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CCT WG8 CMC Review Protocols: Development and Implementation

G. F. Strouse · M. Ballico · J. Bojkovski · M. de Groot · H. G. Liedberg · A. I. Pokhodun

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Abstract The primary objectives of the Consultative Committee on Thermometry Working Group 8 (CCT WG8) are to establish and maintain lists of service categories, to agree on detailed technical review criteria of submitted calibration and measurement capabilities (CMCs), and, where necessary, to develop rules for the preparation of CMC entries. One of the main tasks of CCT WG8 is the creation of harmonized CMC review protocols for thermometry and humidity that are scientifically based. The work of CCT WG8 is performed by the Regional Metrology Organization (RMO) Working Group on Thermometry chairpersons and invited technical experts. The CCT WG8 develops practical, pragmatic guidelines for CMC reviews that let the CMC review process proceed according to a set of objective numerical criteria and specified technical evidence to reduce the possibility of disagreement. The CCT WG8 CMC review protocols are designed so that CMC reviews are scientifically based and not designed to bluntly increase uncertainties. The CMC review protocols currently developed and

G. F. Strouse (✉)
Process Measurements Division (836), National Institute of Standards and Technology,
100 Bureau Drive, Stop 8363, Gaithersburg, MD 20899-8363, USA
e-mail: gregory.strouse@nist.gov

M. Ballico
National Measurement Institute, Australia, Lindfield, Australia

J. Bojkovski
University of Ljubljana, MIRS/FE-LMK, Ljubljana, Slovenia

M. de Groot
Nederlands Meetinstituut/Van Swinden Laboratorium B.V., Delft, The Netherlands

H. G. Liedberg
CSIR - National Metrology Laboratory, Pretoria, South Africa

A. I. Pokhodun
D.I. Mendeleyev Institute for Metrology, St. Petersburg, Russia

accepted by CCT WG8 cover International Temperature Scale of 1990 (ITS-90) fixed-point cells, ITS-90 calibration temperature subranges for standard platinum resistance thermometers, industrial thermometers, radiation thermometry, and humidity. This article describes the methods used by the CCT WG8 committee to create the review protocols.

Keywords BIPM KCDB · Calibration · Calibration and measurement capability · CCT WG8 · CMC · Humidity · Key comparison · Temperature

1 Introduction

In 1999, the 38 directors of the national metrology institutes (NMIs) of the Metre Convention voted to accept the International Committee of Weights and Measures' (CIPM) Mutual Recognition Arrangement (MRA) as a means to create world-wide uniformity of measurements and their traceability to the International System of Units (SI) [1]. In general, the MRA established a mechanism for NMIs to authenticate the degree of equivalence of national measurement standards, to achieve mutual recognition of calibration and measurement capabilities (CMCs), and to provide a scientific basis for acceptance of global trade. The MRA Appendix E also established the terms of reference for the Joint Committee of the Regional Metrology Organizations (JCRB). Appendix E empowers the JCRB to implement part 2 of the MRA by coordinating and managing CMC reviews and to develop MRA operational policy and guidelines to assist the RMOs and the CIPM.

The origin of the Consultative Committee for Thermometry (CCT) Working Group 8 (WG8) dates from the first thermometry-related regional metrology organization (RMO) meeting that occurred in Chicago, Illinois at the 7th Temperature Symposium in October 2002. This RMO meeting was an attempt by the RMO representatives to gain understanding of the then non-harmonized CMC review and acceptance practices that were occurring across the RMOs. These philosophical differences in the implementation of both MRA and JCRB directives created unforeseen problems in having an RMO accept the Temperature and Humidity CMCs of another RMO. From a practical perspective, the variability of calibration services and interpretation of measurement uncertainties among various NMIs causes confusion for calibration customers.

As part of the solution to this issue, the JCRB created terms of reference for the establishment of Consultative Committee Working Groups on CMCs to facilitate the CMC review process [2]. This JCRB document calls for Working Groups to establish and maintain service category lists, to agree on detailed technical CMC review criteria, to coordinate and conduct the CMC review process, and to identify the need for future Key and Supplementary comparisons to validate CMCs. Additionally, to insure the availability of appropriate technical expertise, each Working Group is comprised of members from the pertinent RMO Technical Committees of that particular metrology area.

