CGPM

CCT President's Report

27th CGPM (2022)

Working together to promote and advance the global comparability of measurement

www.bipm.org

Report by the President of the CCT

Dr Yuning Duan, President of the Consultative Committee for Thermometry (*Comité consultatif de thermométrie,* CCT) reported on the activities of the CCT since the 26th meeting of the CGPM (2018).

Preparation of this report received the strong support of Prof. Graham Machin, National Physical Laboratory Senior Fellow (UK) and chair of the CCT Working Group for Non-Contact Thermometry (CCT-WG-NCTh).

Executive summary

The CCT covers metrology linked to temperature, humidity and thermophysical quantities[1].

A precise and accurate knowledge of temperature and related quantities is important in many domains of science, technology and industry. For example:

- Temperature is a key control parameter in industry; its reliable measurement is inextricably linked to efficient energy use and product quality.
- Temperature and humidity metrology play important roles in climate studies.
- Reliable thermophysical quantity measurements are essential to quantify, for example, the performance of thermal insulations.

Since the 26th meeting of the CGPM (2018), the CCT has given attention to realizing and disseminating the redefined kelvin, focused on improving climate-based measurements and contributed to improving clinical thermometry during the Covid-19 pandemic. The CCT strategy underwent a major refresh in 2021 and is now fully aligned with the "CIPM strategy 2030+: responding to evolving needs in metrology". There are significant emerging challenges for the CCT, for example how to conduct key comparisons for thermodynamic temperature and implementing digitalization, especially through validating approaches that provide *in situ* traceability to the kelvin (for example practical primary thermometry).

Scope of the CCT

The CCT gives advice to the CIPM on all scientific matters and issues that influence metrology in the fields of temperature, humidity and thermophysical quantities. It acts as the focus and network for this diverse community, to develop common aims and facilitate collaboration between national metrology institutes (NMIs) and designated institutes (DIs) in Member States or with other relevant bodies. The CCT assures the global measurement infrastructure for thermometry through promoting and supporting the international temperature scale of 1990 and providing extensive best practice in thermometry and related quantities. It also identifies and organizes key comparisons in its fields to establish global comparability of measurements and traceability to the SI, assuring the quality of reported data. It also encourages research in NMIs in progressing the kelvin realization and dissemination and supports the measurement infrastructure needed to respond to global challenges, such as climate change and pandemics.

Activities and achievements since the last meeting of the CGPM

The CCT and the redefinition of the kelvin

Until May 2019 the kelvin was defined by the temperature of the triple point of water – the temperature where ice, water and water vapour coexist. Incremental improvements to its realization have been made; for example by deriving corrections for the influence of the isotopic composition of the water. However in May 2019, the kelvin, along with the ampere, kilogram and mole were redefined in terms of defined values of fundamental constants.

[1] Thermophysical quantities describe thermal behaviour in matter, such as thermal conduction or thermal insulation.

The redefinition of the kelvin by the Boltzmann constant was a key objective of the CCT, which played a key coordinating role in achieving a successful outcome for the kelvin redefinition. A large number of metrology institutes, using different techniques and realizations, determined the Boltzmann constant *k* with low uncertainty. Four main approaches were investigated; the speed of sound in Ar or He gas (Acoustic Gas Thermometry, AGT); a capacitance approach through the dielectric constant of He (Dielectric Constant Gas Thermometry, DCGT), Johnson (electrical) noise in a resistor (Johnson Noise Thermometry, JNT) and Doppler broadening of a spectral line (Doppler Broadening Thermometry, DBT).

International collaboration between involved institutes was indispensable to get a clear picture of the results, especially an understanding of the systematic uncertainty components. The set acceptance criteria for the Boltzmann constant (CCT Recommendation T1 (2014) on the new definition of the kelvin)

