Strategy Document for Rolling Programme Development for 2018 to 2027

The Consultative Committee for Thermometry

1. General Information on the Consultative Committee for Thermometry

Consultative Committee for Thermometry (CCT)

Established in 1937

23 members and 2 official observers[1]

62 participants at last meeting in 2017

7 working groups and 5 task groups

CCT meetings every 2 to 3 years

Last meeting held 1 to 2 June 2017

CCT President Dr DUAN Yuning, Vice Director of NIM (from 2012)

14 KCs carried out from 1999 to 2017, 8 KCs in progress (see section 7).

In addition, 51 RMO key comparisons are registered in the KCDB[2] and 31 of these have been approved and published – 2551 CMCs entries in the KCDB are supported by the CCT (including 2017).

2. Terms of Reference

To establish and maintain global compatibility of thermal measurements through promotion of traceability to the SI[3]. To ensure that the SI units of the quantities relevant to thermal metrology are realized and disseminated worldwide in a uniform and appropriate manner. Thermal metrology includes temperature, humidity, 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 "Responsibilities of Consultative Committees";
- Providing recommendations to the International Committee for Measures and Weight (CIPM) for the definition and realization of the SI unit of temperature - the kelvin - and of temperature scales and derived quantities;
- Recommending research in thermal metrology in specific domains to maintain the SI in relation to the kelvin, including the definition of the kelvin and its realization, and that of the units of derived quantities;

[1] Access to the CCT meeting on request for 1 person of Member States not being member nor official observer of the CCT was decided by the CIPM in 2016.
[2] Archived comparisons excluded
[3] Système Internationale

- Supporting the National Metrology Institutes[4] (NMIs) provision of traceability to thermal metrology quantities;
- Encouraging NMIs to address emerging thermal metrology needs;
- Providing guidance on thermal metrology to users;
- Maintaining an exchange with stakeholders and awareness of the stakeholder needs.

3. Stakeholders and stakeholder needs

Stakeholders' interests are conveyed to the CCT through the NMI representatives in the CCT and with specific attendance at WGs and TGs of members of key Institutions, such as WMO experts in the WG Environment. They are involved indirectly in shaping the groups priorities through the NMI representatives explaining the user's needs particularly in the field of secondary thermometry. They cover a wide range of interests from instrument manufacturers to industrial users. There are also a large number of possible stakeholders represented by other CCs, institutions, organizations, committees, scientific communities, users' associations, manufacturers and others.

Needs and interests on thermal metrology for climate monitoring, meteorology and environmental studies are also conveyed to CCT by the members of the WG Environment officially nominated as BIPM representatives in the expert teams of the WMO Commissions of Instruments and Methods of Observations and of Climatology. A significant cooperation with IAPWS was also established to work towards universal definitions of humidity quantities and measurands, such as relative humidity, which to date are not coherent across fields. That mutual inter-membership is aimed at allowing continuous and fruitful exchange of information and long-term planning of common activities**.**

The **stakeholder´s needs** are currently dominated by the following challenges:

- **Energy** (supply and security) – through supporting sustainable production, conversion, transportation, increasing the amount of renewables and low carbon dioxide generation methods (e.g. nuclear, carbon capture storage [CCS]) in the energy mix and supporting ways for saving energy (e.g. energy harvesting), energy efficiency measures through improved thermal efficiency and utilisation of energy. All thermal quantities are concerned by these challenges.
- **Global warming** - Temperature and humidity are the fundamental quantities involved in a wide range of climate studies and environmental observations. Air temperature measurement, from ground level to the upper atmosphere is the key parameter in understanding the climate of our planet. A number of techniques and measuring system and instruments are now adopted, all of them requiring comparability, traceability and evaluation of measurement uncertainties: those are important open issues requiring the contribution of the thermal metrology community. Temperature of soil, ice and sea water, from the surface to the deep ocean is also included among the GCOS[5] Essential Climate Variables due to the importance of the records. Also for such quantities, the data quality still requires specific metrological investigations. Water content in air and soil moisture need dedicated research within the CCT community, due to the complexity of measured ranges and measurement methods.

