Strategy Document for Rolling Programme Development from 2021 to 2030

The Consultative Committee for Thermometry

1. General Information on the Consultative Committee for Thermometry

Consultative Committee for Thermometry (CCT)

Established in 1937

25 members and 3 official observers

79 participants at last meeting in 2020 - 2021

7 working groups and 8 task groups

CCT meetings every 2 to 3 years

Last meeting held from 20 October 2020 to 9 February 2021[1]

CCT President Dr DUAN Yuning, Vice Director of National Institute of Metrology (NIM), China (from 2012)

24 KCs carried out from 1999 to 2021, 8 KCs in progress (see section 6).

In addition, 51 RMO key comparisons are registered in the KCDB[2] and 35 of these have been approved and published – 2915 CMCs entries in the KCDB are supported by the CCT.

2. Terms of Reference

To be informed of technical developments and evolving stakeholder needs in different areas of metrology, the CIPM has Consultative Committees with agreed scopes and objectives.

The CCT has the following terms of reference, *in common with the other CCs*:

- to progress the state-of-the art by providing a global forum for NMIs to exchange information about the state of the art and best practice,
- to define new possibilities for metrology to have impact on global measurement challenges by facilitating dialogue between the NMIs and new and established stakeholders, and
- to demonstrate and improve the global comparability of measurements.

Particularly by working with the RMOs in the context of the CIPM MRA to:

1. plan, execute and monitor KCs, and to
2. support the process of CMC review.

[1] The 29th meeting of the CCT was held as a series of five on-line meetings.
[2] Archived comparisons excluded

Flowing from those high-level objectives agreed by the CGPM, the CCT has the following specific objectives:

1. To establish, maintain and improve global compatibility of thermal measurements through promotion of traceability to the International System of Units (the SI).
2. To ensure that the SI unit of temperature and derived quantities are realized and disseminated worldwide in a uniform and appropriate manner. Derived quantities include: humidity and moisture, thermophysical quantities and thermal energy (heat).

This is achieved by:

- Fulfilling the terms of reference relevant to thermal metrology as defined by the CIPM as stated in the "Rules of procedure for the Consultative Committees (CCs)."
- Providing recommendations to the International Committee for Weights and Measures (CIPM) for the realization and dissemination of the SI unit of temperature and derived quantities.
- Recommending research in thermal metrology to maintain and develop the SI in relation to the kelvin, including its realization, and that of the units of derived quantities.
- Supporting the National Metrology Institutes[3] (NMIs) provision of traceability to thermal metrology quantities, such as through provision of guidance documents & training materials.
- Encouraging NMIs to address emerging thermal metrology needs.
- Providing definitive guidance on thermal metrology to users.
- Maintaining liaison with relevant stakeholders to ensure deep awareness of their needs.

3. Stakeholders and stakeholder needs

Stakeholders' interests are identified at the top level of metrology from the document "CIPM strategy 2030+: responding to evolving needs in metrology[4]". There seven key priority areas are identified: climate change and environment, health and life sciences, food safety, energy, advanced manufacturing, digital transformation and "new" metrology. The activities of CCT are profoundly cross-cutting and can certainly contribute to addressing the needs of all these stakeholders.

The **stakeholder´s needs** relevant to the CCT community (as per the CIPM 2030+ strategy document) are currently dominated by the following challenges:

- **Climate change and environment** – Temperature and humidity are Essential Climate Variables (ECVs) and as such reliable traceable values of these parameters are key for monitoring global climate and for providing hard data for environmental protection and climate change mitigation policies. Measurement capabilities by CCT members undergird reliable determination of ECVs in the whole biosphere, for example sea, ice and soil temperature, air RH and soil moisture. There are still many aspects of these measurements that are not well understood (e.g. air temperature) whilst even the expression of relative humidity is not yet standardised. On-going engagement with the relevant climate specialists, e.g. WMO, through the WG for Environment, WG for Humidity and the Metrology for Meteorology and Climate conference, is essential and ensures that the input from CCT has significant influence. Furthermore, this topic is strongly connected to energy and advanced manufacturing. Improving industrial process efficiency and building energy efficiency reduces industrial emissions and energy consumption and contributes to minimising energy-loss from building envelopes.

[3] The term « NMI » includes also Designated institutes in this document.
[4] The version of this document used in preparation of the CCT Strategy is 0.5.

- **Health and Life Sciences** – Temperature measurement is a key indicator to human health. One challenge for the CCT is to ensure "traceability to the SI for the calibration of regulated clinical devices" (that is, clinical thermometers) something that is not currently in place in many countries. More widely, an important key driver is the need to improve routine body temperature measurement practice, especially by non-contact thermometry, to improve diagnosis and treatment of diseases in both a clinical and non-clinical (i.e. home) setting. Advanced traceable temperature measurements are required in hospitals for safe active thermal therapies (e.g. cancer ablation and improved diagnostics, the latter through e.g. truly quantitative thermal imaging). Improved non-contact thermometry and fever screening is required to address the challenge of future pandemic preparedness (the inadequacy of current practice has been highlighted by the current COVID-19 pandemic). Humidity and moisture as well as thermal quantities have a key role to play in medicines manufacture, wound care management and humidity control in medical gases.
- **Food safety** – Temperature and humidity/moisture measurement and control, and hence ultimately the support of CCT, has a critical role to play in food safety. The safe transport and storage of food requires guaranteed temperatures both for those that are frozen and refrigerated (this is often regulated by national standards). Food needs to be properly cooked (which means attaining the right temperature) to ensure sterility and safety for consumers. Control of moisture transport through packaging is also essential to prevent food spoilage and contamination. Drying of foodstuffs (measurement and control of moisture levels in e.g. powders/grains) to low moisture levels to ensure long-term storage is also essential.
- **Energy** (supply and security) – The world is facing what is known as the "energy trilemma" that of reducing carbon emissions, maintaining affordable energy and securing supply. CCT has significant contribution to make in addressing the trilemma by supporting the temperature, humidity/moisture and thermal quantity measurements that underpin: low carbon generation of energy (nuclear, renewables, hydrogen), energy efficiency at point of generation, relevant both for combustion-generated electricity, but also for renewables such as solar, and energy efficiency at point of use; transport, industry or in homes. Improved energy efficiency improvements are generally linked to thermal quantity measurements if the energy is used for heating, or temperature/humidity if thermal processing is involved, whilst the transport sector is moving to electrification, and in the longer term fuel cells, and thermal measurement and monitoring are critical for the efficient use and long life of batteries and fuel cells. Reliable measurement of moisture content of fuel gases at varying pressures is critical to their performance, safety and environmental impact and is a developing area for thermal metrology.
- **Advanced manufacturing** – This strategic area is undergoing a rapid transformation through the digitisation of industrial processes, leading to full-autonomous/semi-autonomous production. As nearly all industrial production requires some form of thermal processing, the need for always-right *in-situ* traceability for thermal quantities will become essential in the future. These *in-situ* traceable thermal sensors would in all probability form the reference sensors for larger embedded sensor networks monitoring and controlling complex industrial processes. It is anticipated that such developments may well flow out of metrology advances arising from kelvin redefinition[5]. Advanced manufacturing areas with specific metrology challenges are semiconductor device production where very tight tolerances with very low moisture levels are required and additive manufacturing which has outstanding thermometry measurement challenges. Additionally, materials with temperature-dependent properties are used for such applications and new and innovative approaches for thermal quantity characterization of, for example, powders and wires are required. However, it is important

[5] There is an open question here about the role of CCT in ensuring the reliability of *in-situ* traceability.

that, despite the current focus on digitalisation, the CCT must not neglect the on-going metrology requirements of more traditional industries, whose output currently forms the bulk of the world's economic activity and where reliable temperature and humidity sensing is essential. Incremental improvements in thermal sensing in these areas will reap benefits through optimising use of resources (raw materials and energy) and improving process control to facilitate "zero waste" manufacture, product quality and user benefits.

