1. Executive summary

The CCT covers metrology linked to temperature, humidity and thermophysical quantities. In 2012 it carried out a significant analysis of its accomplishments since the introduction of the CIPM MRA and a forecast of its impact. Following on from the strategic planning process, it became clear that a large increase in the number of future key comparisons is not expected. The number of Working Groups was reduced in a recent reorganization of the CCT.

A precise and accurate knowledge of temperature is important in science, technology and industry where precision and pushed limits are targeted. Temperature and humidity metrology play important roles in climate studies, whereas thermophysical quantities represent essential information to balance costs linked to energy consumption.

2. Scope of the CCT

The CCT gives advice to the CIPM on all scientific matters and issues that influence metrology in the fields of temperature, humidity and thermophysical quantities. It assures continuity and reliable precision of a common international temperature scale and promotes best practice. The CCT identifies and organizes key comparisons in its fields to establish global comparability of measurements and traceability to the SI, and assures the degree of quality of reported data. The CCT also acts as the focus and network for this diverse community, to develop common aims and collaboration among national metrology institutes (NMIs) and designated institutes (DIs) in Member States of the BIPM or with other relevant bodies.

3. Strategy

In 2012, the CCT carried out a significant analysis of its accomplishments since the introduction of the CIPM MRA and a forecast of its impact. The CCT strategic plan now provides a global picture of the present and future needs in thermal metrology. No thermometry activities are carried out at the BIPM, so the strategic plan is of relevance to the NMIs, DIs and their stakeholders, and will be updated regularly.

Following the strategic planning process, it became clear that a large increase in the number of future key comparisons is not expected. The comparison phase within thermometry has matured and is presently dominated by repeats of previous key comparisons. During the last decade, a number of humidity comparisons have been initiated and face continued technical challenges. The most recent discipline is represented by the cross-disciplinary field of thermophysical quantities for which three supplementary comparisons of different quantities are presently in progress.

The CCT has seen an increase in the number of Working Groups and large increase in its membership over the last 20 years. As an outcome of its strategic planning exercise, and in line with a general request expressed by the NMI Directors, the CCT reviewed its Working Groups, their mission and membership at its 27th meeting in 2014. The number of Working

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1 Thermophysical quantities describe thermal behaviour in matter, such as thermal conduction or thermal insulation.
Groups was reduced from ten to six. Three of these Working Groups undertake continuous tasks of the CCT to assure quality of reported key comparisons, relevance of submitted data on calibration and measurement capabilities (CMCs) and strategic planning; the other three cover the fields of contact thermometry, non-contact thermometry and humidity.

Some of the essential CCT activities were brought together into five Task Groups, which will have a limited duration dependant on achievement of the objective and/or time. Two of these Task Groups are responsible for the recent ongoing revisions of guidance on the realization of the international temperature scale and guidance on secondary thermometry; one Task Group is specifically dedicated to the new definition of the kelvin; a fourth Task Group addresses imperative issues linked to thermophysical quantities. A new Task Group was created to study how the CCT may best contribute to addressing environmental problems.

The CCT Strategic Planning document, which has already been published, gives a detailed analysis of each separate CCT discipline. To offer a concise assessment, Section 5 of this document gives a shorter summary of the needs and impact of thermal metrology within a selected number of larger areas.

4. Activities and achievements since the last meeting of the CGPM

The CCT has met twice since the 24th meeting of the CGPM (2011). As recommended by the CIPM ad hoc Working Group on Governance in 2012, the RMO TC-T chairs were invited to the last CCT meeting, as well as to participate at the Key Comparison and Strategic Planning working group meetings. The Actions and Decisions were identified after each meeting and uploaded to the open CCT web pages to rapidly make a summary publicly available before the publication of the minutes. A monthly newsletter on CCT activities is communicated to all CCT participants.

Main activities

The Strategic Planning exercise acted as a catalyst to identify the urgent needs in thermometry, such as the updated confirmation of national realizations of ITS-90 above the silver point by radiation thermometry. Rapid actions were carried out among potential participants and a new key comparison was registered in the key comparison database (KCDB) at the 2014 CCT meeting, ready to start in the third quarter of 2014.

The Final Report of the first key comparison on humidity was completed, and a renewed key comparison of standard platinum thermometers, involving 15 participants, was initiated and for which all measurements have been completed.

Guidance documents on the realization of the ITS-90 and secondary thermometry are being revised. The “Mise en Pratique of the realization of the kelvin” was drafted and submitted to the Consultative Committee for Units (CCU), ready to be published after the new definition of the kelvin has been adopted by the CGPM.