At the 22nd CCT Meeting (2003), the CCT WG8 terms of reference were expanded to meet the JCRB directives. In the spirit of the JCRB terms of reference, the objective of the CCT WG8 (with the help of technical experts) is to determine and maintain

the temperature and humidity service categories, create harmonized CMC review protocols, facilitate the CMC submission and approval process, perform necessary CMC reviews, and arbitrate differences that occur between RMOs. Since 2003, the CCT WG8 consists of RMO Working Group on Thermometry (WG-T) Chairpersons from the Asia Pacific Metrology Program (APMP), Euro-Asian Cooperation of State Metrology Institutions (COOMET), European Collaboration in Measurement Standards (EUROMET), Southern African Development Community—Cooperation in Measurement Traceability (SADCMET), and Sistema Interamericano de Metrologia (SIM).

Table 1 shows the CMC service categories for temperature and humidity. CCT WG8 uses this list to determine which submitted CMCs are allowed and which CMC review protocol is applied to the submitted CMC. Additionally, the service category list helps CCT WG8 to identify needed CMC review protocols and key comparisons (KCs). The CMC service categories are used by NMIs to select the service category for the submitted CMC. The JCRB uses the list for classifying the accepted CMCs within Appendix C of the BIPM Key Comparison Database (BIPM KCDB). Changes to the listed service categories are performed through a request made to the NMI's RMO representative for discussion and vote by CCT WG8.

2 Discussion of CMC Review Protocols

The primary goal of the CCT WG8 is to create CMC review protocols for thermometry and humidity that are scientifically based, uniformly applied across the RMOs, and publicly available to all NMIs. The harmonized CMC submission and review process is designed to judge NMI-submitted CMCs on their technical merit and remove any political discussions that might hinder the acceptance of the CMCs. The CCT WG8 review protocols generally include the following key elements:

- Agreed cutoff criterion based on literature uncertainty values (e.g., CCT WG documents, 25th and 75th percentile values of KC participant uncertainties)
- Agreed list of specific evidence items required for CMC acceptance (e.g., melt and freeze curve, internal cell comparison data)
- Mathematical process to use key comparison data to review a CMC (e.g., how to use the KC uncertainty with the claimed CMC uncertainty with respect to the NMI – KCRV result)

Two basic types of CMC review protocols exist: (1) a protocol that uses cutoff tables and (2) a protocol that uses algorithms relating the claimed uncertainties to specific levels of review. In either case, the protocols contain general requirements and specific criteria to determine what level of review and acceptance is needed. It is necessary to emphasize that a CMC uncertainty value lower than the cutoff criterion does not mean rejection of the submitted CMC, but that further scrutiny is required. An NMI's successful completion of the relevant KC is not the only requirement for acceptance of a CMC. Within each review protocol, there are specific scrutiny criteria as well as required supporting documentation for CMC acceptance that depend on the CMC service category. The general requirements for CMC acceptance are as follows: the

Table 1 CMC service categories for temperature and humidity

Temperature
1. Temperature—Items used for defining ITS-90
1.1 Primary fixed-point cells
1.1.1 Cells for contact thermometry
1.1.2 Cells for radiation thermometry
1.2 Complete apparatus realizing fixed points
1.2.1 Apparatus for contact thermometry
1.2.2 Apparatus for radiation thermometry
1.3 Standard platinum resistance thermometers
1.3.1 Capsule-type SPRTs
1.3.2 Long-stem SPRTs including HTSPRTs
1.4 Standard radiation thermometers
2. Temperature—items used for disseminating ITS-90
2.1 Secondary fixed-point cells and apparatus for contact thermometry
2.2 Resistance thermometers (RTs)
2.2.1 Rhodium-iron resistance thermometers
2.2.2 Industrial platinum resistance thermometers (IPRTs)
2.2.3 Thermistors and other resistive thermometers
2.3 Thermocouples
2.3.1 Noble-metal thermocouples
2.3.2 Base-metal thermocouples
2.3.3 Pure-metal thermocouples
2.4 Liquid-in-glass thermometers
2.5 Radiation thermometry
2.5.1 Secondary fixed-point blackbody cells and complete instruments
2.5.2 Variable temperature blackbody radiation sources
2.5.3 Strip lamps
2.5.4 Radiation thermometers including blackbody radiation sources
2.6 Other thermometers
2.6.1 Air temperature sensors
2.6.2 Other
2.7 Temperature sensors with display unit
2.8 Other measurement services
2.8.1 Bridge linearity
2.8.2 Compensation wires for cold junction
2.8.3 Wires for melting-point measurements
2.8.4 Temperature indicators