- **Digital transformation** – There is some linkage between Advanced manufacturing and Digital transformation. In this case the focus is on the traceability and dissemination aspects of thermal quantities, e.g. providing measurement traceability to digital sensors, and the impact of digital transformation, in the Advanced manufacturing part (immediately above) the focus was on applications and outcomes. The challenge here is for CCT to identify what are the key aspects of the digital NMI agenda that are relevant to our Consultative Committee such as provision of digital calibration certificates, machine readable and actionable data and provision of SI traceability at the point of measurement. It would be worth considering the establishment of a CCT TG to identify the "digital transformation" requirements relevant to CCT.
- **"New" metrology** – Here the CIPM strategy identifies some disruptive trends that could challenge the traditional view of traceability. The rise of and interconnectedness of low cost sensors– for e.g. mobile phones measuring temperature and humidity or smart watches "measuring" body temperature – give rise to questions such as what is the reliability of such data? How do you assign an uncertainty? What is CCT's role in ensuring traceability to the kelvin? Other areas that are mentioned are "distributed instrumentation" – that is the sensor is significantly remote from the measurement device – and "intrinsic measurement standards" such as self-calibrating sensors and *in-situ* traceability. "Artificial Intelligence and Big Data" is also mentioned in this context and is linked to the growing use of low-cost un-calibrated and often interconnected sensors. CCT already has some activity in this area through the TG on Emerging Technologies. It could be that the remit of this group should be expanded to examine the wider questions posed by the "New" metrology and what are its implications for the CCT.

Beyond the high-level stakeholders identified by the CIPM document and more generally, the CCT identifies stakeholder needs through the NMI national representatives. These can range from instrument manufacturers to industrial, research base (e.g. universities), healthcare and other users. There are also many possible stakeholders represented by other CCs, within or known to regional metrology organization technical committees for thermometry (RMO TC-Ts), institutions, organizations, standardization bodies and committees, scientific communities, users' associations, manufacturers and others.

Finally, there is a growing need for education in thermal metrology. There is a lack of understanding among many stakeholders of uncertainties, sensor selection and use, of traceability and accreditation. There is a rising generation of thermal metrologists in the NMIs who would benefit from such training. The CCT guides are a good starting point but possibly a summer school (modelled on the EURAMET Summer School of Thermal Metrology[6]) would be an effective way of rapidly and effectively passing on skills and experience to future generations.

4. Structure of the CCT

[6] https://www.euramet.org/publications-media-centre/news/news/first-euramet-summer-school-on-thermal-measurements-a-big-success/

The field of thermometry covers a wide range of temperature and therefore a wide range of techniques is necessary for its realization. Humidity and thermophysical quantities are closely related fields and they are therefore integrated in the CCT activity. The CCT relies on seven different working groups, covering the different fields and aspects of its responsibility:

WG-SP	Strategic Planning
WG-CTh	Contact Thermometry
WG-NCTh	Non-contact thermometry
WG-Env	Environment
WG-Hu	Humidity
WG-KC	Key comparisons
WG-CMC	Calibration and measurement capabilities

The CCT is also supported by several flexible Task Groups. These are created to carry out a distinct mission and are hence limited in time. When this revision of the CCT Strategic Planning was prepared (June 2021), there were eight Task Groups:

TG-CTh-ET	Emerging technologies
TG-Env-AirT	Air temperature
TG-NCTh-BTM	Body temperature measurements
TG-ThQ	Thermophysical quantities
TG-CTh-CalMed	Guide on calibration media
TG-CTh-IPRT	Guide on industrial platinum resistance thermometry
TG-NCTh-IRadT	Guide on industrial radiation thermometry
TG-CTh-TC2	Guide on thermocouples, part 2

The key distinction between a Working Group and a Task Group is that Working Groups act on a long-term basis, while a Task Group carries out a limited-time restricted mission. The CCT interacts also with other Consultative Committees, as well as with international organizations and bodies where appropriate.

5. Achievements from 2017 to 2020 and future scan from 2021 to 2030+

The achievements of the CCT and its working groups and the future scan are summarized below. The different fields have been separated to facilitate the identification of each.

<table>
<tr><th>Achievements 2017-2020</th><th>Future Scan 2021-2025</th><th>Future Scan 2025-2030+</th></tr>
<tr><td colspan="3">Definition of the kelvin and MeP-K</td></tr>
<tr><td>Low uncertainty value of Boltzmann constant measured by multiple approaches, CODATA consensus value agreed and established successful kelvin redefinition put in place.

CCT recommends that member states take full advantage of the opportunities for the realisation and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the MeP-K-19.

Mise en pratique for the definition of the kelvin (and annexes) formally published 20th May 2019 https://www.bipm.org/documents/20126/41489682/SI-App2-kelvin.pdf/cd36cb68-3f00-05fd-339e-452df0b6215e?version=1.4&download=true

The appendix for Johnson Noise Thermometry (JNT) at temperatures around and below 1 K was finalized, an appendix for JNT at higher temperatures was drafted.</td><td>ITS-90 continues to be the key output of the CCT, facilitating reliable, traceable temperature measurement on a global basis. CCT affirms its continued relevance and it is clear that defined temperature scales and thermodynamic temperature will co-exist for many years to come.

ITS-90 to be kept up to date by incremental improvements in realization and dissemination (e.g. non-uniqueness studies and possible alternative fixed point to Hg if needed).

It is envisaged that the operation of the MeP-K-19 will be reviewed 2025-2027 with recommendations about how to proceed regarding thermodynamic temperature realization and dissemination. It is likely that T realization and dissemination will become dominant in some temperature ranges <25 K (and maybe up to 300 K by 2030 or sooner) and >1300 K.

Finalize appendix for JNT at higher temperatures, prepare possible case for incorporating Coulomb Blockade Thermometry (CBT) into the annex of MeP-K-19.

Background research and preparation into possible future ITS-XX undertaken, in case needed.</td><td>CCT review (2027-2030), led from CCT-SP, into on-going relevance of current temperature scales PLTS-2000 and ITS-90 and examining the requirement for ITS-XX, review to encompass stakeholder needs, cost of implementation and need (i.e. how much remains to be superseded by T realization and dissemination).

Revision of the MeP-K-19 in latter part of decade to incorporate if appropriate, new practical primary thermometers, preselected by the TG-CTh-ET, to allow for a future direct realization and dissemination of thermodynamic temperature above 25 K. PLTS-2000 may be completely superseded by primary methods before 2030.</td></tr>
<tr><td>Results of T-T_{90} in the range from 430 K to 1358 K (acoustic and radiometric) and in the range from 1 K to 200 K (acoustic, refractive-index and dielectric constant methods) measured as part of the EMPIR InK2 project and at NRC. Presented in Tempmeko ’19.</td><td>Demonstration and establishment of traceability directly to the redefined kelvin from ~1300 K to ~3000 K via low uncertainty thermodynamic temperatures of four new HTFPs (WC-C, Ru-C, Pd-C and Fe-C). Real-K EMPIR Project.</td><td></td></tr>
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Achievements 2017-2020	**Future Scan 2021-2025**	**Future Scan 2025-2030+**
InK2 EMPIR Project results on three novel thermometry methods (Doppler Broadening Thermometry [DBT], Double Wavelength Thermometry and Radiation Thermometry Traceable to Synchrotron Radiation), intended to establish novel primary thermometry approaches to attain uncertainties required to probe the underlying systematic uncertainties in T-T_{90}. Presented in Tempmeko '19.	Further development of DBT encouraged as a possible approach to small scale optically-based primary thermometry.	Practical small scale fibre-coupled DBT developed and demonstrated.
In view of a possible ban of mercury, the sources for high-purity xenon (Xe) as fixed-point substance were positively evaluated. Other candidate fixed-points are (sulphur hexafluoride) SF_6 and (carbon dioxide) CO_2. A first survey of the possible interpolation functions without the Hg-TP or with a possible replacement by Xe was performed. Many new thermodynamic temperature results in the range between 5 K and 300 K obtained by Acoustic Gas Thermometry, Refractive Index Gas Thermometry and Dielectric Constant Gas Thermometry have been published. It was agreed that the new values for $T - T_{90}$ in the range below 300 K are sufficient for an evaluation to deduce new consensus values.	In view of a possible ban of mercury, the fixed-point realizations with different substances like Xe, SF_6 or CO_2 should be evaluated for calibrating CSPRTs and LSPRTs. Alternative interpolation functions using a substitution for the Hg-TP to be established to be able to accommodate a possible ban of mercury (this is being examined in EMPIR Real-K). If substitution was required, a minor amendment to the ITS-90 (if the influence on the realized temperature values is sufficiently small) would be needed. The collation of T-T_{90} data below 300 K will be finalized and new consensus values with much smaller uncertainties will be published. Further new experiments with primary thermometry in the temperature range between 5 K and 25 K will allow to recommend alternatives to the ICVGT prescribed in the ITS-90. These are underway e.g. within the Real-K consortium.	

