Strategy Document for Rolling Programme Development for 2013 to 2023

The Consultative Committee for Thermometry

1. General Information on CCT

Consultative Committee for Thermometry

Established in 1937

23 members and 1 observer

48 participants at last meeting in 2012

10 working groups

CCT meetings every 2 y

Last meeting held 24 - 25 May 2012

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

11 KCs carried out from 1999 to 2012, 6 KCs in progress (see appendix)

58 RMO comparisons are registered in the KCDB and 22 of these have been approved and published – 665 CMCs entries in the KCDB are supported by the CCT (including 2012)

2. Terms of Reference

To ensure that the SI units of the quantities relevant to thermal metrology are realized and disseminated worldwide in a uniform and appropriate manner in order to establish and maintain global compatibility of such measurements through promotion of traceability to the SI. 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, and stated in the "Responsibilities of CCs" [1];
- Providing recommendations to the CIPM for the definition and realization of the SI unit of temperature, the kelvin, and of temperature scales and derived quantities;
- Recommending research in specific domains on thermal measurement at NMIs to ensure the appropriate development of the SI in relation to the kelvin, including its definition and realization, and that of the units of derived quantities;
- Supporting the NMIs provision of traceability to thermal metrology quantities;
- Encouraging NMIs to address emerging thermal metrology needs;
- Providing thermal metrology guidance to users.

3. Baseline (description status of activities and achievements up to and including 2012)

Introduction

The field of thermometry covers a wide range of temperature and therefore a wide range of techniques is necessary for its realization. Further, humidity and thermophysical quantities are closely related fields and they are therefore integrated in the CCT activity. For these reasons, the CCT has established ten different working groups to cover the different fields and aspects of its responsibility:

WG1	Defining fixed points and interpolating equations of the ITS-90 and the dissemination of the kelvin
WG2	Secondary thermometry
WG3	Uncertainties
WG4	Thermodynamic temperature determinations and extension of the ITS-90 to lower temperatures
WG5	Radiation thermometry
WG6	Humidity measurements
WG7	Key comparisons
WG8	Calibration and measurement capabilities
WG9	Thermophysical quantities
WGS	Strategy

For the same reasons, the CCT interacts with several other Consultative Committees, as well as with different 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 way towards 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 new 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.

A special Task Group on the SI, the **TG-SI**, was established by the CCT in 2006 to consider the implications of changing the definitions of the base units of the SI from the point of view of metrology in thermometry, and with particular emphasis on the kelvin.

Since the establishment of the CIPM MRA in 2009 until today, six different fields of Key Comparison have been completed and these currently underpin 665 CMC entries of the KCDB database.

The achievements of the CCT and its working groups are summarized below. The different fields have been separated to facilitate the identification of each. A complete strategic plan and review has been established for each WG and may be consulted upon request. Detailed resource requirements will be derived from these documents by CCT in the near future.

Achievements to 2012

To improve and document the techniques for using defining fixed points and interpolating instruments of the ITS-90 the general publication ***Supplementary Information for the ITS-90*** was edited in 1990. Additional recommendations have been established for the comparison of fixed-point cells and the optimal realization of the defined fixed points of the ITS-90, both applied to contact thermometry. The *Supplementary Information for the ITS-90* is presently being revised.

The influence of chemical impurities is usually the dominant uncertainty component for the realization of the defining fixed points of the ITS-90. Methodologies were therefore developed to make a reliable estimate of this component [2].

The first version of the ***Mise en Pratique of the definition of the kelvin*** (MeP-K) was published in 2006. This version was an overall guideline for the two International Temperature Scales ITS-90 and PLTS-2000. It includes links to the official documents on the two scales, the Technical Annex for the ITS-90, and supplementary information for and approximations to the ITS-90. The Technical Annex gives clear guidance on the specified isotopic abundances of the hydrogen and water fixed points. The CCT is revising the MeP-K in anticipation of the kelvin redefinition and to ensure an appropriate level of consistency with the documents for the other base units.

The CCT publication previously entitled ***Techniques for Approximating the ITS-90***, is also being revised with the new title ***CCT Guidelines on Secondary Thermometry***. Major revisions are required to accommodate technological advances in most sections.

In the survey of **measurement uncertainties**, one of the major achievements was the drafting and publication of the **CCT Guide on Uncertainties in the realisation of the SPRT sub-ranges of ITS-90** [3]. Current tasks are to document the uncertainty analysis for the extrapolation of long-stem standard platinum resistance thermometers (SPRT) calibration to liquid nitrogen temperatures, and prepare an uncertainty guide for rare metal thermocouples. The continuing revival of Bayesian statistics is also monitored.