The CCT Working Groups have all been active and many of them met at the TEMPMEKO conference which was held Madeira, Portugal, in October 2013. The Task Group on the SI continuously monitors the progress on experimental determinations of the Boltzmann constant and has worked closely with the International Council for Science: Committee on Data for Science and Technology (CODATA) on this issue.

As described above, the Working Group structure of the CCT was rationalized in 2014.
Contact with the CCT’s stakeholders is achieved mainly through its Working Groups and Task Groups. Stakeholders include international bodies such as the International Association on Properties of Water and Steam (IAPWS), the International Union of Pure and Applied Chemistry (IUPAC), the International Confederation for Thermal Analysis and Calorimetry (ICTAC), the International Association of Chemical Thermodynamics (IACT) and groups within the World Meteorological Organization (WMO). Colleagues from the IAPWS and WMO were invited to the CCT meeting in 2014.

The Mittateknikan Keskus, Centre for Metrology and Accreditation (MIKES - Finland) became full member of the CCT in 2011 and the Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO - Brazil) became full member in 2012. The Croatian Metrology Institute - Laboratory for Testing of Mechanical Properties (HMI/FSB-LPM - Croatia) and the Czech Metrology Institute (CMI – Czech Republic) obtained observer status in 2012 and 2014, respectively.

Challenges and difficulties

A challenge faced by the CCT, which is linked to the new definition of the kelvin, is the balance between pushing the measurement uncertainties for determining the Boltzmann constant to unprecedented limits, versus the growing need to systematically measure the difference between the present temperature scale (the ITS-90) and thermodynamic temperature using new primary instruments and methods. This is of course the responsibility of NMIs, some are already transferring resources from the Boltzmann constant determination to the latter measurements, but this may also influence the final uncertainty achieved for the value of the Boltzmann constant.

Further, for the scientific community, the future redefinition of the kelvin is clear and consistent but appears abstract to most of the user community; there is a challenge in how to make this concept more accessible, for example to schoolchildren and students.

Comparisons to accomplish traceability are made by circulating travelling standards, such as high precision thermometers, hygrometers or reference materials. This process is unavoidably time consuming where the outcome of global comparisons depends on the stability of the circulated standard. Unfortunately, transport problems are regularly encountered; some of the instruments are extremely sensitive to shocks but are of such dimensions that they must be carried by hand. Other problems are linked to customs procedures which can be particularly troublesome for the sensitive and fragile instruments involved. One realization of fixed-points involves mercury, which is very difficult to transport for regulatory and safety reasons.

Thermometry is regarded by many people as “old” science and fewer students are attracted to this academic area today. There is real concern over how to maintain existing know-how in this particular discipline, not only in the metrology sector but also in the manufacturing industry, as this is fundamental to high precision science and technology. The onus is on the thermometry community to communicate more clearly the importance of the discipline.

The future technical and scientific challenges are reported below.
5. **Outlook in the short and long term**

**Science and Support to Metrology**

Precise and accurate knowledge of temperature is important in all scientific fields where precision and pushed limits are targeted. The SI unit for temperature, kelvin, is defined by the temperature when ice, water and water vapour co-exist (0.01 °C). This may be represented by a physical artefact in the form of a water-filled sealed glass cell and is generally known as a ‘water triple point cell’. However, physical artefacts are generally not constant over time; for example the impurities in the water will slowly shift the measured reference with time. Nevertheless, in contrast to this, temperature may be defined by a natural constant of a fixed value: the Boltzmann constant $k$.

Many institutes worldwide have, during the last decade, carried out sophisticated measurements to prepare for such a redefinition of the kelvin, which is planned for 2018. They have used very different techniques which will allow for a robust and definitive determination of the Boltzmann constant. These developments have also allowed better understanding of, and in some cases the discovery of, important influencing factors. Furthermore, the new devices developed for this purpose will be used to measure thermodynamic temperature over a wide range of temperatures. This will allow determination of the difference between the present temperature scale (ITS-90) and the realization of temperature using these new primary instruments and methods. This phase has already started in some NMIs and is expected to last at least until the early to mid-2020s.

Methods to determine the Boltzmann constant. From left to right: acoustic gas thermometer measuring the speed of sound, dielectric-constant gas thermometer measuring the electric capacitance change, electrical noise thermometer, and optical laser spectroscopy determining the broadening induced by heat of a gas absorption line.

One particularly important task for the CCT is the maintenance and revision of an internationally accepted common temperature scale. Recent progress linked to the new definition of the kelvin, but also previous work, in particular at extreme low temperatures, will stimulate the need for a new temperature scale.