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Working Group for Contact thermometry		
New data on T_{90}-T_{2000} was published, supporting the already known deviation of T_{90} from T below 1.5 K. First tests of a direct dissemination of thermodynamic temperature via Polarizing Gas Thermometry (Dielectric Constant Gas Thermometry and Refractive Index Gas Thermometry) in the range between 5 K and 25 K were encouraging.	Alternatives as scale carriers to no longer produced rhodium-iron resistance thermometers for the range below 25 K must be found and tested (e.g. platinum-cobalt thermometers).	
There is a requirement for $T - T_{90}$ values above 400 K: a CCT recommendation was drafted "Requirement for new determinations of thermodynamic temperature above 400 K." First tests with new HTSPRTs have been performed and analyzed. Modified recommendations for the use of Sealed Metal Fixed Point Cells have been agreed.	New experiments with primary thermometers in the temperature range above 400 K will be started to clarify the discrepancies between different primary thermometer results. New work supported by agreed CCT recommendation 2021. Further tests with new HTSPRTs can overcome the problem of the realization of ITS-90 via contact thermometry above 933 K. An Approximation with pure-metal thermocouples will be investigated. A new appendix of the Guide to the Realization of the ITS-90 dealing with the application of SMFPCs to be prepared in 2021. The non-uniqueness of the SPRT part of the ITS-90 is being investigated both theoretically and experimentally at NRC and in the Real-K project. It is a permanent task of CCT Working Group for Contact Thermometry to collate crystallographic and other data necessary for estimating the uncertainty component due to chemical impurities.	Different primary thermometers can approximate the ITS-90 below 4 K and 25 K. Recommendations for the approximation of the scale applying them should be prepared. The recommendations for the estimation of the uncertainty of fixed-point realizations and the validation of fixed-point cells must be updated. This should be based on the experience gained and includes the determination of the overall impurity content by measuring the residual resistance ratio of the fixed-point materials. New thermodynamic temperature data above 400 K, obtained with new or improved primary thermometry methods, will lead to much better estimates of T-T_{90} and, therefore, facilitate the access to T via T_{90} for the users.

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Task Group for Emerging technologies		
Prepared a report for the CCT documenting a range of disruptive technologies including primary and defined scale thermometry techniques based on optics, nanophotonics and quantum optomechanics. Report details anticipated performance metrics of various new techniques as compared to resistance thermometers. Report details the relative advantages and short-comings of various techniques.	Study use of embedded quantum thermometers in QIS. Study potential impact of photonic sensor networks in energy production, materials processing and long-term monitoring. Study the impact of AI/DML on enabling emerging technologies. Promote communication/collaborations between the innovator and metrology community e.g. publish review article on emerging technologies that introduces terms-of-art and physics of emerging technologies to a broad audience including metrologists and entrepreneurs.	Study the impact of AI/DML on enabling emerging technologies.

Achievements 2017-2020	**Future Scan 2021-2025**	**Future Scan 2025-2030+**
Guides on thermometry		
See Annex 1 for full list of guides published during this period. The different parts were written as independent documents, which will make future updates easier. Above all, state-of-the-art uncertainty budgets are included for all realization methods. This is most important for the influence of chemical impurities that is usually the dominant uncertainty component for the realization of the defining fixed points of the ITS-90.	Within this period it is expected that the following Secondary Thermometry guides will be published: • Thermistor thermometry (minor update needed) • Specialised fixed points above 0 °C • Thermocouples I: General usage • Thermocouples II: Calibration and reference thermocouples • Industrial Platinum Resistance Thermometry • Industrial radiation thermometry • Calibration media In addition, the Specialised Fixed Points Above 0 °C guide and Appendix 1 of the Metal Fixed Points for Thermometry guide will be updated to reflect current guidance on the use of sealed metal fixed point cells. The production of CCT authorised guides could be widened beyond thermometry to encompass other quantities e.g. humidity (a guide is in preparation, key Thermophysical Quantities?	Future guides to be written include: • Guide for fixed points below 0 °C (including updates to best practice for alternatives to the mercury fixed-point) In addition, it is desirable to make available online a database of up-to-date values for primary and secondary fixed-point temperatures, uncertainties and references to various papers.

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMIs and RMOs towards the development of guidelines: • For calibration of thermometers in air • For the evaluation of uncertainty components for temperature measurements in air, water (deep sea and sea surface, rivers, lakes, underground), ice and soil • To support the definition of target uncertainties and instrumental aspects in the creation of reference observing networks for climatology • To support metrology aspects in managing changes and transition from different instrument typologies (manual to automatic recordings) • To support metrology aspects in adoption of digital calibrations, i.e. electronic generation of calibration certificates and electronic dissemination thereof	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMIs and RMOs towards the development of appropriate actions: • To disseminate best practice and adoption of metrological methods and terminology, also considering the opportunity of adapting such methods and terminologies, to practical use and input from the external communities • To increase awareness of metrology, and in particular the importance of uncertainty and traceability, within universities, to provide science undergraduates with the necessary tools to perform measurements properly • To support metrology aspects in adoption of self-calibration techniques (with e.g. fixed points and practical primary thermometry)

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Working Group for Non-contact thermometry		
Definitive temperatures for Re-C, Pt-C and Co-C established (through EMRP InK1 project). Publication of definitive temperatures of High Temperature Fixed Points Re-C, Pt-C and Co-C: Lowe, D.H., et al "The equilibrium liquidus temperatures of rhenium-carbon, platinum-carbon and cobalt-carbon eutectic alloys" *Metrologia*, **54**, 390–398 (2017) https://doi.org/10.1088/1681-7575/aa6eeb Values incorporated in appropriate *MeP*-K-19 annex.	Determination of low uncertainty thermodynamic temperatures of four new High Temperature Fixed Points (WC-C, Ru-C, Pd-C and Fe-C) (via EMPIR Real-K project). Addition of revised values of temperatures to *MeP*-K-19 annex. Demonstration and establishment of traceability directly to the redefined kelvin from ~1300 K to ~3000 K by indirect radiometry (via HTFPs).	Indirect (and possibly direct) primary radiometry increasingly used to realise and disseminate *T* above the silver point. ITS-90 above the Ag point progressively superseded.
HTFP publications examining remaining uncertainty sources for HTFPs by the WG members: Todd, A.D.W., *et al* "On the uncertainties in the determination of thermodynamic temperature of high temperature fixed points", *Metrologia* **58** 035007 (8pp) (2021) https://doi.org/10.1088/1681-7575/abe9c5 Yamada, Y., "Investigation on the cause of the furnace effect of high-temperature fixed points", *Meas. Sci. Technol*. **32** 015009 (2020) https://doi.org/10.1088/1361-6501/abafe2	Remaining uncertainty sources regarding the implementation of HTFPs as reference standards identified and quantified.	
New radiometric methods such as double wavelength technique and radiation thermometry linked to Synchrotron radiation were rigorously investigated in the InK2 EMPIR Project to assess suitability for *MeP*-K, or for use as possible alternative approaches to classical radiometry. Results presented in Tempmeko '19.		Exploring the use of Planck Law for intrinsic measurement standards, or other optical based thermometry approaches for example Doppler broadening for "NMI on a chip" use.
Standardization of thermal imagers, new IEC TS 63144-1 "Industrial process control devices -Thermographic cameras - Part 1: Metrological characterization", 2020-04.	Future IEC TS 63144-2 is intended to specifically address the absolute calibration procedures and the corresponding uncertainties for thermographic cameras in more depth and detail.	