Between 1999 and 2001, the activity on **thermodynamic temperatures** was dominated by the study of temperature scales below 0.65 K based on ^{3}He melting pressure to extend the range of international temperature scales down to about 1 mK. At its 20th Session, the CCT recommended that the CIPM adopts the Provisional Low Temperature Scale from 0.9 mK to 1 K: PLTS-2000. The necessary supporting information was prepared and submitted to the CIPM, which duly adopted PLTS-2000 in October 2000. The document ***Supplementary Information for the PLTS-2000*** was produced to give practical guidance on ^{3}He melting pressure thermometry.

Later, the main task was to update and critically review the data collection on measurements of the differences between thermodynamic temperature T and temperatures in terms of the scale ITS-90, T_{90}. The results are summarized in the document CCT/08-13/rev [4]. The paper is the first complete account of the differences T-T_{90} since the adoption of the ITS-90 more than 20 years ago. The data are published in the present MeP-K. Considering the various weaknesses discussed in CCT/08-13/rev, it would be premature to base a new temperature scale on these estimates.

The **TG-SI** prepared the "Report to the CIPM on the implications of changing the definition of the base unit kelvin", which was presented at the CCU meeting in June 2007. The CCU was unanimous in agreeing that a **new definition of the kelvin** should be adopted by fixing the value of the **Boltzmann constant**.

To monitor the results of new experiments relevant to the new definition of the kelvin and solicit input from the wider scientific and technical community, 3 international workshops and several conference sessions have been organized. The conditions to be met before changing the definition were updated in the RECOMMENDATION T2 (2010) of CCT to CIPM: "Considerations for a new definition of the kelvin" [5]. Further, the progress in determining the Boltzmann constant and the conditions for the new definition are regularly reported at the CCU and CODATA meetings.

The first main task in the field of **radiation thermometry** was to establish uncertainty budgets and to ensure consistent usage of terminology within the community. For this reason, uncertainty documents were produced for scale realization according to the formal definition of the ITS-90 and also for secondary measurements at lower temperatures.

The innovation of high temperature fixed points (HTFPs) in 1999 by NMIJ has led to a major world effort in characterizing HTFPs that is expected to continue until at least 2015. The majority of the work in this area has been coordinated through the CCT who published a strategic research plan in 2007 [6]. Its overall objective was to assign thermodynamic temperatures to a selected set of HTFPs for use as temperature references. This work is ongoing with anticipated completion in 2015.

Humidity is a relatively mature but developing field of measurement, related to most industries and sectors. At least 20 distinct humidity measurement techniques are in widespread use, many of these now evolving to a level of sophistication where they are relevant to NMIs. Consequently, the number of NMIs establishing humidity capabilities, or significantly increasing their capability, is large and has almost doubled in the last decade. Key areas of development at NMIs are: a step-change extension of scope beyond air atmospheric pressure, to humidity in other (industrial) gases and at range of pressures; and development of metrology capabilities for moisture in materials.

A document on uncertainty in humidity has been in preparation since 2003. It contains *mise-en-pratique* like information for humidity primary realizations, and detailed models for uncertainty evaluation. Although the main target audience is NMIs and CMC reviewers, much wider use is expected.

While humidity quantities are mainly addressed in the CCT, trace water in gas is also covered by CCQM in terms of amount fraction. In addition, moisture in materials is a growth area of metrology, addressed in some NMIs alongside humidity work, and in others as chemical metrology. Links are provided with CCQM interests in one or other of these topics. There is currently an agreement for liaison of CCT with CCQM IAWG on Grain Moisture, where KCs and CMCs are being considered.

Humidity metrology uses a variety of quantities, units, and symbols; in a few cases with specialized usage not completely covered by provisions in the SI. Consequently, long running activities include agreed definitions of humidity quantities and their realizations. Recently this activity was expanded in collaboration with the International Association on Properties of Water and Steam (IAPWS), and also with particular links to meteorology and climate science community.

Of interest to both humidity and **secondary thermometry**, the CCT adopted in 2010 a recommendation on the involvement of the thermal metrology community in support of **climate studies**. The RECOMMENDATION T3 (2010) to CIPM is entitled "*On climate and meteorological observations measurements"* with which the CCT recommends

- to encourage NMIs and the scientific community, especially temperature metrologists, to face new perspectives, needs, projects and activities related to the traceability, quality assurance, calibration procedures and definitions for those quantities involved in the climate studies and meteorological observations
- to support a strong cooperation between NMIs and Meteorological Institutions at local, national and international levels
- to encourage NMIs to work with the relevant meteorological networks to support a monitoring framework for traceable climate data over long temporal terms and wide spatial scales based on best practice metrology
- to consider the most effective means by which CCs involved in climate and environmental activities should cooperate in order to establish a common response to the stated needs of the meteorological community
- to encourage CCs to alert their relevant working groups to the measurement, calibration and quality assurance needs of the climate change and monitoring communities.