One of the missions of the CCT is to promote best practice and this is realized through several initiatives:

- A new document on the realization of the ITS-90, that will supersede the current version, is presently being prepared and will be published on the open-access CCT web pages by 2015;
- A revised version on guidance for secondary thermometry, particularly useful for the end-user, is in progress and is planned for web publication by 2016;
Guidance on how to estimate uncertainties linked to fields within thermometry have been and continue to be developed for temperature (Standard Platinum Resistance Thermometers), humidity and thermophysical quantities, and are planned to be openly available web publications.

**Technology and Economy**

Credible thermal design for production control in the metallurgical and ceramic industries relies on thermophysical quantity data related to transfer and storage of heat (thermal conductivity, heat capacity and thermal diffusivity). Improvements to the insulation of buildings, refrigerators, furnaces, kilns, boilers, pipelines etc. represent huge cost reductions world-wide. Thermal conductivity as a direct index of performance for insulating materials, and heat flux density determinations as a direct index for heat loss will become increasingly important. One key technology is represented by 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 and the thermal expansion of heat spreaders is of significant importance. Industries such as aerospace require improved thermometry both in manufacture of large structures and in the design of new turbine engines, as well as during their routine operation. In addition, many high-tech industries from nuclear power to laser material processing require precise temperature control to maintain safe and effective operation.

Advanced industrial technologies, such as highly integrated electrical devices, optical disks, magneto-optical disks and thermoelectric devices, require precise knowledge of thermophysical quantity values, in this case for thin films, to achieve a reliable thermal design.

In the longer term, increasing computer power through quantum computing is a potential growth industry requiring accurate temperature measurement at very low temperatures.

**Environment and climate**

Climate and meteorology are priority areas. Temperature and humidity are fundamental quantities involved in a wide range of climate change investigations. Comparatively small uncertainties are required for reliable temperature measurements in some environments, but where perturbing effects may induce large additional uncertainty components. This puts a high demand on technology and methodology, and is a metrological issue.

The need for reliable humidity measurements in extremely different conditions represents a serious challenge where standardized validation methods and methods of how to quantify uncertainty are required. A significant cooperation with the IAPWS has been established to develop universal definitions of humidity quantities. It is driven by needs in the observation and modelling of land and sea surface humidity conditions.

Further developments in the humidity field are required to support climate and weather observation and research, involving measurements in diverse gases such as carbon dioxide, hydrogen and fuel gas mixtures. There will be an increasing need for NMIs to demonstrate impact in these areas, including support for 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, represents a significant step-change in this field.
There is a **lack of comparability today for meteorological observations** and poor traceability to international measurement standards. The CCT’s extensive network of stakeholders and expertise in this area could potentially lead to a tangible contribution by the CCT, which is a part of its short and long-term planning. The creation of a new Task Group for Environment was a first step in this direction.

**Energy**

Improved thermometry in industry is an essential step towards optimizing energy use and minimizing emissions. It is also critical for enhancing the performance of the current generation of power plants. Reliable values of thermophysical quantities are particularly important for the reduction of global **energy consumption**. The knowledge of the released thermal energy by combustion of natural gas, bio-diesel and bio-ethanol are important for trade, while energy linked to fusion and heat storage are required by the automotive and housing industries. Thermoelectric properties and the performance of thermoelectric modules required for the recycling of heat are other examples where thermophysical quantities play an important role.

**Annex: CCT Data**

CCT set up in 1937  
President: Y. Duan  
Executive secretary *ad interim*: S. Picard  
Membership: 23 members and 2 observers  
Meetings since the 24th CGPM meeting: 24-25 May 2012 / 21-23 May 2014  
Full reports of the CCT meetings:  
6 Working Groups:  
Key Comparisons (WG-KC)  
CMC Coordination (WG-CMC)  
Strategic Planning (WG-SP)  
Contact Thermometry (WG-CTh)  
Non-Contact Thermometry (WG-NCTh)  
Humidity (WG-Hu)  
5 Task Groups:  
SI (TG-SI)  
Kelvin (TG-K)  
Guide to Thermometry (TG-GoTh)  
Thermodynamic Quantities (TG-ThQ)  
Environment (TG-Env)  

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<th>CCT Comparison activity</th>
<th>Completed</th>
<th>In progress</th>
<th>Planned [2015-2018]</th>
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<td>CCT key comparisons (and supplementary comparisons)</td>
<td>11</td>
<td>7 + (3)</td>
<td>3</td>
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<tr>
<td>BIPM comparisons*</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>CCT pilot studies</td>
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<td>0</td>
<td>3</td>
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<tr>
<td>CMCs</td>
<td>2222</td>
<td>CMCs in 46 service categories registered in the KCDB</td>
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* One of the completed CCT comparisons was piloted by the BIPM.