Achievements 2017-2020	**Future Scan 2021-2025**	**Future Scan 2025-2030+**
InK2 EMPIR Project results on measurements of T-T_{90} in the range from 430 K to 1358 K (radiometric). Presented in Tempmeko '19. Higher uncertainties than expected.		
Task Groups for primary radiometric temperature uncertainties, Non-Contact Thermometry CMCs, Non-Contact Thermometry HTFP Uncertainties – were established and completed their activities during this period. WG technical workshop: "The use of InGaAs detectors in radiation thermometry and radiometry" Sep 2018.	Future workshops are envisaged for e.g.: • Quantitative thermal imaging • Superseding ITS-90 >Ag using primary radiometry – what needs to be in place? Review guide/s in non-contact thermometry to ensure that they remain current and fit for purpose, incorporating and providing guidance on new non-contact thermometry methods; e.g. thermal imaging, phosphor thermometry.	TG established to examine how to put thermal imaging thermometry onto a sound metrological footing.
Task Group for Body Temperature Measurements		
CCT TG on Body Temperature Measurement (CCT-TG-BTM) established July 2020.	Key comparison of calibrators for body temperature thermometers (ear/forehead). Launch 2021, finish by 2024. Collect and consolidate current best practice of body temperature measurement; ear/forehead clinical thermometry and thermal imager fever screening – publish best practice guides by 2022 after consultation with clinicians. Work with IEC/ISO/CEN standards bodies to improve metrology content of clinical thermometer guides.	Launch of Key comparison of calibrators for body temperature thermal imager calibration. Review BTM guides and if required issue second edition. Continue work with IEC/ISO/CEN standards bodies to improve metrology content of clinical thermometer guides – aim to have new standards before 2030 which include robust metrology.

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Working Group for Environment		
CIPM RECOMMENDATION T3 (2010) "On climate and meteorological observations measurements" and the ToR of the CCT WG Environment are the basis for establishing long term collaboration with the scientific community involved in research on climate and environmental monitoring and motivates specific projects and actions from the NMIs.	Data comparability: Include as reliable as possible uncertainty analysis in historical data; study and assess traceability. Water content measurements (air and soil): Develop suitable measurement techniques and guides. Evolving technologies, such as non-contact instruments, for meteorological and climatological measurements will be constantly followed, with dedicated activities and studies.	CCT recommends NMIs to include in their vision documents all possible actions within the expertise of the thermal metrology community contributing to improve measurement quality and knowledge on observation and monitoring of the environment and climate.

Achievements 2017-2020	**Future Scan 2021-2025**	**Future Scan 2025-2030+**
The "Metrology for Meteorology and Climate" – MMC **Conference series** and associated workshops and satellite events • were fully participated in and endorsed by CCT WG ENV members • represent world top level events for increasing the collaboration between thermal metrologists and the stakeholder communities. Joint Research projects such as MeteoMet, INCIPIT, CRS, COAT progressed the scientific studies and technical research on improving calibration and measurement procedures and uncertainty evaluation. A metrology network on climate and ocean observation has been formed by EURAMET. The "ATM – Air Temperature Metrology" EURAMET project was launched in 2018, to execute an intercomparison of calibration procedures for thermometers in air and produce a guide. The project formed the basis to launch global initiatives on solving calibration and measurement issues for air temperature. APMP comparison on air temperature thermometers was also started in 2018. TG Air Temperature established.	Improved techniques, proposals of best practices (also for inclusion in the WMO guide no. 8) and on-site calibration devices will be addressed to cryosphere observations (high mountains and polar areas). Establishing reference test sites with the highest quality SI-traceable measurements of ECVs, including prototypes of climate reference stations and research infrastructures to support the implementation plan of the GSRN. Arctic Metrology: polar activities will continue with on site calibration campaigns, the implementation of the "Metrology Laboratory" at the arctic station in Ny-Ålesund, and a WMO intercomparison of thermometers and shields in polar environment. On-site thermometer shield with the minimum environmental effects will be designed and tested. Support in the validation of records associated with extreme events (such as temperature extremes and heat waves, precipitation events, pressure, wind speed etc.), through metrological analysis of the whole measuring process and instrumentation. Improved monitoring techniques for essential fresh water natural and artificial reservoirs and the creation of measurement recommendations.	The WG-ENV will continue to facilitate project proposals for funding and joint activities among the members on activities. WG-ENV members will continue studying and characterizing temperature, humidity and radiation sensors for ocean applications, ground based systems and radiosondes. Provide roadmap to address needs of data quality arising from possible new climate evolution scenarios. The CCT-WG-ENV will promote and contribute to interdisciplinary initiatives, worldwide and at regional level, to create forums and expert teams, to address the stakeholder's needs under coordinated efforts with other areas of metrology, also under future CIPM initiatives.

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Collaboration and stakeholders WG-ENV members are formally members of expert teams in the WMO INFCOM and SERCOM, in the Global Cryosphere Watch, the GCOS (GRUAN and GSRN Task Teams) and the BSRN. WG-ENV members are involved and supporting official WMO worldwide laboratory intercomparisons in Europe, Asia, Latin America and Africa. Formal collaborations with national meteorological and hydrological services, universities, research centres and manufacturers have been established.	**Collaboration and stakeholders** The relationships with key world and international Institutions such as WMO, GCOS, and IAPWS will be sustained to provide channels for impact in the work of the WG-ENV. CCT-WG-ENV members will continue to contribute as experts in WMO, GCOS task teams. CCT-WG-ENV, together with operational meteorologists, climatologists and metrologists, to contribute with studies and activities to GCOS for the definition of the key aspects of GSRN in terms of station features, data characteristics and target uncertainties.	**Collaboration and stakeholders** Impact: CCT members continue to organize events, meetings, workshops, conferences and training to discuss and plan common activities with the climate and environmental communities. The GCOS Surface Reference Network (GSRN) of observing stations on land implementation plan was approved by WMO in 2021 and will require a continuous support from the thermal metrology community, temperature and humidity of air and soil being key observables.
Task Group for Air Temperature		
In 2020 a new Task Group on "Air temperature" was formed, tasked: • To work towards and propose a practical definition of air temperature • To work towards and propose how to evaluate the uncertainty contributions in air temperature measurements • To develop guidelines for the calibration of thermometers in air	Practical definition of air temperature proposed. Method proposed on how to evaluate the uncertainty contributions in air temperature measurements. Draft guide for the calibration of thermometers in air.	Practical definition of air temperature agreed by CCT and promulgated to key stakeholders. Method for evaluating the uncertainty contributions in air temperature measurement agreed by CCT. Guide for the calibration of thermometers in air published on CCT website.

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Working Group for Humidity		
Quantities, units, symbols and realizations relating to humidity measurement: Work has continued on humidity terms and definitions, and consideration of a fugacity-based rigorous definition of relative humidity. A workshop on relative humidity definition was held as a joint event between IAPWS and BIPM, in association with the International Conference on the Properties of Water and Steam in 2018. A plenary presentation was given to Tempmeko '19 on the position of relative humidity in the SI.	Work towards definition of relative humidity in the SI, including suitable unambiguous terminology and units, working with relevant partners such as CCU, IAPWS, WMO, IUPAC, and ISO. Continue development of relative fugacity as real-gas alternative for conventional relative humidity definition, together with options for realization within the SI. Continue work on equations for evaluation of, and interconversion between, the wide set of humidity quantities, in cooperation with IAPWS and others.	Definition of relative humidity agreed by CCT and core partners.
Guidance Guidance on evaluating uncertainty in humidity metrology in support of KCs and CMC reviews is near to completion. A document on humidity primary realisations has been initiated.	Guidance document to be published, available.	
Collaboration and stakeholders Coordination and collaboration with IAPWS. Liaison with CCQM in areas of trace moisture in gases and moisture in materials. WG-Hu representation on CCT-TG-ENV to maintain interests in the key field of environment, including climate.	WG-Hu participation CCT-TG-ENV in keeping with significance of humidity variables and soil moisture as identified Essential Climate Variables. Active role in the Task Group for Air Temperature: air temperature is critical to humidity realisations of dew point and relative humidity. Consider contributions to humidity metrology especially related to climate and net-zero emissions, such as through guidance, training, support for uncertainty evaluation.	Continued collaboration on humidity metrology, especially related to climate and net-zero emissions.
	Finalise and fan-out of guidance.	