The CCT made a survey of the growing field of **thermophysical quantities** and collaborated with an ad hoc working group of material metrology in the CIPM (WGMM). One of the observations that could be made was the need for reference materials for thermal conductivity, thermal diffusivity, specific heat capacity and bulk density. Further, thermodynamic quantities such as specific heat capacity and enthalpy of fusion have been studied mainly by the academic community of chemical research related to the International Union of Pure and Applied Chemistry (IUPAC), the International Confederation for Thermal Analysis and Calorimetry (ICTAC) and the International Association of Chemical Thermodynamics (IACT). Because there are only limited numbers of NMIs that can measure specific heat capacity with adiabatic calorimeters, it is essential to collaborate with the academic community related to IUPAC, ICTAC and IACT.

Conference events such as NEWRAD 2008, TEMPMEKO 2010, the 9th International Temperature Symposium in 2012, and the International Symposium on Humidity and Moisture (ISHM) represent important occasions to interact with other experts in the particular field. A number of workshops focusing on particular topics have also been a helpful means to bring about progress.

4. Stakeholders

Stakeholders' interests are conveyed to the CCT mainly through the NMI representatives in the CCT. They cover a wide range of interests from instrument manufacturers to industrial users. 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. There are also a large number of possible stakeholders represented by other CCs, institutions, organizations, committees, scientific communities, users' associations, manufacturers and others.

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

- **Energy** (supply and security) – through supporting sustainable generation, increasing the amount of renewables and low carbon dioxide generation methods (e.g. nuclear, carbon capture storage [CCS]) in the energy mix and supporting energy efficiency measures through improved thermal efficiency and utilisation of energy.
- **Global warming** - aiming to reduce carbon dioxide emissions, transition to a low carbon economy whilst in the short to medium term improve monitoring measures including establishing traceability for data series. Temperature is the fundamental quantity involved in a wide range of climate change investigations.
- **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 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.
- A key priority is currently climate and meteorology, especially in the context of **climate change**. Recently a significant cooperation with IAPWS was established to work towards universal definitions of humidity quantities and measurands, such as relative humidity, which to date are not coherent across fields. The cooperation is particularly driven by needs in observation and modeling of land and sea surface humidity conditions.

- 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 index 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 **housing 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.

5. Future Scan (2013-2023)

The future scan for the CCT fields is informed by recent strategy work, such as EURAMET road mapping for temperature, humidity and moisture, and thermophysical quantities along with strategies of EMRP as well as national strategies at all NMIs and across regions.

- The CCTs basic documents are being revised in anticipation of the new definition of the kelvin:

  The complete revision of the ***Supplementary Information*** for the ITS-90 is expected by the end of 2013. For future revisions of the Supplementary Information for the ITS-90, an **update interval of approximately five years** is anticipated. The interval for updating the Supplementary Information for the PLTS-2000 will depend on the progress of thermometry in the temperature range below 1 K.

  The second version of the **MeP-K** must be prepared in time for the new definition of the kelvin, i.e. in time for adoption by the CCT before the meeting of the CCU in June 2013. Criteria were established for including primary thermometry methods in the MeP-K. The first method to be included will be spectral radiometry, which is increasingly being used as an alternative to ITS-90 above 960 °C. Acoustic gas thermometry is also being considered in light of the progress achieved in determining the Boltzmann constant.

  Future versions of the MeP-K will include noise thermometry, dielectric-constant gas thermometry and other kinds of gas thermometry. The best estimates of the differences between thermodynamic temperatures and the ITS-90 will be updated regularly.

  On-going work is expected in preparing and reviewing the ***CCT Guidelines on Secondary Thermometry*** keeping sections modular and stand-alone.

  For those sensors for which revised guides will not be prepared in the near future, a list of references will be published on the open access part of the BIPM website, to provide users with some guidance, in lieu of a document replacing the relevant chapter of Techniques for Approximating the ITS-90.

- The workload of the CCT has increased with the **new definition of the kelvin** and will increase further with consideration of a range of primary methods as well as novel secondary techniques for disseminating the temperature unit.