- a relative standard uncertainty of the adjusted value of *k* less than 1×10^{-6},
- a determination of *k* based on at least two fundamentally different methods, of which at least one result for each have a relative standard uncertainty less than 3×10^{-6},

were exceeded in that AGT, DCGT and JNT had sufficiently low uncertainties to contribute to the consensus value of the Boltzmann constant. The set criteria ensured there was no discernible difference in temperature between the old and new definitions. The CODATA special adjustment in 2017 provides the exact value

$$\boldsymbol{k = 1.380\,649\ 10^{-23}\ \text{J/K}}$$

The preparation for the new definition of the kelvin was accompanied by a *mise en pratique*[2]. The *mise en pratique* is a document that guides the user from the kelvin definition based on *k* to a practical (laboratory) realization of the unit. It contains the following: the definition of the kelvin, definition of terms related to primary thermometry, criteria for inclusion of a thermodynamic method, an outline of primary thermometry methods for realizing the kelvin based on fundamental laws of physics [Acoustic gas thermometry, Radiometry, Dielectric Constant Gas Thermometry, Refractive Index Gas Thermometry, Johnson Noise Thermometry] and the text of the defined temperature scales, ITS-90, PLTS-2000. This document is not only a guide but represents the current state of the art in thermometry and condenses decades of experience.

The present temperature scales ITS-90 and PLTS-2000 are not affected by the redefinition. A comprehensive electronic guide "*Guide to the realization of the ITS-90*"[3] was updated and is available on the BIPM website. Guides for secondary thermometry (specialist fixed points and thermocouples) have also been produced.

Recent publications of relevance include a *Metrologia* focus issue on the Boltzmann constant[4] in 2015, a special edition of *Phil. Trans. A* by the UK Royal Society on implementing the new kelvin[5] in 2016 and an invited summary paper on the redefined kelvin[6] in 2018.

The different primary instruments developed for the determination of the Boltzmann constant are now being used to measure thermodynamic temperature over a wide range of temperatures to determine the difference between thermodynamic temperature to the present temperature scale ITS-90. This phase is expected to last until the mid- to late-2020s. This will result in a revised evaluation of T-T_{90}, which is necessary for the community of users where precise values

[2] Mise en pratique - kelvin - Appendix 2 - SI Brochure (bipm.org)
[3] https://www.bipm.org/en/committees/cc/cct/guide-its90.html
[4] http://iopscience.iop.org/journal/0026-1394/page/Focus_on_the_Boltzmann_Constant
[5] Machin, G., "Towards implementing the new kelvin" *Phil. Trans R. Soc. A.* **374**: 20150053, (2016) http://dx.doi.org/10.1098/rsta.2015.0053
[6] Machin, G., "The Kelvin redefined", *Meas. Sci. Technol.* **29** 022001 (11pp) (2018) https://doi.org/10.1088/1361-6501/aa9ddb

of thermodynamic temperature are required. It is not envisaged that a new temperature scale will be needed in this decade. The temperature community is instead focused on putting into practice two recent CCT recommendations:

- T1 (2017) where Member States' National Metrology Institutes (NMIs) are encouraged to "take full advantage of the opportunities for the realization and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the *mise en pratique* for the definition of the kelvin (*MeP*-K)".
- T1 (2021) that NMIs establish capability to determine T-T_{90} above 400 K, and in so doing establish the background capacity for dissemination of thermodynamic temperatures approaching 700 K.

It is clear that at high temperatures >1300 K and low temperatures <25 K dissemination of thermodynamic temperature is feasible. The ongoing research in NMIs will show how wide a temperature range dissemination of thermodynamic temperature is possible in the longer term.

Strategy

In 2012, the CCT carried out a significant analysis of its accomplishments since the introduction of the CIPM MRA and a forecast of its impact. This analysis in the form of a Strategic Plan was updated and published in 2017[7] and provided a global picture of the present and future needs in thermal metrology. The CCT strategic plan underwent a complete revision in 2021 and now covers the period 2021 to 2030[8]. In a break with the way in which the previous CCT Strategic Plan was formulated this one identified stakeholders' interests at the top level of metrology aligning its priorities with the document "CIPM strategy 2030+: responding to evolving needs in metrology". The activities of the CCT are profoundly cross-cutting and as its strategy was developed it was clear that the CCT could contribute to all seven key priority areas identified in the CIPM document namely: climate change and environment, health and life sciences, food safety, energy, advanced manufacturing, digital transformation and "new" metrology. The full CCT Strategy can be found on the BIPM website and a summary[9] is given in the table below:

The CCT Strategy has been aligned to the "CIPM Strategy 2030+". Stakeholder needs were categorized within the identified priority areas. Additional stakeholder needs, particular to CCT, were also considered. In the light of these issues CCT considers the following to be its priorities from now to 2030+.