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
The **International Symposium on Humidity and Moisture** has been agreed to run jointly with the next Tempmeko.	Joint Tempmeko-ISHM event at date to be confirmed.	Future ISHM events to be sought at intervals of 5 to 10 years.
Emerging or developing techniques for humidity metrology have been monitored: • Extended capabilities for humidity realisations in varied gas species, pressure, and temperature ranges relevant to energy and industrial needs • Moisture in materials • New and improved water vapor spectrometers • Evaluations of water vapour enhancement factor	Continue monitoring and response where developments are relevant to SI metrology and traceability, with collaboration across consultative committees as required. Emerging needs for establishing international equivalence or CMCs to be considered. Develop and support metrology infrastructure for moisture in materials.	Continue monitoring and response where developments are relevant to SI metrology and traceability.
Task Group for Thermophysical Quantities		
The following actions have been led: **TQ research** • Within APMP, new proposals for international comparisons have been discussed, approved and registered by BIPM. • Within EURAMET/EMRP/EMPIR, new Joint Research Projects have been launched and performed. Some of them are still in progress. CCT-TG-ThQ members are strongly involved. • Comparisons have been performed.	• Develop further collaborations with relevant bodies or institutes mainly involved in e.g. energy, environment or industry. • When CCT needs to address ThQ measurements at the primary level, TG-ThQ will support the community with useful knowledge of or research on ThQ. • Review the service categories and identify research topic priorities in the field. • Initiate writing of guidelines for assessing uncertainties. Quantities to be selected among radiative properties, transport properties and caloric quantities	• Continue to develop collaborations with relevant entities involved in the fields of energy, environment or industry. • Support of CCT will be followed. • Continue writing of guidelines for assessing uncertainties. • TG-ThQ will continue to monitor emerging technologies or developing new metrology techniques (e.g. SThM).

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Comparisons: Detailed here, summarized in Section 6. CCT-S1; Infrared spectral normal emissivity: • This supplementary comparison was successfully completed. Final report has been approved by the WG-KC. All documents are available on the BIPM-KCDB. Comparison has been published in Metrologia journal. CCT-S2; Thermal Conductivity: • This supplementary comparison was successfully completed. Final report has been approved by the WG-KC. All documents are available on the BIPM-KCDB. Comparison has been published in Metrologia journal. CCT-S3; Thermal Diffusivity: • Final report and publication of the results in Metrologia journal.	CCT-S1; Infrared spectral normal emissivity: CMC protocol should be approved in 2021 CCT-S2; Thermal Conductivity: CMC protocol to be forwarded to CCT-WG-CMC CCT-S3; Thermal Diffusivity: CMC protocol should be approved in 2021 New Comparisons: • Finalise short list of new comparisons • Prepare draft of protocols and planning • Start and manage inter-laboratory comparisons • Perform the comparisons and manage the risks • Analyse the results and circulate draft reports • Publish within a reasonable time Thermal quantities have been recommended for this chapter: **Dilatometry:** Thermal Expansion Coefficient (TEC) **Calorimetry**: Heat of Combustion Additionally, Specific Heat of materials and Calorific Value of Gases have been mentioned as alternative or of additional interest. Ongoing support of CCT-WG-CMCs for the set of quantities under discussion and ranges will be considered.	Ongoing Comparisons: • Terminate the comparisons • Complete, edit the final report and publish the results in Metrologia Tech, Suppl New Comparisons: • Finalise short list of new comparisons • Prepare draft of protocols and planning • Start and manage inter-laboratory comparisons • Perform the comparisons and manage the risks • Analyse the results and circulate draft reports • Publish within a reasonable time Ongoing support of WG-CMCs for the set of quantities under discussion and ranges will be considered.

Achievements 2017-2020	**Future Scan 2021-2025**	**Future Scan 2025-2030+**
Communication/education		
Final wording of SI kelvin text agreed and incorporated in SI brochure 9th edition. Text for *MeP*-K-19 finalized and launched to coincide with launch of redefined SI in May 2019.	Important outputs from the Realising the redefined kelvin (Real-K) project will be >20 technical papers and discussion documents to the CCT. These together with papers such as White, D.R., & Rourke, P.M.C., "**Standard platinum resistance thermometer interpolations in a revised temperature scale**", 2020, *Metrologia* **57** 035003 https://doi.org/10.1088/1681-7575/ab6b3c , White, D.R., (2021): "**Hot and cold: defining and measuring temperature**", *Contemporary Physics*, DOI: 10.1080/00107514.2021.1896132 and those from the "Emerging Technologies" TG, will help inform CCT thinking regarding the future realisation and dissemination of the kelvin. The outputs of this and other research will also feed into a revision of the *MeP*-K-19 which should be initiated mid-2020s.	Revision of the *MeP*-K-19 to be agreed and issued by end 2020s. WG-SP to continue to review reports, papers etc and to consider and recommend how CCT should respond. (example: is ITS-XX needed, the scope and validity of *T* realisation and dissemination)
Stakeholder communication has been through papers and conference presentations. Examples of which are: Papers published detailing the achievements of the kelvin redefinition, how it was performed and possible future paths for temperature realization and dissemination. Machin, G., "**The Kelvin redefined**", *Meas. Sci. Technol.* **29** 022001 (11pp) (2018) https://doi.org/10.1088/1361-6501/aa9ddb	Important papers will arise from the Realising the redefined kelvin (Real-K) project (>20). These will focus on how to realise and disseminate *T* above 1300 K and below 25 K and extend the life of ITS-90 through quantifying non-uniqueness values as well as put in place foundational activities to facilitate practical gas based primary thermometry for realisation and dissemination of *T.*	Papers and conference presentations will elaborate evolving thinking surrounding realization and dissemination of the kelvin, including realization and dissemination to *T* and the rise of practical primary thermometry.

Achievements 2017-2020	Future Scan 2021-2025	Future Scan 2025-2030+
Fischer, J., Fellmuth, B., Gaiser, C., Zandt, T., Pitre, L., Sparasci, F., Plimmer, M., de Podesta, M., Underwood, R., Sutton, G., Machin, G., Gavioso, R., Madonna R.D., Steur, P., Qu, J., Feng, X., Zhang, J., Moldover, M., Benz, S., White, D. Gianfrani, L., Castrillo, A., Moretti, L., Darquie, B., Moufarej, E., Daussy, C., Briaudeau, S., Kozlova, O., Risegari, L., Segovia, J., Martín, M C., del Campo, D., "**The Boltzmann Project**", *Metrologia* **55,** R1-R20, (2018) https://doi.org/10.1088/1681-7575/aaa790 Machin, G., Engert, J., Gianfrani, L., H McEvoy, H., Sparasci, F., "**The European Metrology Programme for Innovation and Research project: Implementing the new kelvin 2 (InK2)**", XXII World Congress of the International Measurement Confederation (IMEKO 2018) IOP Conf. Series: Journal of Physics: Conf. Series **1065** (2018) 122002 IOP Publishing doi:10.1088/1742-6596/1065/12/122002 (open access) Machin, G., "**The redefinition of the kelvin**," in *IEEE Instrumentation & Measurement Magazine*, **22**, no. 3, (2019) p. 17-20 doi: 10.1109/MIM.2019.8716270 Conference dedicated to temperature metrology was Tempmeko/TempBeijing Jun '19 (plenaries on redefined kelvin and RH) Thermophysical quantities conferences: ECTP-2017-Graz Austria; EURAMET TC-T-2017-2020; TEMPMEKO 2019-China; Boulder Symposium 2018, Colorado, USA; CIM 2017-2019, Paris, France; ATPC-2019, Xian, China. More general conferences presenting to wider audiences CIM (France), SMSI (Germany) etc.	These papers together with papers such as White, D.R., (2021): "**Hot and cold: defining and measuring temperature**", *Contemporary Physics*, DOI: 10.1080/00107514.2021.1896132 and those from the "Emerging Technologies" TG among others will help communicate to the wider thermal measurement community. Future key conferences for the thermal metrology community will be ITS-10 March 2023, California, USA and Tempmeko '25, France. It is envisaged that there will be a workshop or dedicated conference session at ITS-10 related to Realising the redefined kelvin. For thermal quantities: there will be repeats of Symposium Thermophysical Properties, Jun 21, TEMPMEKO 2025; CIM; 2023-2025, ECTP and ATPC. For humidity and moisture, ISHM is planned with next Tempmeko. More general conferences presenting to wider audiences CIM (France), SMSI (Germany) etc.	Future key conferences will be Tempmeko '28, Tempbeijing '29/'30. For thermal quantities there will be repeats of Symposium Thermophysical Properties, ECTP and ATPC. More general conferences presenting to wider audiences CIM (France), SMSI (Germany) etc. Possible inclusion of thermophysical quantities in future editions of the SI brochure and/or related material.