An increase in cooperations and liaisons is anticipated with other CCs, institutions, organizations, committees, scientific community, users' associations, manufacturers and other stakeholders, in order to provide guidance to traceability and good practice in secondary thermometry.

There will be an increased frequency of invited attendees, from the mentioned communities, as initially done in the 2012 meeting with a representative of IAPWS. Representatives of the World Meteorological Organisation (WMO-CIMO or WMO GCOS-GRUAN), and of the Association of Hydro-Meteorological Equipment industry will be among the first to be invited to present their needs and involvement on active cooperation with the thermal metrology community.

A new structure organised by tasks will be discussed and adopted to focus members participation on:

- Liaisons with relevant Institutions outside CCT and with other CCs on common issues
- Progress of the *CCT Guidelines on Secondary Thermometry* sections
- Monitoring the stakeholders needs
- Producing training and tutorial material

- In the field of **uncertainties,** there is on-going involvement with the key comparison working group and ad hoc task groups supporting KCs and other CCT activities.

  On-going work is expected in preparing and reviewing uncertainty guides prepared by other WGs. Major increase in workload is anticipated with the new definition of the kelvin with a large number of CCT documents describing different methods for realization of the kelvin, and the uncertainties associated with those methods.

  The increased use of the MRA for traceability purposes is increasing the pressure for harmonisation in uncertainty evaluation.

- A major problem with revision of GUM if the Bayesian approach is adopted must be anticipated. The approach would change uncertainty analysis from a characterisation of error processes to a characterisation of information or evidence.

- For **ultra-low temperatures** the Shot Noise Thermometer, Magnetic Field Fluctuation Thermometer, Single Junction Thermometer, or Coulomb Blockade Thermometer could be developed to **primary thermometers**, but these need further work and evaluation by the CCT to demonstrate reliable operation.

  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 would represent a major step change in thermometry.

  Experimenters 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 these values **of approximately 5 years is anticipated** until a new defined scale ITS-XX is adopted which sets the differences $T - T_{XX}$ back to zero.

  For a new defined scale, the two smooth interpolation functions have to be developed to new reference functions for the platinum resistance thermometers.

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.

Primary thermometry, notably acoustic gas thermometry, dielectric constant gas thermometry, Johnson noise thermometry, Doppler broadening thermometry and most of all, methods based on primary radiometry are gaining more importance. This may result in a disruptive step change if ITS-90 is superseded in certain ranges by primary thermometry. Before including new primary thermometers in the MeP-K, the CCT needs to review and evaluate the attainable uncertainty.

For the new definition of the kelvin, further determinations of the Boltzmann constant remain under way. CCT will continue to review these measurements and the fulfilment of the conditions until the kelvin is redefined.

- 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 the CCT in the coming decade.

  Support of HTFP research to its completion in 2015 remains essential. It is anticipated that a disruptive change will occur through the widespread uptake of HTFPs for dissemination of temperature scales to industry.

  The rapid rise in the use of thermal imagers is posing a challenge to radiation thermometrists. Spot pyrometers are easy to understand and characterize, whereas thermal imagers have a number of additional and significant issues and work is needed to develop techniques to calibrate and characterize such devices, preferably in cooperation with manufacturers.

  Other **non-contact thermometry** approaches such as phosphor thermometry, require standardization. Additionally, methods for very high temperatures, i.e. above 3300 K, need standardization/improvement due to the growing use of plasmas in industry.

  Finally, key comparisons will play a key role in supporting implementation of the MeP-K and dissemination of scales by HTFPs. Identifying the ideal artifact for a KC is still a matter of debate.

- Increasing drivers for advances in **humidity metrology** include carbon reduction, energy efficiency, advancement of production processes, and global interoperability of industries.

  These will drive increasing humidity developments in support of climate and weather observation and research; measurements in diverse gases such as CO_2, H_2 and fuel gas mixtures; and measurements in extreme industrial process conditions. NMIs generally will need increasingly to achieve and demonstrate impact in these areas, including impact of CMCs and other harmonization in the field.

  The broadening of NMI capabilities, to make primary realizations and disseminate traceability for humidity quantities in diverse gases at a range of pressures, is a significant step-change in this field.

- For the **thermophysical quantities**, it will be necessary to investigate, especially, measurements in support of the climate and energy sectors.

  Metrological support of dynamic measurements must also be advanced.

  Spectral emissivity is important for solar thermal measurements and these types of measurements will increase in conjunction with climate studies.

6. Rationale for various activities (2013-2023)

- To give the stakeholders access to the most recent progress of the techniques for realizing the scales and the associated decrease in uncertainty, the *Supplementary Information for the ITS-90* and the *Supplementary Information for the PLTS-2000* needs to be regularly updated.