Table 1 continued

Humidity
3. Hygrometers
3.1 Dew-point Hygrometers
3.2 Psychrometers
3.3 Relative humidity sensors
3.4 Others
4. Dynamic generators
4.1 Dew-point generators
4.2 Relative humidity generators
4.3 Flow mixing
4.4 Permeation tube/diffusion tube
5. Static generators
5.1 Salt solution (saturated/unsaturated)
5.2 Reference gases

CIPM MRA requires that any NMI submitting a CMC must be an MRA signatory, the NMI's quality system must be accepted by its RMO, and the NMI must participate in the pertinent KC (under the auspices of either the CIPM or an RMO). The CMC review protocols reflect the change in acceptance criteria and continue to evolve. For example, the original CMC review protocol for ITS-90 fixed-point cells used to calibrate standard platinum resistance thermometers (SPRTs) allowed for non-KC participation through the BIPM/JCRB transition period that lasted until the end of 2004. The post-2004 CMC review protocols require satisfactory KC participation, where KCs are available.

Most of the CMC review protocols are a three-tier review screening process that identifies the level of review that is required for CMC acceptance. The current exception is that for industrial thermometers which uses only the first two tiers of the review screening process. The first tier of review requires no RMO-level detailed review, the second tier of review requires an RMO-level detailed review, and the third tier requires a CCT WG8-level detailed review. The review detail level is stipulated in the CMC review protocols. Normally, most NMI CMCs will receive an "acceptance" during the RMO-level review of the CMCs. Those CMCs not accepted during the RMO-level review process require a CCT WG8-level review. For those CMCs "under review" at either the RMO or WG8 level, the NMI is asked to submit supporting documentation to substantiate the submitted CMC. For those CMCs not receiving an "acceptance," the NMI is notified; however, the CCT WG8 does not decide the uncertainty that the NMI should use to achieve CMC "acceptance" as the NMI has the responsibility to scientifically substantiate its CMC submission in a sufficient way through supporting documentation (e.g., calibration procedures, published papers, internal and external comparisons, KC results).

Figure 1 gives a simplified flowchart diagram of the NMI CMC submission, review, and acceptance process. The primary pathway is through the NMI's RMO WG-T. The