Achievements 2017-2020	**Future Scan 2021-2025**	**Future Scan 2025-2030+**
Guide to the realization of ITS-90 (complete) and Guide to Secondary Thermometry (in progress). Full list of guides given in Annex 1. See section on "Guides" above. This entry is about communicating the guides to stakeholders and more general education of users.	There is a growing need for education in thermal metrology. There is a lack of understanding among many stakeholders of uncertainties, sensor selection and use, of traceability and accreditation. Wide dissemination of CCT guides to and by the RMO TC-Ts should be encouraged. Production of user relevant guides is underway (see Guides section of this document). There is a rising generation of metrologists in the NMIs who would benefit from such training. A CCT summer school in thermal metrology as an effective way of rapidly and effectively passing on skills and experience to future generations could be considered for the late 2020s.	In general the outputs of CCT should be reviewed to make sure they remain **fit for purpose** now and for the foreseeable future. CCT outputs include ITS-90, PLTS-2000, the kelvin, CMCs and guides related to thermal measurements. WG -SP to discuss and, if appropriate, agree plans for thermal metrology summer school under the auspices of CCT hosted by 1 or more NMIs to be held before 2030.
	WG-SP should initiate the formation of TGs to consider and report on the impact and requirements for the CIPM identified challenges a) "digital transformation" and b) "New metrology" relevant to CCT. Of particular relevance is the rise of in-situ traceability and practical primary thermometry leading to traceability at the point of measurement and the possible disruption to established metrological traceability.	WG-SP recommend and through discussion whole CCT response to the digitisation and new metrology agendas in response to TG findings to ensure continued relevance of CCT activities into 2030s.

6. Required Key comparisons and pilot studies 2021-2030+ with indicative repeat frequency

The status of past and progress of currently active key comparisons are discussed separately below for the 3 technical fields of the CCT: Thermometry (Section 6.1), Humidity (Section 6.2) and Thermophysical Quantities (Section 6.3). Section 6.4 closes this section with recommendations for future comparisons that are not just repeats of previous comparisons (the latter are discussed in the relevant section.

Finally it should be noted that some guides and cmc review protocols have been prepared relevant to key comparisons and CMC review, namely: CCT Guidelines for comparisons https://www.bipm.org/documents/20126/50817864/CCT-Guidelines-on-comparisons.pdf/d1352c60-eea8-99cb-b281-4c295617e773; CMC review protocol for thermal diffusivity measurements, Part 1: solid materials by the flash method, approved, to be published (2021); CMC review protocol for infrared spectral emissivity measurements Part 1: normal emissivity (emittance), approved, to be published (2021). A specific guide for comparisons in the humidity field is being considered by CCT-WG-Hu.

6.1 Thermometry

The first round of CCT key comparisons (CCT-K1 to CCT-K5 and CCT-K7) is completed.

The second round of CCT key comparisons was initiated in 2012 with CCT-K9, which is the repetition of CCT-K3 and covers the ITS-90 temperature range from 84 K to 693 K. CCT-K9 is now close to completion (Draft B being prepared). CCT-K10, which is a comparison of ITS-90 above the silver point, was initiated in 2014 and is currently in the reporting stage (Draft B being prepared). In principle CCT-K10 is similar to CCT-K5 but nearly all technical aspects are different, the range is wider (up to 3000 ^{o}C) and the transfer artefacts are different (this time radiation thermometers, more in keeping with industrial practice, and also unknown temperature high temperature fixed points were circulated). CCT-K7.2021, the repeat of CCT-K7 key comparison of triple point of water cells, was initiated in 2021 and is expected to be completed in 2022.

The repeat of the key comparisons in the low temperature range of the ITS-90 (CCT-K1 in the range 0.65 K to 24.6 K and CCT-K2 in the range 13.8 K to 273.16 K), was attributed a frequency of 20 years or more, based on the demonstrated long-term stability of cryogenic fixed-point cells. Given the limited number of original realizations in the world, the significant workload required by classical vapour pressure and interpolating gas thermometry, and the advancement of low-temperature primary thermometry methods, a repeat of CCT-K1 and CCT-K2 is not foreseen in the coming decade. Specific issues related to the ITS-90 in this range will be addressed by the CCT-WG-CTh. At the same time, the investigations on alternatives to the mercury fixed point (Xe, SF_6 and CO_2) have yielded significant results and could justify dedicated pilot studies in the latter part of the 2020s or 2030s.

The results of the repeat of CCT-K3, CCT-K9, were not completely satisfactory for many laboratories, but, given the required workload, the limited resources foreseen in the coming years and the lack of more stable transfer artefacts, a repeat of CCT-K9 is not expected in the short term.

As more than 20 years passed since CCT-K4 was carried out (1998-2000), a repeat of CCT-K4 (660 ^{o}C and 962 ^{o}C) is recommended in the coming decade.

The thermometry key comparisons, carried out in the first round and being repeated in the second round, were designed to compare the different ITS-90 realizations. This was appropriate because, although the definition of the kelvin refers to the thermodynamic temperature T, for all practical measurements the ITS-90 temperature T_{90} (or the temperature T_{2000} of the other defined scale PLTS-2000) was used.

Concerning the other defined scale PLTS-2000, only three National Metrology Institutes in the world maintain it. Two European NMIs have resolved the longstanding problem of discrepancies between the PLTS-2000 and the ITS-90 in their range of overlap (0.65 K to 1 K). In the 2020s, the main activities should be directed to promote the use of low-temperature primary thermometry methods and to extend the range of reliable thermometry to even lower temperatures according to the growing demand resulting from intensifying research work in this field.

Air temperature measurements are relevant for both relative humidity measurements and climate monitoring. An RMO supplementary comparison of air temperature has already been initiated and a CCT supplementary comparison in the same field can be foreseen in the coming decade.

6.2 Humidity

In the humidity field, two key comparisons were carried out in the first round: CCT-K6 covering dew-point temperatures from -50 ºC to 20 ºC and CCT-K8 covering dew-point temperatures from 30 ºC to 95 ºC. CCT-K6 was completed in 2015 and CCT-K8 is in the reporting stage.

During the CCT meeting 2020, the initiation of a repeat of CCT-K6 was formally approved. It is expected that the repeat of CCT-K6 will be carried out in the first half of the coming decade. In the planned repeat of CCT-K6, a reduction of the effort and duration will be considered. Aligned with this, a revision of the CMC review protocol for humidity is being considered, because in its current form it forces dew-point comparisons to be at close intervals and therefore requires many comparison points.

A repeat of CCT-K8 will likely be needed at the end of the 2020s (ten years from the end of CCT-K8 measurements).

Below -50 °C dew-point, it has been agreed that, if there would be a CIPM comparison, it would be a supplementary comparison. Concerning the trace moisture range, some members of the WG-Hu have participated in a CCQM comparison (CCQM-K116 and associated pilot study, 10 $\mu mol \cdot mol^{-1}$ of water vapour in nitrogen). If this or similar comparisons were to be repeated, relevant NMIs would participate again, if invited.

Relative humidity is being addressed through supplementary comparisons and non-CIPM comparisons at RMO level.