  The on-going first revision of the *Supplementary Information for the ITS-90* is imperative considering that the original edition was published in 1990. This revision is expected to be completed by the end of 2013. From then on, **an update interval of approximately five years is anticipated**.

  Deficiencies of the ITS-90 and the PLTS-2000, observed during the progress in realizing these scales, may yield input for constructing a **future International Temperature Scale**.

- Because the repeatability of the fixed-point realizations is in most cases smaller than the total uncertainty by an order of magnitude, the collation of data on the influence of impurities on the fixed-point temperatures is necessary to definitively understand and quantify their role. Presently a complete uncertainty budget can be established only for the triple point of water.

  In the SPRT sub-ranges, the uncertainty in the realization and dissemination of the ITS-90 depends critically on the performance of the interpolating instruments. The improvement or replacement of the current interpolating instruments by new devices in some sub-ranges is desirable due to their poor performance or difficulty of operation (see next paragraph).

- Although very much better than the thermocouples they replaced, the performance of some high-temperature platinum resistance thermometers used above the aluminum freezing point at 660 °C have been found to be not as anticipated at the adoption of the ITS-90. Information about the current performance of these thermometers needs to be collated and analyzed and, in addition, research into potential replacements in any successor scale (such as practical primary acoustic thermometry or high performance thermocouples) should be a priority.

- The new definition of the base unit kelvin by fixing the value of the Boltzmann constant will facilitate the application of different primary thermometry methods for its realization. This development is useful for stakeholders, especially the increasing number of those who need measurements with respect to thermodynamic temperature, as in the fields of precise determination of thermodynamic and thermophysical quantities. Thus, activity of CCT will necessarily concern updating of the MeP-K. This requires a careful evaluation of the uncertainty budgets for proposed methods in collaboration with different working groups.

- Although PLTS-2000 is a reliable low temperature scale, it is founded on discrepant data at the lowest temperatures, amounting to some 6% below 7 mK. Measurements are required to address this discrepancy so that reliable values of $T - T_{2000}$ can be established, and a revision of PLTS-2000 and merging with ITS-90 can be effected.

- Since the adoption of the ITS-90, deviations of the scale from **thermodynamic temperature** have been detected below 1.5 K. Instead, the CCT recommends the vapour pressure polynomial of PTB-2006 below 2 K. However, additional independent measurements are required below 2 K to confirm this recommendation.

  In the temperature range from 25 K to 255 K, the review of thermodynamic measurements revealed unexplained inconsistencies between the uncertainties claimed for specific data sets and the consensus estimates of $T - T_{90}$. CCT needs urgently additional data before that it can provide a low-uncertainty estimate of $T - T_{90}$ in this temperature range.

  Also, more thermodynamic measurements are needed between 550 K and 693 K and at 1358 K. Recent measurements are insufficient to resolve the weaknesses identified in the report CCT/08-13/rev.

- CCT strongly encourages NMIs to improve their support to the thermometry sections performing new measurements of $T - T_{90}$. Otherwise, deployment of the MeP-K is endangered, and the elaboration of a new temperature scale ITS-XX will be impossible.

  At temperatures above the silver point, some institutes already realize and disseminate T rather than T_{90} through the use of primary radiometry. After the new definition of the kelvin has been approved, it is likely that the number of institutes doing this – also in other temperature ranges - will increase and this will be regulated through the MeP-K. Input data of higher precision of $T - T_{90}$ is required to provide the users with a tool for easy conversion from T to T_{90} and vice versa with low uncertainty.

- All values contributing to the **2010 CODATA adjustment of the Boltzmann constant** were based on acoustic gas thermometry. For the new definition of the kelvin this is insufficient. The RECOMMENDATION T2(2010) of the CCT states "*that before proceeding with the redefinition of the kelvin a relative standard uncertainty of the value of k of order one part in* 10^6 *be obtained, based on measurements applying different methods of primary thermometry*" and "*that these measurements ideally include at least two fundamentally different methods such as acoustic gas thermometry and dielectric constant gas thermometry and be corroborated by other measurements such as Johnson noise thermometry, total radiation thermometry or Doppler broadening thermometry.*" [5]. One may hence conclude that several techniques must be employed in order to provide a robust value for the Boltzmann constant.

- **Non-contact thermometry** is a rapidly growing segment of temperature measurement, particularly thermal imaging. As such it is important that NMIs maintain and develop CMCs that meet their national requirements in these areas. It is unacceptable that an industrially-important temperature region, such as high temperatures, is not properly supported by a KC. This issue must be resolved as a matter of urgency.