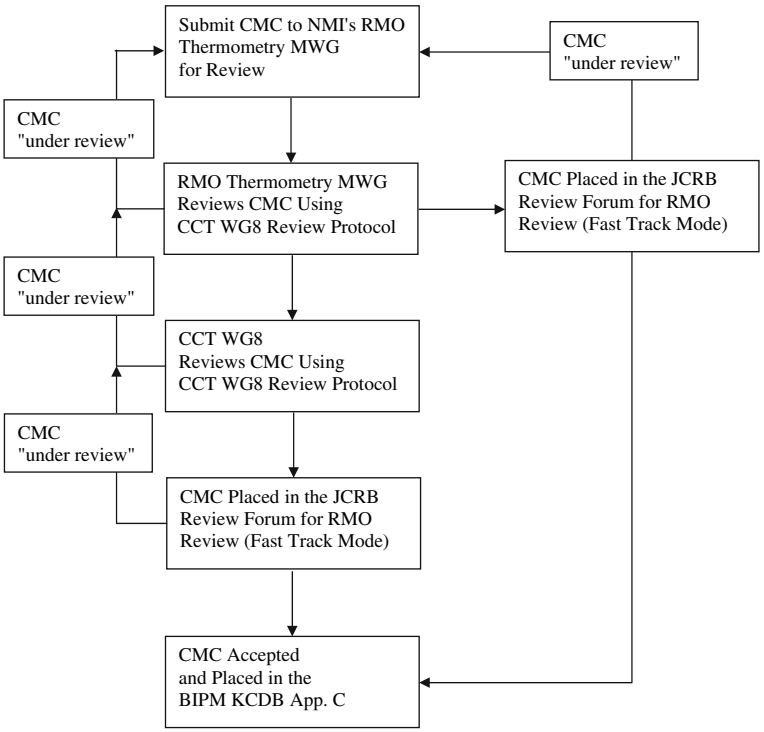

Fig. 1 Flowchart diagram of the thermometry and humidity CMC submission, review, and acceptance process

RMO WG-T is responsible for implementing the appropriate CCT WG8 CMC review protocol to determine the "acceptance" or "under review" status of a submitted CMC. Those CMCs that do not gain acceptance at the RMO level either require a CCT WG8-level review or are kept at the RMO level as "under review." The "under review" status means that either the CMC uncertainty is too low without proper documentation and could not be passed up to the CCT WG8 level for review, or the CMC did not gain RMO "acceptance" and the CMC review protocol does not allow for a CCT WG8-level review, or the NMI still requires a successful Key Comparison participation, or the NMI's quality system is not yet approved by their RMO.

For those CMCs that require only an RMO-level review for "acceptance", the accepted CMCs are placed on both the CCT WG8 BIPM discussion forum and JCRB CMC review forum for 30 days. The two forums are web-based with usernames and passwords to facilitate the review and voting process. This allows other RMOs to judge the fairness in the implementation of the RMO-level review process, but is not intended for other RMOs to judge the uncertainties of the submitting RMO's NMI CMC entries.

For those CMCs that require a CCT WG8-level review, the RMO representative places those CMCs on the CCT WG8 BIPM discussion forum for either electronic review or until the next CCT WG8 meeting. The CCT WG8 voting requires a

simple majority to make final decisions. Those CMCs with low uncertainty claims and enough supporting documentation to satisfy CCT WG8 will receive an "acceptance" for Appendix C of the BIPM KCDB.

2.1 CCT WG8 CMC Review Protocol Overviews

The following overviews of the CCT WG8 review protocol are designed to show how each review protocol was developed and is applied in practice. Prior to submitting a CMC, NMIs should use the actual review protocols to completely understand the review process applied to that submitted CMC. All CCT WG8 review protocols now require either a KC or Supplementary Comparison to substantiate the submitted CMCs. If the CMC review protocols that contain a CCT-WG8 level review tier are properly administered, then approximately 20–30% of all submitted CMCs will require a CCT WG8-level review. In the case of the industrial thermometer review protocol, no CCT WG8-level review is allowed.

For any submitted CMC, there are five CCT WG8 specific expectations and information items needed for CMC acceptance [3]: (1) CMC service categories 1, 3.1, and 4 require either satisfactory participation in or linkage to a KC result (CCT K1 through K7, or the RMO equivalents); (2) for the "Review Protocol for Thermometry CMCs" used to review the CMCs for ITS-90 fixed-point cells, only the KC participant review section is now used to review all newly (as of 01/01/2005) submitted CMCs. The JCRB transitional period allowing for non-KC participation or linkage is no longer valid; (3) for unsatisfactory KC results, an NMI must provide the following information: linkage of new artifact to a KC artifact (e.g., old artifact, other NMI, other accepted comparison), plausible explanation for the difference between artifacts, performance results (e.g., melt, freeze, heat flux, fixed-point cell comparisons) and uncertainties of the linkage, and submission of a description and evaluation method for the impurity uncertainty component; (4) the use of the KC difference from the baseline value as a correction term is not allowed; and (5) technical responses to questions regarding "under review" CMCs are expected within 2 months after a request is made by the NMI's RMO WG-T (the CCT WG8 requests are made through the NMI's RMO WG-T chairperson).