In the relatively new areas of development (humidity in non-air gases and at pressures other than atmospheric, above 100 °C, moisture in materials etc), there are no specific plans for key comparisons in the 2020s. Depending on the number and interest of NMIs/DIs working in these areas, as well as demand by research and industry, either supplementary comparisons or pilot comparisons might be appropriate.

6.3 Thermophysical Quantities

Thermophysical Quantities, being the newest field of the CCT and encompassing a large number of quantities, is in a stage in which a coherent system of comparisons is being developed.

Three major comparisons, formally categorized as CCT supplementary comparisons but in fact representing the best capabilities available in the world for the respective quantities, were completed: CCT-S1 (spectral normal emissivity), CCT-S2 (thermal conductivity) and CCT-S3 (thermal diffusivity).

It is expected that the next major comparison, thermal expansion coefficients, will be carried out in the first half of the 2020s.

6.4 Recommendation for future comparisons

While the comparison measurements of the past cycle of comparisons were completed within acceptable time, data analysis and Draft A/B reporting took substantial amounts of time, typically considerably longer than the measurement time itself. In the coming cycle of comparisons, an effort will be made to contain the data analysis and reporting time within acceptable limits.

With the redefinition of the kelvin (2019) and the introduction of its *Mise en Pratique*, it is expected that the direct measurement of thermodynamic temperature will be increasingly practiced in the 2020s and the design of key comparisons testing T, besides the existing key comparisons testing T_{90}, is currently under consideration. Given the recent advances, two regions of temperature could be subject to such a comparison: a) at high temperatures CCT-WG-NCTh has already established a CMC review process for thermodynamic temperature at high temperatures (above the silver point) and it is envisaged that some form of thermodynamic temperature comparison, either by direct and/or indirect radiometry, could well be initiated before the end of the 2020s; and b) low temperature primary thermometry could also achieve sufficient maturity in the coming years to carry out a key comparison of thermodynamic temperature in the CCT-K2 range (13.8 K to 273.16 K) and possibly lower encompassing the PLTS-2000 and ITS-90 up to the Ne point.

Finally, in part response to the Covid-19 pandemic and in part to the poor clinical thermometry that is being undertaken around the world, a comparison of non-contact clinical thermometer calibration systems, led from CCT-TG-BTM, coordinated by NIM, China is currently being organised and will start in late 2021, finalising reporting by end 2024.

7. Summary table of comparisons, dates, and the laboratories already having institutional agreement to pilot particular comparisons

Metrology Area **CCT**

KC Completed	KC In Progress	KC Planned

Date updated **10 June 2021**

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory / Number of participants	Start date	Status	Comments	Horizon for repeating (or not) with timeline	How far does the light shine?
Thermometry	CCT-K1	Realization of the ITS-90 from 0.65 K to 24.6 K	NPL / 7	1997	Approved for equivalence		20 - 25 y, subject to new NMI capabilities.	ITS-90 from 0.65 K to 24.6 K. 5 CMC entries.
Thermometry	CCT-K2	Realization of the ITS-90 from 13.8 K to 273.16 K	NRC / 7	1997	Approved for equivalence			ITS-90 from 13.8 K to 273.16 K. 54 CMC entries.
Thermometry	CCT-K2.1	Realization of the ITS-90 from 13.8 K to 273.16 K	NRC / 2	2003	Approved for equivalence			ITS-90 from 13.8 K to 273.16 K. CMC entries: cf. CCT-K2.
Thermometry	CCT-K2.3	Realization of the ITS-90 from 13.8 K to 273.16 K	NRC / 2	2006	Approved for equivalence			ITS-90 from 13.8 K to 273.16 K. CMC entries: cf. CCT-K2.
Thermometry	CCT-K2.4	Realization of the ITS-90 from 13.8 K to 273.16 K	NRC / 3	2006	Approved for equivalence			ITS-90 from 13.8 K to 273.16 K. CMC entries: cf. CCT-K2.
Thermometry	CCT-K2.5	Realization of the ITS-90 from 13.8 K to 273.16 K	NRC / 3	2006	Approved for equivalence	Draft B approved on 15 January 2015		ITS-90 from 13.8 K to 273.16 K. CMC entries: cf. CCT-K2.
Thermometry	CCT-K3	Realization of the ITS-90 from 83.8058 K to 933.473 K	NIST / 15	1997	Approved for equivalence		cf. CCT-K9	ITS-90 from 83.8058 K to 933.473 K. 435 CMC entries.

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory / Number of participants	Start date	Status	Comments	Horizon for repeating (or not) with timeline	How far does the light shine?
Thermometry	CCT-K3.1	Realization of the ITS-90 from 273.16 K to 302.9146 K	BIPM / 2	2009	Approved for equivalence	Draft B approved on 19 September 2016		ITS-90 from 273.16 K to 302.9146 K. CMC entries: cf. CCT-K3.
Thermometry	CCT-K3.2	SPRT calibration comparison using ITS-90 fixed points from -190 °C to 420 °C	NIM / 2	2010	Approved for equivalence			ITS-90 fixed points from -190 °C to 420 °C
Thermometry	CCT-K4	Comparison of local realizations of Aluminium and Silver freezing-point temperatures	PTB / 12	1998	Approved for equivalence			ITS-90 from 933 K to 1235 K. 68 CMC entries.
Thermometry	CCT-K5	Realization of the ITS-90 from 961 C° to 1700 °C	VSL / 14	1997	Approved for equivalence			ITS-90 from 961 C° to 1700 °C. 46 CMC entries.
Thermometry	CCT-K5.1	Realization of the ITS-90 from 961 C° to 1700 °C	PTB / 2	2001	Approved for equivalence	Complement to CCT-K5	no repeat foreseen	ITS-90 from 961 C° to 1700 °C. CMC entries: cf. CCT-K5.
Humidity	CCT-K6	Comparison of humidity standards: dew and frost point temperatures	NPL / 10	2003	Approved for equivalence	Draft B approved on 24 April 2015		CMC coverage from -55 °C to +30 °C: 27 CMC entries.

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory / Number of participants	Start date	Status	Comments	Horizon for repeating (or not) with timeline	How far does the light shine?
Thermometry	CCT-K7	Comparison of water triple point cells	BIPM / 18	2004	Approved for equivalence	Many NMIs have changed their TPW cells since CCT-K7. The reference to water with the isotopic composition of V-SMOW should now lead to a much reduced spread and this is to be verified with a comparison.	During the CCT Meeting 2017 it was decided that CCT-K7 has the highest priority and NMIs should consider piloting with a start in 2018-2019.	In principle only 273.16 K, but impacts on range 13.8033 K to 1234.94 K in ITS-90. 57 CMC entries.
Thermometry	CCT-K9.1	Realization of the ITS-90 from 83.8058 K to 692.7 K	PTB / 2	2018	Approved for equivalence		Repeat of CCT-K9	cf. CCT-K3
Thermometry	CCT-K1.1	Realization of the ITS-90 from 0.65 K to 24.6 K	NIST / 2	2006	Report in progress, Draft A	Measurements at NIST completed in 2007, measurements at NMIJ completed in 2015. Draft B will be under preparation and confirmation by the pilot and participant.		ITS-90 from 0.65 K to 24.6 K
Thermometry	CCT-K2.2	Realization of the ITS-90 from 24.5 K to 273.16 K	INRIM / 2	2005	In progress	Expected to be completed by end 2017.		ITS-90 from 24.5 K to 273.16 K