[4] The term « NMI » includes also Designated institutes in this document.
[5] Global Climate Observing System

- **High-value manufacturing** – in particular enhancing competitiveness through optimum use of resources (raw materials and energy) and improving process control to facilitate "zero waste" manufacture and improved product quality, lifetime, and user benefits. In the longer term increasing computer power (through quantum computing) is a potential growth industry in the future requiring accurate temperature measurement at very low temperatures.
- **Health, safety and security** – advanced traceable temperature measurements are required in hospitals for safe active thermal therapies (e.g. cancer ablation and improved diagnostics, through for e.g. truly quantitative thermal imaging) and in ports of access (buildings and boarders) for pandemic control.
- **Humidity stakeholders** span all endeavors affected by **physical, chemical or biological interaction of materials with water**, and wherever optical, electrical, thermal and other properties of gases are of interest.
- Reliable values of **thermophysical quantities** are particularly important for the reduction of global **energy consumption**. It is expected that improvement of the insulation of buildings, houses, refrigerators, furnaces, kilns, boilers, pipelines and chemical plants will reduce the tremendous amount of heat losses in the world. Thermal conductivity is the direct quantity of performance of insulating materials and the importance of heat flux density determinations will increase since it is a direct index of loss of heat. Stakeholders are the **building industry**, **home electric appliances industry and users, materials industry, and chemical engineering**.
- Efficient use of electric energy can also **reduce the emission of carbon dioxide**. One of the key technologies is **power electronics** to control high current for inverters, power transmission, hybrid cars, electric vehicles and electric trains. High thermal conductivity heat spreaders are necessary to reduce overheating of power devices under high-current operations. Thermal expansion and the electrical quantities of the heat spreader are key quantities. Stakeholders are **electronic power engineering and users**.
- In order to develop advanced industrial technologies, such as highly integrated electrical devices, optical disks, magneto-optical disks and thermoelectric devices, knowledge of thermophysical quantity values of thin films are required for reliable thermal design. Stakeholders are the **electronics industry** and users.

4. Structure of the CCT

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 a number of 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 drafted, there were five Task Groups:

TG-CTh-ET	Emerging technologies
TG-GoTh	Guides on Thermometry
TG-NCTh-CMC	Non-Contact Thermometry CMCs
TG-NCTh-HTFPU	Non-Contact Thermometry HTFP Uncertainties
TG-ThQ	Thermophysical quantities

The Working Groups act on a long-term basis, while a Task Group carries out a limited mission. The CCT interacts with other Consultative Committees, as well as with international organizations and bodies.

Although the current definition of the kelvin defines a thermodynamic temperature scale, almost all practical measurements are made using the International Temperature Scale of 1990 (ITS-90) and the Provisional Low Temperature Scale of 2000 (PLTS-2000). Progress in metrology has prepared the adoption of a new definition of the kelvin. Accompanying the new definition, there will be increased recognition of the two complementary methods to realize temperature. The traditional route using the defined **International Temperature Scales** and the alternative route based on direct measurements of **thermodynamic temperatures** employing primary thermometers. The dissemination of the SI unit of temperature is supervised through the *Mise en Pratique of the definition of the kelvin* (MeP-K), including both routes.

Since the establishment of the CIPM MRA in 2009 until today, eight different fields of Key Comparison have been completed and these contribute to underpin 2551 CMC entries of the KCDB database.

5. Achievements from 2013 to 2017 and future scan from 2018 to 2027

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. The rationale of the activities is given in detail in the CCT strategy document of 2013.