  HTFPs are a disruptive technology that is becoming pervasive in high temperature metrology. The impact will increase as the current research, led by CCT, comes to a conclusion.

  Due to the rapid decrease in price thermal imagers are becoming common place and are increasingly being used for quantitative measurement rather than diagnostic measurement. For example, they are increasingly replacing spot pyrometers in industrial process control, and are already pervasive in non-destructive testing. There are great concerns about how to specify and characterize performance, and about calibration of these devices. These are important questions and should be addressed by CCT by the middle of this decade.

- In the **humidity field**, the first round of KCs and CMCs are still being completed. The next few years should see this finished, and follow-on actions defined with decisions on needs for KCs and CMCs beyond current scope.

  Dew-point temperature is the main area of key comparison, due to this being the main humidity quantity realized and disseminated at the primary level. Rationale for repeat interval depends on readiness of pilots and others to undertake the work, rate of change of existing NMI facilities, and emergence of new NMIs into this field.

  Other issues are: the fitness of the KCs to support CMC claims, and the phasing relative to completion of RMO KCs. All this will be reviewed at the conclusion of the draft B stage for CCT-K6. However it is foreseeable that a repeat of CCT-K6 will be proposed in the next few years.

  It is currently held that the derived quantity relative humidity will not be the subject of a key comparison, although RMO comparisons have been, and will be, undertaken. CMCs for relative humidity are not fully in place yet, but can be supported by CMCs in dew point and temperature.

  Trace humidity ranges (known as “trace moisture”) are addressed in CCT but also partially in gas chemistry within CCQM, as is moisture content in materials. Rationales have yet to be decided for CCT KCs or other CC activity in either of these areas, but will take into account corresponding actions in CCQM. Both trace moisture and moisture in materials are fields with distinct measurement challenges, several measured quantities, and multiple techniques. Any decision on a KC will consider all these points.

  Areas under development across NMIs include humidity in industrial (non-air) gases as this capability becomes widely established at NMIs. A view will be formed as to whether key comparisons are needed specifically for this, including realizations at increasingly wide range of pressures.

- There are extensive needs for metrology of **thermophysical quantities** from science, industry, energy conservation, safety and trade.

  Thermophysical quantities are represented by SI-traceable derived units. Heat, heat capacity, heat flux density and thermal conductivity are considered to be fundamental quantities of thermal metrology in addition to temperature. Thermal diffusivity is a complementary quantity to thermal conductivity if heat capacity is known. Temperature dependence of a thermophysical quantity is essential information.

  In order to make reliable thermal design for production control in metallurgy and ceramic industries, reliable thermophysical quantity data related to transfer and storage of heat, such as thermal conductivity, heat capacity and thermal diffusivity are required. Combustion enthalpy of fuels such as natural gas and bio diesel, bio ethanol importance for trade; fusion enthalpy of heat storage material required by the automobile and housing industry; thermoelectric properties and the performance of thermoelectric modules required for the recycling of heat, constitute examples where thermophysical quantities play an important role.

  It is therefore necessary to carry out KCs to support CMCs in a timely manner, in particular for global energy issues in the field of thermophysical quantities.

- Reviewing comparison reports to **fulfill the requirements of the MRA** on behalf of the CCT is detailed in CIPM MRA-D-05. The principal end-user beneficiaries are the NMI signatories to the MRA who wish to have their CMCs published in the KCDB. The verification of capabilities provided by successful participation in comparisons is a significant factor in the evaluation of CMCs. CCT provides a credible review process that adds confidence to the comparison results, much as an on-site peer review provides confidence that the procedures and quality system of the NMI are appropriate to its tasks***.***

7. Required Key comparisons and pilot studies 2013-2023 with indicative repeat frequency

The second round of the fundamental temperature key comparisons has just been started. The first to get under way is CCT-K9, which covers the temperature range from 84 K to 693 K and is entitled “Realization of the ITS-90 from 83.8058 K to 692.7 K” (see appendix).

The second round for the other fundamental key comparisons will follow. However, the repeat frequencies have still to be decided by CCT. Data for firm decisions will be available only after the completion of CCT-K9.

- Already it is clear that a key comparison at **high temperatures** is badly needed as claimed CMCs cannot currently be substantiated. It is expected that the KC above the silver point can be started as early as 2015 which will allow to link RMO KCs of different approaches.

- **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.

- Following the new definition of the kelvin, 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.