- The influence of the **redefinition of the kelvin (K)** and the associated ***MeP*-K-19** is increasingly being felt by stimulating long-term research into primary thermometry approaches for temperature realization and dissemination. Realization and dissemination of thermodynamic temperature: a) at high temperatures **by indirect primary radiometry** through high temperature fixed points and b) at low temperatures **by Johnson Noise Thermometry** below ~5 K and **Gas Based thermometry approaches (acoustic gas thermometry**, **dielectric constant gas thermometry, refractive index gas thermometry) >**5 K, will increasingly become common place as the decade advances, especially in the latter case for the calibration of CSPRTs.
- In the short-medium term, the ITS-90 **(International Temperature Scale)** will still be relevant and continue needing incremental improvements (fro example to address the possible ban in the use of Hg). It is likely that at high and low temperatures ITS-90 will increasingly be supplanted by primary thermometry. In the medium-long term the PLTS-2000 (**Provisional Low Temperature Scale**) could be completely supplanted by primary thermometry.
- In the longer term, photonic thermometry, *in-situ* calibration and *in-situ* primary thermometry all have the potential to disrupt current approaches to temperature dissemination.
- A **key role of the CCT** will be to monitor this increasingly mixed situation regarding temperature dissemination (i.e. defined scales, primary thermometry and *in-situ* thermometry) and agree how to ensure ongoing world-wide equivalence of temperature measurement.

[7] https://www.bipm.org/utils/en/pdf/CCT-strategy-document.pdf
[8] https://www.bipm.org/documents/20126/41598583/CCT+Strategy/145827b2-4f6a-42ed-bd77-bbffa782e2f7
[9] https://www.bipm.org/documents/20126/41598622/CCT+Strategy+Summary/f3f211d0-a520-17ae-089f-c70719e39771

– In the **long term, primary thermometry** regulated by the *MeP*-K **may meet temperature dissemination needs**. However, it is prudent to continue investigation into a range-restricted future scale (ITS-XX). Any decision to introduce ITS-XX would need to be carefully balanced against real stakeholder needs and cost of implementation. – **Humidity and moisture** metrology is driven notably by environmental needs and climate observations, advanced production processes and future energy gases for exampe hydrogen. The WG is seeking to resolve the issues regarding ambiguous definitions of terms in this area and to repeat a KC. – Key **Environmental observations** are inextricably linked to temperature and humidity measurements. Collaboration with WMO, GCOS, and IAPWS via a CCT WG ENV allows a reciprocal exchange of expertise and advice and will lead to ever increasing traceability of the measurement of these Essential Climate Variables. Work is ongoing to improve the reliability of air temperature measurement (not just for climate). – The TG for **Body Temperature Measurement** will work to improve the metrology of BTM in response to the plethora of inappropriate BTM for triage that was performed during the COVID-19 pandemic. – Reliable determination of **Thermophysical quantities** are particularly valuable to support the energy and advanced manufacturing sectors. Comparisons of key TQs are being led by the TG to support CMCs.
Workload Trend and Workload Management – KC workload is managed carefully within CCT by WG KC. This ensures that only KCs that are essential to underpin CMCs are performed. – In the light of accelerated developments in thermometry practice, arising from the kelvin redefinition, a key CCT activity will be ensuring ongoing world-wide equivalence to temperature measurement. – CCT will continue to grow engagement with a broad range of stakeholders to ensure its work meets perceived future needs. – Production of best practice guides relating to thermal measurements and other aspects of education/training will form a growing part of CCT's activities in the coming decade.
BIPM – references to laboratory activity at the BIPM – BIPM has no laboratory activity in thermometry.

CCT working and task groups

There are seven Working Groups within the CCT: Contact Thermometry (WG-CTh); Environment (WG-Env); Non-Contact Thermometry (WG-NCTh); Humidity (WG-Hu); Key Comparisons (WG-KC); CMCs (WG-CMC); and Strategic Planning (WG-SP). The CCT is also supported by a number of Task Groups, which will have a limited duration depending on achievement of the objective and/or time.

WGs and TGs of particular note are:

- WG CTh and WG NCTh, in conjunction with WG SP, worked closely together to ensure the kelvin redefinition was effective.
- WG on Environment focuses on engagement with the meteorological community and climate measurements.
- TG on Body Temperature Measurement was established to improve fever screening on a global basis in response to the Covid-19 pandemic and has published guides for non-contact body temperature measurement[10] in English and Spanish.
- TG on emerging technologies – with emphasis on detailing and promoting novel photonic approaches to thermometry such as ring-resonators, Doppler Broadening Thermometry and self-calibration: a recent paper[11] described some of its findings.
- TG on Digitalization – focused on ensuring the CCT responds appropriately and is ready for the needs of digitalization.