Achievements 2013-2017	Future Scan 2018-2022	Future Scan 2023-2027
Definition of the kelvin		
• To monitor the results of new experiments relevant to the **new definition of the kelvin** several workshops and conference sessions (e.g. at TEMPMEKO 2013 and TEMPMEKO 2016) have been organized. • Invited talks on the new definition of the kelvin to solicit input from the wider scientific and technical community have been given (among others) at the 9th International Temperature Symposium in 2012, at TEMPMEKO 2013, TEMPMEKO 2016 and Metrologie 2017. • In 2015 a Metrologia special issue „Focus on the Boltzmann Constant“ has been edited. It contains a general review on the progress towards a new definition of the kelvin and 15 technical papers from all relevant research groups. • Recommendation T1 2014 has been adopted where the conditions for the new definition of the kelvin have been updated. • The progress in determining the Boltzmann constant and the conditions for the new definition of the kelvin have been regularly reported at the CCU and CODATA meetings.	The **ITS-90** is the key output of the CCT, it impacts millions of users around the world everyday facilitating reliable, traceable temperature measurement. CCT affirms its continued relevance and CCT continues to support the ITS-90. ITS-90 and primary thermometry will coexist for a long period of time.	• ITS-90 is kept up-to-date by incremental improvements of its realization and dissemination (e.g. performance of high-temperature platinum resistance thermometers). • Requirement for **ITS-XX** is to be reviewed in terms of stakeholder needs and cost of implementation.
After all conditions have been fulfilled, Recommendation T1 2017 has been adopted. CCT states its clear preference for a new definition of the kelvin based on a **fixed value of the Boltzmann constant** resulting from the CODATA special adjustment in 2017. The measurement of **thermodynamic temperatures** and thus the difference to the values realized by the defined scales is crucially important for the new definition of the kelvin and the revised SI: • Results have been reviewed in several working group meetings and presented in an invited talk at TEMPMEKO 2013 and as well at TEMPMEKO 2016. • The advances made since 2010 and the weaknesses in certain temperature ranges have been identified.	• Due to the new definition of the kelvin multiple realizations could arise in the same temperature region and a formal way of addressing this needs to be developed – particularly when key comparisons are performed. • CCT will keep under review both the acceptance of the **PLTS-2000** in the ultra-low temperature community and evidence that may help resolve the uncertainties in the lower parts of the range. In the long-term, merging of the scales ITS-90 and PLTS-2000 into a new scale ITS-XX depends on the dissemination status of primary low temperature thermometry. • The *implementing the new kelvin* projects are undertaking a comprehensive, multi-method examination of the thermodynamic fitness of ITS-90 and PLTS-2000. These will report to CCT in May 2019 with the development of new consensus values of T-T_{90} to follow.	• Users requiring values of thermodynamic temperature T rather than T_{90} must have access to the most recent values of T-T_{90} from the MeP-K. An update interval for the values of T-T_{90} of approx. 5 years is anticipated until a new defined scale ITS-XX is adopted which sets the differences $T - T_{XX}$ back to zero, or defined scales are completely supplanted by primary thermometry (not likely to happen in the time frame of this strategy document). • At high temperatures the MeP-K will support the use of **primary radiometry** and also HTFPs to disseminate low-uncertainty thermodynamic temperature realizations. There is a possibility that the ITS-90 in this region will be superseded as increasing numbers of institutes opt for these alternatives. Ensuring world-wide equivalence of temperature in this increasingly mixed situation will be a key role of CCT.

Achievements 2013-2017	Future Scan 2018-2022	Future Scan 2023-2027
Mise en Pratique of the definition of the kelvin		
The second version of the **MeP-K**, called MeP-K-19, has been prepared and submitted to the CCU. This version will come into force at the time of the redefinition of the base unit kelvin (20 May 2019). The following details are emphasised: • The MeP-K has been reworded considering the new definition of the kelvin and rearranged with five sections including scope and introduction. • The explicit-constant definition of the kelvin is briefly explained. • A nomenclature (taxonomy of methods for the realisation of the kelvin) is included. • Criteria for the inclusion of primary-thermometry methods in the MeP-K are listed. Abstracts are describing briefly four primary thermometry methods for the first time within the MeP-K, namely • *acoustic gas thermometry* • *radiometric thermometry* • *polarising gas thermometry* (*dielectric-constant* and *refractive-index gas thermometry*) • *noise thermometry*. Details, including uncertainty estimates or references to them, are given in appendices.	• CCT recommends that member state NMIs take full advantage of the opportunities for the realisation and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the MeP-K-19. • A disruptive step change may result if ITS-90 or PLTS-2000 is superseded in certain ranges by primary thermometry. Before including additional primary thermometers in the MeP-K, the CCT needs to review and evaluate the attainable uncertainty. • Disruption to ITS-90 may occur if the use of Hg is banned by health authorities. Research should be stimulated into appropriate alternatives and CCT develop outline plan of how to keep ITS-90 functioning in the light of that eventuality. • For the content of the appendices, the respective authors are responsible. CCT will take care that these will be updated regularly.	Reviewing novel primary-thermometry methods for inclusion in the MeP-K is a permanent task of the CCT Working Groups for Contact and Non-Contact Thermometry. A reasonable time interval (certainly beyond 2027) needs to be given for the MeP-K-19 (and potential first iteration MeP-K-2X) to be fully implemented and the 2017 CCT recommendation concerning primary thermometry to be explored before substantive discussions concerning ITS-XX are undertaken.
• The revision of the *Supplementary Information for the ITS-90* has been completed. It is now called ***Guide to the realization of the ITS-90*** and posted on the BIPM website. • The different parts were written as independent documents, which will make future updates easier. • Above all, state-of-the-art uncertainty budget 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.	• 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. • It is a permanent task of CCT Working Group for Non-Contact Thermometry to ensure that the guide remains current and fit for purpose, incorporating and providing guidance on new non-contact thermometry methods; e.g. thermal imaging, phosphor thermometry	