- In the **humidity field,** the requirement for key comparisons has been established for dew-point temperature from -50 °C to +20 °C and from 30 °C to 95 °C. The repeat intervals have to be decided on completion – possibly a nominal 10 year interval.

  Possible requirements are under discussion for a KC or supplementary comparison in trace moisture ranges (frost points approaching -100 °C).

  Requirements have to be considered for a KC or supplementary comparison for moisture in materials and for a KC or supplementary comparison for humidity in non-air gases, and/or realized at a wide range of pressures.

- Key comparisons are considered for **thermal conductivity**, heat flux density, and heat capacity of bulk materials, generated by the demand of high-performance insulating materials to reduce energy consumption.

  Since thermal diffusivity, 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 considered.

- Supplementary comparisons of CCT or RMO 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 materials;
  - Thermal conductivity of insulation materials;
  - Combustion enthalpy of fuels;
  - Fusion enthalpy of heat storage material;
  - Thermal resistance of vacuum insulation panel.

8. Resource implications for laboratories for piloting comparisons

The resources used in some of the completed CCT key comparisons are shown in Fig. 1, to illustrate possible man power implications.

Generally, resource implications are associated with coordinating a comparison, including the supply and characterization of a travelling standard (or pair) sufficient to have confidence in stability and reliability for a comparison lasting several years. However, it is not typically required for these instruments to be held as the long-term "carriers" of key comparison reference values.

For a future key comparison in radiation thermometry above the silver point it is impossible to estimate the resources needed until the method of KC is established. However, the resources do not need to be onerous if HTFPs are used despite their shortcomings as transfer device such as lack of blindness of the temperature value and limitation in the choice of temperature.

For all KCs consideration should be given to the post KC regional linkage loops, which can be more costly than the KC themselves.

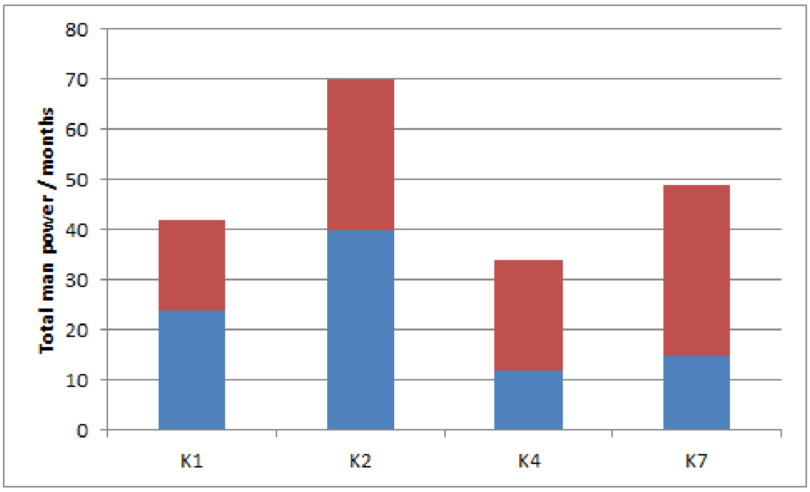

Figure 1. Histogram showing the estimated man power in terms of months for the CCT-K1, CCT-K2, CCT-K4 and CCT-K7 Key Comparisons. The blue part represents the time dedicated by the pilot laboratory, while the red part represents the total time spent by participants. It should be noted that the CCT-K2 includes not only the main key comparison, but also several added bi-lateral comparisons.

CCT-K1	Realization of the ITS-90 from 0.65 K to 24.6 K
CCT-K2	Realization of the ITS-90 from 13.8 K to 273.16 K
CCT-K4	Comparison of local realizations of Aluminium and Silver freezing-point temperatures
CCT-K7	Comparison of water triple point cells

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

See Appendix.

10. Document Revision Schedule

Revision of the Strategic Planning document is suggested at 2 y.

The *CCT Guidelines on Secondary Thermometry* is under continuous revision.

For all other CCT documents an update interval of approximately five years is anticipated.

References

[1] Rules of procedure for the Consultative Committees (CCs) created by the CIPM, CC working groups and CC workshops, CIPM-D-01.

[2] Methodologies for the estimation of uncertainties and the correction of fixed-point temperatures attributable to the influence of chemical impurities 2005 Fellmuth B, Hill KD, Bloembergen P, de Groot M, Hermier Y, Matveyev M, Pokhodun A, Ripple D and Steur PPM, 15 pp., CCT/05-08rev.