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory / Number of participants	Start date	Status	Comments	Horizon for repeating (or not) with timeline	How far does the light shine?
Thermometry	CCT-K4.1	Comparison of local realizations of Silver freezing-point temperatures	NMIA / 2	2012	In progress	Ag cell was broken. Characterization of a replacement cell is on the way.		ITS-90 961.78°C
Humidity	CCT-K6.1	Comparison of humidity standards: dew and frost point temperatures	NPL / 2	2008	Draft B completed, currently under review			cf. CCT-K6
Humidity	CCT-K6.2	Comparison of humidity standards: dew and frost point temperatures	NIST / 2	2015				CMC coverage: dew-point temperatures from -20 °C to -75 °C
Humidity	CCT-K8	Comparison of realiza-tion of local scales of dew-point temperatu-res of humid gas	INTA / 10	2008	Report in progress, Draft A	To be completed in period 2021-2025		CMC coverage: dew-point temperatures from +20 °C to +95 °C
Thermometry	CCT-K9	Realization of the ITS-90 from 83.8058 K to 692.7 K	NIST / 15	2011	Report in progress, Draft B		Repeat of CCT-K3	cf. CCT-K3
Thermometry	CCT-K10	Realization of the ITS-90 from 960 °C to 3000 °C	NPL / 15	2014	Report in progress, Draft B	Measurements are complete and advanced draft B (June 2021)	Repeat of CCT-K5	cf. CCT-K5
Thermometry	CCT-K7-2021	Comparison of water triple point cells	NRC / 19	2021	Measurements in progress			

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory	Expected start date	Estimate of resources in person months (PM) for piloting and participating (per participant)	Rationale for Key Comparison	Interested / agreed / expressed by:	How far does the light shine?
Humidity	CCT-K6.202X	Comparison of humidity standards: dew and frost point temperatures	To be decided	To be decided	Planned			
Thermometry	CCT-K11	Comparison of non-contact clinical thermometer calibration standards	NIM	Late 2021	Planned	To support in clinical thermometry on a global basis	Participants agreed	

Annex 1: Published guides in thermometry from CCT: 2017-2021

Guide to the realization of ITS-90

Part 1 - Introduction https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_1_Introduction_2018.pdf/1cbdf00e-441e-e154-536b-62e96ef7f4c7?version=1.8&download=true

Part 2.1 - Fixed points: Influence of impurities https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_2_1_Impurities_2018.pdf/68567148-cc72-e4a8-7dd0-e913a5b42b32?version=1.5&download=true

Part 2.2 - Triple point of water https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_2_2_TPW-2018.pdf/b4feee2a-3e84-cc30-eba7-94592b247bd2?version=1.4&download=true

Part 2.3 - Cryogenic fixed points https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_2_3_Cryogenic_FP_2018.pdf/8289e448-3de9-4688-804e-1187d9215b83?version=1.3&download=true

Part 2.4 - Metal fixed points for contact thermometry https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_2_4_MetalFixedPoints_2018.pdf/665aff3f-b72e-0e28-c520-89197232a06e?version=1.3&download=true

Part 2.5 - Fixed points for radiation thermometry https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_2_5_RTFixedPoints_2018.pdf/1f16763a-7bc6-8331-df33-297fb08b9c41?version=1.3&download=true

Part 3 - Vapour pressure scales and pressure measurements https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_3_VPS_p_2018.pdf/dcd65f47-8699-d2f2-cace-44885f4f49fb?version=1.3&download=true

Part 4 - Gas thermometry https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_4_GasThermometry_2018.pdf/25c0529c-d09b-e121-1762-554550adbc56?version=1.3&download=true

Part 5 - Platinum resistance thermometry https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_5_SPRT_2021.pdf/c4bbbe56-4118-eef7-47cb-3ea234db40b8?version=1.6&download=true

Part 6 – Radiation thermometry https://www.bipm.org/documents/20126/41773843/Guide_ITS-90_6_RadiationThermometry_2018.pdf/f346ba40-fb17-b2a9-5641-ea3f0071532e?version=1.3&download=true

(and annexes)

Guide to Secondary Thermometry

Guide to Secondary Thermometry - Specialized Fixed Points above 0 °C https://www.bipm.org/documents/20126/41773843/Specialized-FPs-above-0C.pdf/10265617-c79f-0ea5-8da9-8d359e21c6be?version=1.3&download=true

Guide to Secondary Thermometry - Thermocouple Thermometry Part 1 https://www.bipm.org/documents/20126/41773843/Thermocouple_Thermometry_Part1.pdf/d23088f8-3bab-bacc-0cae-7358eb2666b4?version=1.2&download=true

Other guides

Guide to uncertainty in primary Radiometry, 2018: https://www.bipm.org/utils/en/pdf/si-mep/MeP-K-2018_Absolute_Primary_Radiometry_Uncertainty.pdf by P. Saunders et al.

Annex 2: CCT Strategy document glossary

AGT	Acoustic Gas Thermometry
AI	Artificial Intelligence
APMP	Asia Pacific Metrology Partnership
ATM	Air Temperature Metrology
ATPC	Asian Thermophysical Properties Conference
BIPM	International Bureau of Weights and Measures
BSRN	Baseline Surface Reference Network
BTM	Body Temperature Measurement
CC	Consultative Committee
CBT	Coulomb Blockade Thermometry
CCT	Consultative Committee for Thermometry
CCQM	Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology
CCU	Consultative Committee for Units
CEN	European Committee for Standardisation
CIM	International Metrology Conference
COAT	EMPIR project Increasing the Comparability of extreme Air Temperature measurements for meteorology and climate studies
Co-C	Cobalt carbon eutectic
CODATA	Committee on Data for Science and Technology
CRS	Climate Reference Station
CSPRTs	Capsule Standard Platinum Resistance Thermometers
CGPM	General Conference on Weights and Measures
CIPM	International Committee of Weights and Measures

CMC	Calibration Measurement Capability
DBT	Doppler Broadening Thermometry
DCGT	Dielectric Constant Gas Thermometry
DML	Deep Machine Learning
ECTP	European Conference on Thermophysical Properties
ECV	Essential Climate Variable
EMPIR	European Metrology Programme for Innovation and Research
EMRP	European Metrology Research Programme
EURAMET	European Association of National Metrology Institutes
Fe-C	Iron carbon eutectic
GCOS	Global Climate Observing System
GRUAN	GCOS Reference Upper Air Network
GSRN	GCOS Surface Reference Network
IAPWS	International Association for the Properties of Water and Steam
ICVGT	Interpolating Constant Volume Gas Thermometer
IEC	International Electrotechnical Commission
IMEKO	International Measurement Confederation
InGaAs	Indium Gallium Arsenide (detectors)
InK	EMRP/EMPIR Implementing the new kelvin 1/2
ISHM	International Symposium on Humidity and Moisture
INCIPIT	European project on ‘Calibration and accuracy of non-catching instruments to measure liquid/solid atmospheric precipitation’
INFCOM	WMO Infrastructure Commission

ISO	International Standards Organization
ITS-10	the 10th International temperature symposium
ITS-90	International Temperature Scale of 1990
ITS-XX	Proposed future temperature scale
IUPAC	International Union of Pure and Applied Chemistry
JNT	Johnson Noise Thermometry
KC	Key Comparison
KCDB	Key Comparison Data Base
LSPRTs	Long Stem Standard Platinum Resistance Thermometers
HTFP	High temperature fixed points (generally those above the freezing point of copper)
HTPRTs	High Temperature Platinum Resistance Thermometers
MeP-K	*Mise en Pratique* for the definition of the kelvin
MeteoMet	Metrology for Meteorology
MMC	Metrology for Meteorology and Climate
MRA	Mutual Recognition Arrangement
NIM	National Institute of Metrology, China
NMI	National Metrology Institute
NRC	National Research Council (of Canada)
PGT	Polarizing Gas Thermometry
Pd-C	Palladium carbon eutectic
Pt-C	Platinum carbon eutectic
PLTS-2000	Provisional Low Temperature Scale of 2000
RIGT	Refractive Index Gas Thermometry

RH	Relative Humidity
RMO	Regional Metrology Organization
Re-C	Rhenium carbon eutectic
Ru-C	Ruthenium carbon eutectic
SERCOM	WMO Service Commission
SI	International System of Units
SMFPC	Sealed Metal Fixed Point Cell
SMSI	Sensor and Measurement Science conference series
SPRT	Standard Platinum Resistance Thermometer
T	thermodynamic temperature
T_{90}	ITS-90 temperature
T_{2000}	PLTS-2000 temperature
TC-T	[RMO] Technical Committee for Thermometry
Tempmeko	triennial conference of thermal metrology held under the auspices of IMEKO
TG	Task Group
TP	triple point
TS	Technical Specification
WC-C	Tungsten carbide carbon peritectic
WG	Working Group
WMO	World Meteorological Organization