Achievements 2013-2017	**Future Scan 2018-2022**	**Future Scan 2023-2027**
Emerging technologies		
	• In this period, CCT is focusing on **photonic devices** that exploit the thermo-optic effect to translate thermal changes into frequency shifts. A range of devices is under review including micro-resonators (optical whispering gallery mode resonators, ring resonators), Bragg waveguides, photonic cavities, and photonic crystal structures. • The task group will put forth a report detailing the various emerging technologies, their benefits and the user population that would benefit from the development and deployment of emerging technologies.	In the long term (probably beyond 2027) realization of photonic temperature sensors will eventually move thermometry away from electrical measurements, along with their attendant limitations, and into frequency measurement, opening up an entirely new landscape of possibilities where photonic temperature sensors can be built with **self-diagnosing and self-calibration capabilities**. Such sensor networks will impact a broad swath of industries including aerospace; green chemistry; fossil fuel energy production; environmental monitoring in office, laboratory, and manufacturing settings; and biomedical devices for bio-telemetry applications.
	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMI and RMOs towards the implementation of dedicated metrology activities, such as field calibration and special laboratories and infrastructures to assist and support **on site and in-process traceability of measurements**.	
Guides on thermometry		
The guide on specialised fixed points has been prepared and is online.	Within the next year to have the two thermocouple guides (general thermocouple thermometry and reference thermocouples) online.	
	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMI 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)	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMI and RMOs towards the identification 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

Achievements 2013-2017	Future Scan 2018-2022	Future Scan 2023-2027
Non-contact thermometry		
Evaluate thermodynamic measurement results obtained using non-contact thermometry, this has mainly been performed trough determining **definitive temperatures of the HTFPs** of Co-C, Pt-C and Re-C, these have now been published and incorporated in the supplementary information for the MeP-K concerning primary radiometric temperature measurement.		
Coordinate activities related to HTFPs. Very significant progress achieved moving HTFPs from research items to usable reliable temperature standards.	Encourage NMIs (through establishing a TG in 2018/9) to complete the work in determining low uncertainty temperatures for the remaining HTFPs, understand and quantify remaining outstanding uncertainty values.	Full implementation of MeP-K at high temperatures using **primary radiometry** both absolute and relative approaches, leading to abandonment of ITS-90 above the silver point.
Provide input into the MeP-K. Summary text for MeP-K-19 text prepared and incorporated. In addition, supplementary information of the MeP-K-19 relating to absolute and relative primary radiometry documented and published on CCT website.	Other possible radiometric methods such as double wavelength technique and radiation thermometry linked to Synchrotron radiation to be rigorously investigated to assess suitability for MeP-K, or for use as possible alternative approaches to classical radiometry	
• Written guidance for **realizing the ITS-90** by radiation thermometry has been produced and is available on the BIPM website. • Standardization into **thermal imagers** is underway – this is being led from IEC with the support of members of CCT NCTh.	• CCT NCTh to discuss (next CCT) and if necessary issue Guidance on Quantitative Thermal imaging (by 2022). • Standardization into thermal imagers, the IEC documentation aims to complete in 2018.	
A **key comparison** is underway in the ITS-90 above the Ag point. The measurements are partly complete.	The measurements for the key comparison in the ITS-90 above the Ag point will be complete by mid-2018 with final reporting envisaged prior to next CCT.	By 2023 consider requirement for a key comparison above the Ag point of realization and dissemination of T by the approved MeP-K methods.
A number of time **limited task groups** have been established: • primary radiometric temperature measurement (aim to complete end 2017) • NCTh CMC review protocol (to complete end 2017) • HTFP uncertainties (to complete and submit paper for publication end 2017)	• Planned meeting of the CCT NCTh to coincide with IMEKO 2018 • A workshop also in conjunction with IMEKO 2018 concerning the use of InGaAs detectors in radiometry/radiation thermometry • Publication of Radiometry uncertainty document by 2019	Investigate and if required produce guidance documentation on novel optical thermometry based on phosphors or for flames/plasmas.