2.1.1 ITS-90 Fixed-point Cell CMC Review Protocol

This CMC review protocol was the first protocol created and accepted and is applied to CMCs for the use of ITS-90 fixed-point cells for contact thermometry under temperature service categories 1.1.1, 1.2.1, 1.3.1, and 1.3.2 [4]. The title "Review Protocol for Thermometry CMCs" is misleading and reflects the early thought process of CCT WG8 of just one document for the review of all CMCs. Primarily, the CMC review protocol covers the fixed-point cells used to calibrate SPRTs and fixed-point cell certification. The CMC review protocol provides three-tier cutoff values for determining whether no review, an RMO-level review, or a CCT WG8 review is necessary. The cutoff values were determined from the statistical derivation of 25th and 75th percentile values of the combined CCT K3 and CCT K4 NMI-participant uncertainties.

If the KC Report does not include a KC Reference Value (e.g., CCT K3), then the pilot laboratory may be asked by CCT WG8 to provide a linkage mechanism to evaluate the CMC entries with respect to the KC results. The scrutiny criteria applied during the review process includes an uncertainty budget and documented technical competence. Participation in or linkage to a KC is mandatory for CMCs covered by this review protocol. The CCT WG8 accepted this CMC review protocol in May 2003. The CMC review for ITS-90 subrange-calibrated SPRTs is covered by a different CMC review protocol [5].

2.1.2 Radiation Thermometer CMC Review Protocol

This CMC review protocol is applied to radiation thermometer CMCs under temperature service categories 1.1.2, 1.2.2, 1.4, and 2.5 [6]. The review protocol provides three-tier cutoff values for determining whether no review, an RMO-level review, or a CCT WG8-level review is necessary. The cutoff values were determined from the arithmetic mean of the normal and best uncertainty ($k = 2$) values from CCT WG5, a published document for Service Category 2.5.4, and the TRIRAT comparison uncertainty ($k = 2$) values [7–9]. The review protocol does not use CCT K5 comparison values due to the fact that the CCT K5 NMI uncertainty values were not available at the time of the review protocol creation. The scrutiny criteria applied during the review process do not require linkage to CCT K5 because the CCT K5 Final Report is not yet available. When the CCT K5 Final Report is available, the review protocol will be updated accordingly. An additional scrutiny criterion is the existence of an uncertainty budget with evidence that the budget follows Table C of [7] for $t > 960$°C. The CCT WG8 accepted this CMC review protocol in December 2003.

2.1.3 Humidity CMC Review Protocol

This review protocol is applied to humidity CMCs covered under humidity service category 4 for dynamic generators [10]. The review protocol provides three-tier cutoff values for determining whether no review, an RMO-level review, or a CCT WG8 review is necessary. The cutoff values were determined from the statistical derivation of 75th and 25th percentile values of the available Euromet P511 and APMP K6 Comparisons. The review protocol does not use the CCT K6 comparison values due to the fact that the CCT K6 NMI uncertainty values were not available at the time of the review protocol creation. Additional cutoffs exist that can trigger an automatic CCT WG8-level review (e.g., frost-point temperatures less than −75°C or dew-point temperatures greater than 75°C). The scrutiny criteria applied during the review process do not require linkage to CCT K6 until the CCT K6 final report is available. When the CCT K6 final report is available, the review protocol will be updated accordingly. Additional scrutiny criteria include the existence of a detailed uncertainty budget and any available supporting documentation. The CCT WG8 accepted this CMC review protocol in June 2005.

2.1.4 Industrial Thermometer CMC Review Protocol

This review protocol is applied to resistance thermometers, thermocouples, digital thermometers, and liquid-glass thermometers CMCs covered under temperature service categories 2.2.2, 2.2.3, 2.3, and 2.4 [11]. This CMC review protocol differs from that of the other CMC review protocols in two ways: (1) a supporting RMO supplementary comparison is desirable, but not required for CMC acceptance and (2) the RMO-level review is the highest level of review allowed.

