
	SUN	Università degli Studi della Campania Luigi Vanvitelli	Italy
	TIPC-CAS	Technical Institute of Physics and Chemistry, Chinese Academy of sciences	China
	NIM	National Institute of Metrology	China
	VNIIOFI	Federal State-Owned Unitary Enterprise All-Russian Research Institute for Optical and Physical Measurements	Russian Federation

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WP2: Measurement of $T–T_{90}$ (5 K ... 200 K)	Fernando Sparasci	CNAM	fernando.sparasci/at/cnam.fr
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WP4: Primary Low-Temperature Thermometry	Jost Engert	PTB	jost.engert/at/ptb.de
WP5: Creating Impact	Ossi Hahtela	VTT	ossi.hahtela/at/vtt.fi

Outcomes of InK2 can be found at project's website: http://www.vtt.fi/sites/InK2/

Project page at ResearchGate: RG/InK2 where you can follow the progress of the project and participate in discussion related to the new definition of the kelvin and its future implementation.

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