Achievements 2013-2017	**Future Scan 2018-2022**	**Future Scan 2023-2027**
Environment		
The RECOMMENDATION T3 (2010) to the CIPM entitled *"On climate and meteorological observations measurements"* is 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.	• 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 recommends NMIs to create **Metrology Networks** to become reference institutions for the interacting and collaborating with the stakeholders and to preserve, improve and disseminate the experience achieved in thermal metrology for climate and environment. • CCT WG ENV members to continue to contribute as experts in WMO, GCOS task team.	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**
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.	• Data comparability: Include as reliable as possible uncertainty analysis in historical data; study and assess traceability. • Spatial and temporal comparability: Systematic evaluation of environmental and instrumental influences on measurement results; complete knowledge on measured quantity. • Temperature measurements: Improve measurement techniques, calibration procedures and develop, supervise and harmonise guides. • Water content measurements (air and soil): Develop suitable measurement techniques and guides. • Impact: CCT members continue to organize events, meetings, workshops, conferences and training to discuss and plan common activities with the climate and environmental communities.	• **Air temperature measurements** still present open issues in identifying the components of the uncertainties budget and in their evaluation. The evaluation of the uncertainty in atmospheric air temperature measurements, both at ground level and in upper atmosphere, together with a fully documented traceability, is the fundamental condition to achieve data comparability within and among observing networks, in space and time and for the validation of different techniques. • WG Environment to initiate studies and publication on this subject. • In a long-term vision, it is expected that the joint work of metrologists and the user community will improve the knowledge on this key measurement for atmospheric studies and climate monitoring.
	The planned creation of a **GCOS Surface Reference Network** (GSRN) of observing stations on land[6] will require a continuous support from the thermal metrology community, being temperature and humidity of air and soil key observables.	• CCT-WG-ENV, together with operational meteoro-logists, 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. • Provide roadmap to address needs of data quality arising from possible new climate evolution scenarios.

[6] AOPC-22 (Exeter, UK, March 2017)

Achievements 2013-2017	**Future Scan 2018-2022**	**Future Scan 2023-2027**
Humidity		
CCT-K6 **key comparison** in dew-point temperature -50 °C to +20 °C was successfully completed, although with many technical difficulties and consequent delays. The results now support CMCs and related bilateral comparisons in progress. Formal linking to RMO comparison is in progress. RMO KCs linking to CCT-K6 have started (APMP).	A repeat for CCT-K6 is likely to be proposed to begin in this time period.	
CCT-K8 key comparison in dew-point temperature +20 °C to +95 °C has been started and, after a long planning stage, measurements have progressed rapidly.	Completion, reporting and linkages of CCT-K8	A repeat for CCT-K8 is likely to be proposed to begin in this time period.
Strategic planning of ongoing and future key and supplementary comparisons in the humidity field has continued. For humidity quantities and ranges outside the scope of CCT-K6 and CCT-K8 it has been decided that only supplementary comparisons will be proposed, rather than KCs.	A timeline for repeats of CCT-K6 and CCT-K8 will be established. The issue of RMO humidity comparisons staggered in time with respect to the KC will be addressed. Ongoing KC support of humidity CMCs for the wider set of quantities and ranges will be kept under consideration.	Ongoing support of humidity CMCs for the wider set of quantities and ranges will be kept under consideration.
Clarification of quantities, units, symbols and realizations relating to humidity measurement: • A further iteration of the WG-Hu document on humidity terms and definitions has been produced. • Awareness has been raised about multiple relative humidity definitions, presenting challenges of non-uniqueness and inapplicability in some regimes. This was reported within a set of landmark review papers in *Metrologia*. • Steps towards a possible fugacity-based rigorous definition of relative humidity have been discussed and presented in a paper in *Metrologia*. • Relative humidity is the most measured quantity to be absent from the SI brochure. Initial proposals have been made to increase the recognition of relative humidity in the SI and to regularize the position for the relative humidity unit symbol.	• Further developments in the awareness and impact of multiple non-unique relative humidity definitions. Consideration of a possible fugacity-based definition of relative humidity. Consideration of the implications for metrological realizations and traceability, and for end-users of measurements (consultation of users required) • Further work to be done to promote relative humidity for inclusion in future editions of the SI brochure and related material • Further elaboration of humidity definitions and *Mise-en-Pratique* type information, and dissemination of best practice. • Possible CCT workshop on humidity definitions (after the busy time window associated with revision of the SI).	• Relative humidity to be promoted for inclusion in future editions of the SI brochure and related material. • Reach conclusions and make recommendations concerning the fugacity approach to defining Relative Humidity.
Guidance on **evaluating uncertainty in humidity** metrology in support of KCs and CMC reviews: Production of a CCT WG-Hu document on uncertainty in humidity has progressed through a number of drafts.	Finalise and fan-out of guidance.	