[10] Best Practice Guide in forehead thermometry

[11] Dedyulin, S., Ahmed, Z., Machin, G., "Emerging technologies in the field of thermometry", *Meas. Sci. & Technol.* **33** 092001 (26pp) (2022) https://doi.org/10.1088/1361-6501/ac75b1

Comparisons

Several comparisons within the CCT are approaching completion since the last CGPM. Notably, on the realization of the ITS-90 using Standard Platinum Resistance Thermometers (CCT-K9) and realizations of the ITS-90 above the silver point (CCT-K10); are nearing conclusion. A repeat of the realization of the triple point of water began in 2021 and is well under way. A comparison of realization of local scales of dew-point temperatures of humid gas is under way and should be completed before the mid-2020s. The CCT has presently identified seven key comparisons, listed in the table below.

SET OF CCT KEY COMPARISONS		REPEATS	
CCT-K1	Realization of the ITS-90 from 0.65 K to 24.6 K		
CCT-K2	Realization of the ITS-90 from 13.8 K to 273.16 K		
CCT-K3	Realization of the ITS-90 from 83.8 K to 933.4 K	**CCT-K9**	Realization of the ITS-90 from 83.8 K to 692.7 K
CCT-K4	Comparison of local realizations of Al and Ag freezing-point temperature		
CCT-K5	Realization of the ITS-90 from 961 °C to 1700 °C	**CCT-K10**	Realization of the ITS-90 from 961 °C K to 3000 °C
CCT-K6	Humidity: Dew and frost point temperaures (-50 °C to 20 °C)	**CCT-K8**	Humidity: Dew point temperaures (30 °C to 95 °C)
CCT-K7	Water triple point cells	**CCT-K11**	Repeat foreseen in 2019

Interaction with international bodies

The CCT, via the Working Group for Environment, has several members on the Commission for Instruments and Methods of Observation (CIMO) Expert Teams of the World Meteorology Organization (WMO), and reciprocal input in the CCT working group. This arrangement has been in place since 2015.

Active exchanges take place between the CCT and the International Association on Properties of Water and Steam (IAPWS) on issues related to humidity.

The TEMPMEKO conference, in conjunction with Tempbeijing held in Chengdu (China) in 2019 was the most recent opportunity for the international thermometry community to exchange information. The forthcoming International Temperature Symposium in California (USA) in April 2023 will be the first global gathering of temperature experts since the Covid-19 pandemic.

CCT Data

CCT was set up in 1937

President: Dr Yuning Duan	Executive Secretary: Dr Stéphane Solve
Membership	25 members and three observers
List of CCT members and observers	https://www.bipm.org/en/committees/cc/cct/members
Meetings since the 26th CGPM meeting:	(20 October, 4 November, 17 November 2020, 19 January, 9 February 2021), 18 January and 8 February 2022
Full reports of the CCT meetings:	https://www.bipm.org/en/committees/cc/cct/publications
Seven Working Groups:	https://www.bipm.org/en/committees/cc/cct

- Calibration and Measurement Capabilities (WG-CMC)
- Contact Thermometry (WG-CTh)
- Environment (WG-Env)
- Humidity (WG-Hu)
- Key Comparisons (WG-KC)
- Non-Contact Thermometry (WG-NCTh)
- Strategic Planning (WG-SP)

Seven Task Groups:

- Digitalization (TG-DIG)
- Thermophysical Quantities (TG-ThQ)
- Emerging Technologies (TG-CTh-ET)
- Calibration media (TG-CTh-CalMed)
- Calibration and reference thermocouples (TG-CTh-TC2)
- Air Temperature (TG-Env-AirT)
- Industrial Radiation Thermometers (CCT-TG-NCTh-IRT)

CCT Comparison activity	Completed	In progress	Planned [2023-2026]
CCT key comparisons (and supplementary comparisons)	10	16 +(18)	0
BIPM comparisons	0	0	0
CCT pilot studies	3	0	3
CMCs	2 940 thermometry CMCs registered in the KCDB (14 September 2022)		