The CMC review protocol provides two-tier algorithms for each thermometer type for determining whether no review or an RMO-level review is necessary. The cutoff values used in the algorithms were determined from several published and unpublished literature sources. Additional cutoffs exist that can trigger an automatic RMO-level review (e.g., pure-metal thermocouple extrapolation from the gold or copper freezing points to temperatures greater than 1,100°C). Due to the lesser likelihood for comparison participation, the scrutiny criteria provided in this CMC review protocol are more extensive than other review protocols. There are general scrutiny items that are applied as well as specific thermometer-type scrutiny items. In general, the scrutiny items focus on calibration method, required uncertainty budget items that must be evaluated and included (e.g., resistance thermometer hysteresis, thermocouple inhomogeneity, ice melting point), and necessary CMC comment-field wording (e.g., "Pre-determined value of inhomogeneity included in the CMC entry"). The CCT WG8 accepted the original CMC review protocol in June 2005. After application of the review protocol by the RMOs, it was determined that further clarification was required to harmonize the CMCs. The CCT WG8 accepted the enhanced and current version of the CMC review protocol in October 2006.

2.1.5 TPW CMC Review Protocol

This review protocol is applied to triple-point-of-water (TPW) cell realization CMCs covered under service category 1.1 [12]. The review protocol provides three-tier cutoff values for determining whether no review, an RMO-level review, or a CCT WG8-level review is necessary. The cutoff values were determined from the statistical derivation of 75th and 25th percentile values of the available CCT K7 and submitted CMC uncertainties. An automatic CCT WG8-level review is triggered if there are significant unresolved deviations, at the $k = 3$ level, for the NMI's KC results, or if the claimed NMI uncertainties are smaller than the uncertainties claimed by the NMI in the KC. The scrutiny criteria applied during the CMC review process include required participation in or linkage to CCT K7 as well as an uncertainty budget that contains 13 specified uncertainty items that must be evaluated and included (e.g., isotopic correction/composition, chemical impurities, and heat flux). The CCT WG8 accepted this CMC review protocol in October 2006.

2.1.6 ITS-90 Subrange CMC Review Protocol

This review protocol is applied to CMCs for ITS-90 subrange-calibrated SPRTs [5]. The review protocol provides three-tier algorithms for determining whether no review,

an RMO-level review, or a CCT WG8 review is necessary. The cutoff values (U_{comb}) used in the algorithms were determined from the statistical derivation of 25th and 75th percentile values of the combined CCT K3 and CCT K4 uncertainties and Type I and Type III non-uniqueness values [13]. The Type I and Type III non-uniqueness values were derived from several published and unpublished literature sources. The U_{comb} values are specified for the minimum and maximum temperature values for ITS-90 temperature subranges (e.g., 0°C to the aluminum freezing point) as well as temperature ranges within a given subrange (e.g., zinc freezing point to the aluminum freezing point). The scrutiny criteria applied during the review process include already accepted CMCs for the pertinent ITS-90 fixed-point cells and an uncertainty budget that contains five specified uncertainty items that must be evaluated and included (e.g., proper propagation of U_{FPs} ($k = 2$), non-uniqueness values used, SPRT stability assessment). An additional requirement is that U_{CMC} ($k = 2$) submission must capture the maximum uncertainty of the specified temperature range; and that if two U_{CMC} ($k = 2$) values for the specified temperature range are given, then a linear function is used to interpolate the U_{CMC} ($k = 2$) between the end points. The CCT WG8 accepted this CMC review protocol in October 2006.

3 Conclusions

The CCT WG8, with the assistance of technical experts, developed six CMC review protocols for temperature and humidity that are used to review NMI-submitted CMCs for inclusion in the BIPM KCDB. These CMC review protocols established a scientifically based process to review uncertainty statements to limit politically based input. The harmonized CMC review process forces an NMI to scientifically substantiate its CMC in a sufficient way through key or supplementary comparisons and required documentation. The successful implementation across the RMOs of the temperature and humidity CMC review protocols is evident in the way that CMCs are now reviewed and accepted. The CCT WG8 will continue to develop new CMC review protocols and call for future KCs as needed.

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