Achievements 2013-2017	Future Scan 2018-2022	Future Scan 2023-2027
Collaboration and stakeholders • Coordination and collaboration with IAPWS, with highly productive results in area of relative humidity definitions • 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	Consideration of further outward-looking engagement and collaboration with relevant bodies such as WMO. Where CCT WG-GoTh addresses thermometry in air, WG-Hu will seek involvement because of the close relevance both for primary dew-point standards and for relative humidity.	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMI and RMOs towards addressing problems in metrology of soil moisture, and of air humidity measurements in challenging ranges such as those met by the instruments in the high atmosphere.
Convening of the International Symposium on Humidity and Moisture (ISHM) has progressed slowly, at least two proposed hosts have to later withdraw the offer to hold the event.	A host to be sought for an ISHM event to be held as stand-alone conference, as agreed within WG-Hu. Colocation with another conference to remain an option for consideration.	Longer-term future of the event to be considered
WG-Hu monitored **emerging or developing techniques** for humidity metrology. NMIs made significant developments in: • Primary facilities for humidity calibrations extending in varied gas species, pressure and temperature ranges • New and improved water vapor spectrometers • Acoustic and microwave resonator hygrometer techniques	Continued monitoring and response where developments are relevant to SI metrology and traceability	
Developments in metrology for measurements of moisture (water) in materials have been pursued by WG members (e.g. through EMRP METefnet project)	Further work on metrology infrastructure for moisture/water content, requiring collaboration across consultative committees.	
Thermophysical Quantities		

• **CCT-S1, Supplementary comparison** on **Infrared spectral normal emissivity** was successfully completed. Final report approved by CCT-WG-KC. All documents are available on the BIPM-KCDB, published in *Metrologia*, 2016, 53, Tech. Suppl.
• **CCT-S2, Thermal conductivity:** After a long stage of technical considerations Draft B is now in progress and will be available for approval by CCT-WG-KC, by the end of 2017. CMC protocol drafted by VNIIM and review in progress in TG-ThQ.
• **CCT-S3, Thermal diffusivity:** Following technical discussions between AIST/NMIJ and LNE, Draft A is still under review within the group. Draft B to be provided by end 2017 or early in 2018. CMC protocol drafted by NMIJ in 2016 and review in CCT-WG-CMC in progress.
	• CCT-S1: CMC protocol to be drafted by NIST and to be submitted to ThQ by early 2018, finalise CMC entries.
	• CCT-S2: Complete and edit the final report and publish the results in *Metrologia Tech. Suppl.*; finalise CMC entries.
	• CCT-S3: Complete and edit the final report and publish the results in Metrologia Tech. Suppl.; finalise CMC entries.
	• New Comparisons:
	  • Finalise short list of new comparisons
	  • Prepare draft of protocols and planning
	  • Start pilot inter-laboratory comparisons
	  • Perform the comparisons and manage the risks
	  • Analyse the results and circulate draft reports
	  • Publish within a reasonable time
		• Terminate ongoing comparisons
		• Complete and edit the final reports and publish the results in *Metrologia Tech. Suppl.*
		• Ongoing support of ThQ CMCs for the set of quantities and ranges
		• New Comparisons: see tasks under future scan 2018-2023

Achievements 2013-2017	Future Scan 2018-2022	Future Scan 2023-2027
Technical discussions launched in 2016 and continued during the CCT-TG-ThQ meeting at BIPM 2017. At least 2 **comparisons** identified related to dilatometry and calorimetry. Preliminary capabilities of the different ThQ Members have been collected. • Dilatometry: Thermal Expansion Coefficient (TEC) • Calorimetry: Heat of Combustion Additionally, specific heat of materials and calorific value of gases mentioned as alternative or of additional interest.	Developing **strategic planning of ongoing and future key and supplementary comparisons** in the thermophysical quantities field will be continued	Strategic planning of ongoing and future key and supplementary comparisons in the thermophysical quantities field to be updated, completed and continued
Metrology Research Programme: At least two actions have been led: • 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.	• Develop **further collaborations** with relevant bodies or institutes mainly involved in the fields of energy, environment or industry (at least). • When CCT needs to address thermal 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.
• TEMPMEKO 2016: EURAMET TC-T WG-ThQ members have been invited to participate in the satellite meetings devoted to the CCT TG-ThQ members. The main objectives were to present work in progress and to review new developments in the field of ThQ currently in progress within the **CCT and EURAMET groups**. • Other events gave several opportunities for the CCT-TG-ThQ to meet the ThQ community and potential members for the group and also for disseminating outcomes from the group.	• **Exchange information** with the ThQ Community on innovative techniques relevant to the field of thermal quantities measurements • TG-ThQ will continue to monitor emerging technologies or developing techniques in the metrology of ThQ. • Opportunities for the CCT-TG-ThQ to meet the ThQ community and potential members for the group and also for disseminating outcomes of the group will be monitored and selected according to current priorities.	Continue tasks outlined in future scan 2018-2022
Examples of **conferences and meetings** where ThQ scientific work have been promoted and valorized: ECTP-14, -17; EURAMET TC-T-2013-2017; Temperatura-2015, St Petersburg, Russia; TEMPMEKO 2013, 2016; Boulder Symposium 2015, Colorado, USA; CIM 2013-2017, Paris, France	• Examples of conferences and meetings where ThQ scientific work to be promoted and valorized: ECTP-20; EURAMET TC-T-2018-2022; TEMPMEKO 2019, 2022; Boulder Symposium 2018, 2021; CIM 2019-2021. • Increase visibility in providing information to one of the electronic tools managed by the CCT and useful for the thermal metrology community including the ThQ community.	• Continue to promote ThQ scientific work at conferences and meetings as outlined in the future scan 2018-2022 • Thermophysical quantities should be promoted for inclusion in future editions of the SI brochure and related material.