[3] Uncertainties in the Realisation of the SPRT Subranges of the ITS-90 2008 White DR, Ballico M, Chimenti V, Duris S, Filipe E, Ivanova A, Kartal Dogan A, Mendez-Lango E, Meyer C, Pavese F, Peruzzi A, Renaot E, Rudtsch S and Yamazawa K, 89 pp., CCT-08/19rev.

[4] Working Group 4: Report to the CCT 2008 Fischer J, de Podesta M, Hill K, Moldover M, Pitre L, Steur P, Tamura O, White DR, Yang I, Rusby R and Durieux M, 17 pp., CCT/08-13/rev.

[5] Consultative Committee for Thermometry *Proc. Verb. CCT* **25** CCT Recommendation T2 (CCT-2010)

[6] A concerted international project to establish high temperature fixed-points for primary thermometry 2007 Machin G, Bloembergen P, Hartmann J, Sadli M, Yamada Y, *Int. J. Thermophys*. **28** 1976-1982.

APPENDIX

The following two pages list the **Key Comparisons within the CCT**:

completed – green

in progress – blue

planned – yellow

as of 15 January 2013.

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory / Number of praticipants	Start date	Status	Comments	Horizon for repeating (or not) with timeline	How far does the light shine?	Estimate of resouces in person months (PM) for piloting and particpating (per particpant) if known
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.	Pilot: 24 PM, Participants: 3 PM
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.	Pilot: 24 PM, Participants: 3 PM
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.	Pilot: 4 PM, Participants: 3 PM
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.	Pilot: 6 PM, Participants: 3 PM
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.	Pilot: 6 PM, Participants: 3 PM
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			ITS-90 from 273.16 K to 302.9146 K. CMC entries: cf. CCT-K3.	Pilot: 2 PM, Participant: 0.5 PM
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.	Pilot: 12 PM, Participants: 2 PM
Thermometry	CCT-K5	Realization of the ITS-90 from 961 C° to 1700 °C	NMI 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.	Pilot: 2 PM, Participant: 2 PM
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 in the SI brochure to water with the isotopic composition of V-SMOW should now lead to a much reduced spread and it might be interesting to verify this with a comparison. This does not appear to be a high priority.	Yes, but not of a high priority.	In principle only 273.16 K, but impacts on range 13.8033 K to 1234.94 K in ITS-90. 57 CMC entries.	Pilot: 15 PM, Participants: 2 PM
Thermometry	CCT-K1.1	Realization of the ITS-90 from 0.65 K to 24.6 K	NIST / 2	2006	In progress	Comparison measurements at NIST completed in 2007 - waiting for NMIJ completion of ITS90 realization for completion of Draft A Report		ITS-90 from 0.65 K to 24.6 K	
Thermometry	CCT-K2.5	Realization of the ITS-90 from 13.8 K to 273.16 K	NRC / 3	2006	In progress			ITS-90 from 13.8 K to 273.16 K	
Thermometry	CCT-K3.2	SPRT calibration comparison using ITS-90 fixed points from -190 °C to 420 °C	NIM / 2	2010	Report in progress, Draft A			ITS-90 fixed points from -190 °C to 420 °C	
Humidity	CCT-K6	Comparison of humidity standards: dew and frost point temperatures	NPL / 10	2003	Report in progress, Draft A			27 CMC entries.	
Humidity	CCT-K6.1	Comparison of humidity standards: dew and frost point temperatures	NPL / 2	2008	Measurements completed				
Thermometry	CCT-K9	Realization of the ITS-90 from 83.8058 K to 692.7 K	NIST / 15	2011	In progress		Repeat of CCT-K3		

Sub Area	Reference No.	Description	Pilot (Coordinating) Laboratory	Expected Start date	Estimate of resouces in person months (PM) for piloting and particpating (per particpant)	Rational for Key Comparison	Interested /agreed/expressed by:	How far does the light shine?	Special aspects related to logistics
Thermometry	CCT-K2.2	Realization of the ITS-90 from 24.5 K to 273.16 K	CNR-IMGC / 2	2005	6 PM per participant and 1 PM for piloting	as for CCT-K2.5	NIM (PR China)	ITS-90 from 24.5 K to 273.16 K	NIM has been quite late, for internal reasons, in proceeding. Now it has almost finished, except for a few issues still depending on NIM. Then INRIM will make the comparison.
Thermometry	CCT-K4.1	Comparison of local realizations of Silver freezing-point temperatures	NMIA / 2	2012	Pilot: 3 PM, participant 1.5 PM			ITS-90 961.78°C	
Humidity	CCT-K8	Comparison of realizations of local scales of dew-point temperatures of humid gas	INTA / 10	2012					