Achievements 2013-2017	**Future Scan 2018-2022**	**Future Scan 2023-2027**
Communication		
The CCT contributed to the New Definition awareness campaign of the CCU with the paragraph “The New kelvin in 100 words”.	• IMEKO 2018 World Congress in Belfast will feature the redefinition of the SI including the kelvin. • Proposal in planning stage for Royal Society Discussion meeting for May 2019 to coincide with implementation of the revised SI including the kelvin	Review the outputs of CCT to make sure they are **fit for purpose** now and for the foreseeable future. CCT outputs include ITS-90, PLTS-2000, the kelvin, CMCs, and all the relevant supporting documentation provided by the BIPM, CCT, and its working groups. (examples: implications of Bayesian uncertainty approach for thermometry; completeness of Guide on the realisation of the ITS-90)
Royal Society workshop **“Towards implementing the new kelvin”.** In May 2015 leading researchers in thermometry gathered (https://royalsociety.org/visit-us/chicheley/) to discuss progress towards implementing the new kelvin (https://royalsociety.org/events/2015/05/new-kelvin/) ahead of the SI revision in 2019. To take stock of the current state of primary thermometry and identify the research required to: a) ensure a smooth implementation of the unit following the redefinition, b) support the evolving MeP-K and c) identify requirements for future defined scale, the ITSxx, possibly to be established in the mid-2020s. A record of the meeting was published in a special edition of *Phil Trans Roy. Soc. A* **374** 2016	Improve future scan: • Ask all WG and TG chairs to include in their reports to the CCT, a section identifying **issues, trends, and speculations** that might impact on thermal metrology in the next 10 years (example: internet of things with the need to calibrate/verify low cost sensors). • WG-SP to collate the reports and to consider how the CCT should respond. (example: cost of ITS-XX)	The working groups have a responsibility to identify technical issues and trends. There is a parallel need for the CCT to understand the political, economic and cultural environment(s) in which it operates, including within the CIPM/BIPM. What are the constraints and opportunities? (example: consistency of implementation and cost of the MRA)
Invited review paper on “the kelvin redefined” to appear in *Meas. Sci. Technol.* late 2017.	Gather **more information** from the thermal metrology community by liaising with relevant standardizing organizations, professional societies, research institutes, etc. Examples: • closer cooperation with the international stakeholder community of temperature, humidity and TQ equipment manufacturers • linkage to end-user stakeholders (IMEKO TC12 or separate forum) • conduit to turn our ideas into practical products and services	At any time, there are several dozen problems that the CCT and its working groups are having to deal with. Are there **unifying themes** or patterns in these issues that might suggest better ways of solving some of the problems and better ways of operating the CCT?
	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMI and RMOs towards continuing the interaction with the stakeholders through organization of joint events, conferences and mutual participation in expert teams.	CCT recommends NMIs to include in their vision documents coordinated efforts of single NMIs, groups of NMI and RMOs towards the creation of formal joint research initiatives involving NMIs staff and the external community.

6. Required Key comparisons and pilot studies 2018-2027 with indicative repeat frequency

The second round of the fundamental temperature key comparisons has been recently started. The key comparison that initiated the second round is CCT-K9, which is the repetition of CCT-K3 and covers the ITS-90 temperature range from 84 K to 693 K. The measurements were completed and the Draft A is currently under preparation. Another repeat, CCT-K10, which is the repetition of CCT-K5, covering the high temperature range of the ITS-90 from 960 ^{o}C to 3000 ^{o}C, was initiated in 2014, the measurements for this KC should be complete in 2018.

The thermometry key comparisons of the first round were designed to compare ITS-90 realizations in different sub-ranges of the ITS-90. 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 PLTS-2000 temperature T_{2000}) was used. It is expected that, with the new definition of the kelvin coming into force in 2019 and its *Mise en Pratique*, the two complementary methods to realize temperature (via the defined ITS-90 and PLTS-2000 scales and via the direct measurement of T) will be increasingly practiced. Such change will have to be considered when designing future key comparisons, as the quantity to be compared can be either T_{90}/T_{2000} or T. This is especially relevant for the high temperature range above the silver point and a KC may need to be initiated in the early 2020s examining the efficacy of realizing and disseminating T by direct and indirect primary radiometry.

Pilot studies shall be carried out where the performance of **primary thermometers** should be compared e.g. through transferring specific reference samples with a repeat frequency of 10 years.

For 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), given the limited number of original realizations in the world and the demonstrated long-term stability of **cryogenic fixed-point cells**, the repeat frequency could be relaxed to 20 or more years and a lower priority could be attributed to it.

For the lowest temperature range (PLTS-2000 in the range 0.1 mK to 1 K), as currently only one NMI in the world is practicing the PLTS-2000), it would be more appropriate to have a comparison between the different primary realizations (significant discrepancies between the different primary realizations, that were used to define the PLTS-2000, are still to be solved). A possible comparison should be considered by the next CCT after the outcomes of the Ink1 and 2 investigations have been concluded.

Given their reproducibility, **triple point of water cells** will continue to play a fundamental role in the realization of the ITS-90. During the CCT Meeting 2017, it was agreed that a new key comparison of triple point of water cells (repetition of CCT-K7) has now the highest priority and should be initiated in 2018-2019. Since the clarification of the definition of the kelvin (2005), which emphasized that the triple point temperature of water is 273.16 K only for water having VSMOW isotopic composition, many NMIs have changed their national reference for the triple point of water temperature, and a new key comparison, performed at the highest level of accuracy, could lead to a considerably reduced spread between the national realizations with respect to the spread obtained in CCT-K7.

Lower temperature radiation thermometry is becoming increasingly important. However, as this is not in the temperature region of a primary realization of the ITS-90, a key comparison is not appropriate. Substantiation of CMCs will be achieved through regional comparisons. Where inter-RMO equivalence needs to be substantiated limited bilateral comparisons under the auspices of CCT are envisaged.

In the **humidity field,** the requirement for key comparisons has been established for dew-point temperature from -50 °C to +20 °C (CCT-K6) and from 30 °C to 95 °C (CCT-K8). The repeat intervals have to be decided – possibly a nominal 10 years interval. Possible requirements are under discussion for a KC or supplementary comparison in trace moisture ranges (frost points approaching -100 °C). Although the humidity field is rapidly expanding its techniques/ranges/parameters, (e.g. moisture in materials, relative humidity above 100 °C, humidity in non-air gases and/or at a wide range of pressures, ...), it is not considered sustainable to have key comparisons for these techniques/ ranges/parameters and these are best validated through RMO KCs.

Key comparisons or supplementary comparisons are considered for **thermophysical quantities** such as thermal conductivity, thermal diffusivity, heat flux density, and heat capacity of bulk or advanced materials, generated by the demand of high-performance insulating materials to reduce energy consumption (applications: e.g. aerospace industry, automotive industry, power plants, building industry…). Since for instance specific heat capacity and thermal conductivity of thin films are key quantities for thermal management of electronics industry and nanotechnology, pilot studies or supplementary comparisons should be also considered. RMO Supplementary comparisons or pilot studies may be organized for the following quantities:

- Thermal expansion coefficient up to high temperatures;
- Hemispherical total emissivity;
- Thermal diffusivity and specific heat capacity of thin films;
- Thermal conductivity of bulk and advanced materials;
- Thermal conductivity of insulation materials;
- Combustion enthalpy of fuels;
- Fusion enthalpy of heat storage material;
- Thermal resistance of vacuum insulation panel.

Interlaboratory comparisons are planned in collaboration between NMIs and WMO Regional Instrument Centers on meteorological temperature and humidity secondary and working standards.

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 **29 Sep 17**

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.
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.

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-K3.2	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.
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.

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-K1.1	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 - waiting for NMIJ comple-tion of ITS-90 realization for completion of Draft A		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
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	Report in progress, Draft A			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			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	Measurements completed	Expected to be completed by end 2017.	Repeat of CCT-K3	cf. CCT-K3
Thermometry	CCT-K10	Realization of the ITS-90 from 960 °C to 3000 °C	NPL / 15	2014	In progress	Measurements expected to be completed by end 2018	Repeat of CCT-K5	cf. CCT-K5

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?
Thermometry	CCT-K7.2018	Comparison of water triple point cells	tbd	2019		Repeat of CCT-K7		cf. CCT-K7