Bureau International des Poids et Mesures

Consultative Committee for Thermometry (CCT)

Minutes of the 29th meeting
Session 5
9 February 2021

Due to the present pandemic, the 29th meeting of the CCT is held on-line.
It is split into five sessions spanning over October 2020 until February 2021.

These minutes will be incorporated at a later stage into the CCT's Report to the CIPM.

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR THERMOMETRY

as of 20 October 2020

President

Y. Duan, member of the International Committee for Weights and Measures

Executive Secretary

S. Picard, International Bureau of Weights and Measures [BIPM], Sèvres

Members

Agency for Science, Technology and Research [A*STAR], Singapore.

All-Russian Scientific Research Institute of Physico-Technical Measurements, Rosstandart [VNIIFTRI], Moscow.

Centro Español de Metrología [CEM], Madrid.

Centro Nacional de Metrología [CENAM], Querétaro.

Conservatoire National des Arts et Métiers/Institut National de Métrologie [LNE-Cnam], La Plaine-Saint Denis.

Czech Metrology Institute [CMI], Brno.

D.I. Mendeleyev Institute of metrology, Rosstandart [VNIIM], St Petersburg.

Instituto Nacional de Metrologia, Qualidade e Tecnologia [INMETRO], Rio de Janeiro.

Instituto Português da Qualidade [IPQ], Caparica.

Istituto Nazionale di Ricerca Metrologica [INRIM], Turin.

Korea Research Institute of Standards and Science [KRISS], Daejeon.

Measurement Standards Laboratory of New Zealand [MSL], Lower Hutt.

National Institute of Metrology [NIM], Beijing.

National Institute of Standards and Technology [NIST], Gaithersburg.

National Measurement Institute of Australia [NMIA], Lindfield.

National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology [NMIJ/AIST], Tsukuba.

National Metrology Institute of South Africa [NMISA], Pretoria.

National Metrology Institute of Turkey [UME], Gebze-Kocaeli.

National Physical Laboratory [NPL], Teddington.

National Research Council of Canada [NRC], Ottawa.

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig.

Slovak Metrology Institute/Slovenský Metrologický Ústav [SMU], Bratislava.

VSL B.V. [VSL], Delft.

VTT Technical Research Centre of Finland Ltd, Centre for Metrology / Mittatekniikan keskus [MIKES], Espoo.

The Director of the International Bureau of Weights and Measures [BIPM], Sèvres.

Official Observer(s)

FSB - Laboratory for Process Measurements [DZM/FSB-LPM], Zagreb.

1 OPENING OF THE MEETING; APPOINTMENT OF THE RAPPORTEUR; APPROVAL OF THE AGENDA

The twenty-ninth meeting of the Consultative Committee for Thermometry (CCT) was held in five separate sessions via the web due to the pandemic crisis.

The following were present at the fifth session:

Z. Ahmed (NIST), N. Al Dawood (SASO-NMCC), N. Alqahtani (SASO-NMCC), M. Anagnostou (EMI-QCC), S. Bell (NPL), J. Bojkovski (MIRS/UL-FE/LMK), J. Brionizio (INMETRO), C. de Bruin (VSL), D. del Campo (CEM), Y. Duan (NIM), E. Ejigu (NMISA), L. Eusebio (IPQ), R. Feistel (IAWPS), X. Feng (NIM), V. Fernicola (INRIM), S. Fil (NSC IM), J-R. Filtz (LNE), C. Gaiser (PTB), R. Gavioso (INRIM), L. Hanssen (NIST), B. Hay (LNE), M. Heinonen (MIKES), M.K. Ho (NMIA), F. Jahan (NMIA), M. Kalemci (UME), L. Knazovicka (CMI), V.G. Kytin (VNIIFTRI), L. Lira-Cortes (CENAM), G. Machin (NPL), A. Merlone (INRIM), M. Milton (BIPM), R. Moretz (INMETRO), T. Nakano (NMIJ AIST), H. Nasibli (UME), P. Pavlasek (SMU), J. Pearce (NPL), A. Peruzzi (NRC), A. Pokhodun (VNIIM), K. Quelhas (INMETRO), P. Rourke (NRC), S. Rudtsch (PTB), M. Sadli (LNE-LCM/Cnam), N. Sasajima (NMIJ AIST), P. Saunders (MSL), Y. Shaochun (NMC, A*STAR), G. Snijders (VSL), F. Sparasci (LNE-LCM/Cnam), W. Tew (NIST), A. Todd (NRC), C.M. Tsui (SCL), E. van der Ham (NMIA), M. Vinge (VNIIFTRI), L. Wang (NMC, A*STAR), R. White (MSL), N. Yamada (NMIJ AIST), I. Yang (KRISS), H. Yoon (NIST), Z. Yuan (NIM), J. Zhang (NIM), D. Zvizdic (DZM/FSB-LPM).

Invited: P. Blombergen (Netherlands), Å.E. Falnes Olsen (JV), C. Sanchez (INM (CO)).

Also present: S. Picard (Executive Secretary of the CCT).

The President of the CCT, Dr Y. Duan opened the meeting and welcomed the participants. He thanked all participants for their contributions. Dr M. Milton joined Dr Y. Duan in welcoming the participants to the final session of the 29th meeting of the CCT. The agenda of the meeting was approved with no changes or additions [CCT/20-07rev2].

Dr P. Rourke (NRC) was appointed *rapporteur* for the fifth session.

S. Picard made screen captures to be used as souvenirs of the meeting.

2 Report from TG-ThQ, Jean-Rémy Filtz (LNE)

Dr J.-R. Filtz informed that all state economies that are represented in the Task Group for Thermophysical Quantities were represented at their meeting [CCT/20-83]. He recalled the supplementary comparisons in the field that have been completed – CCT-S1 (infrared spectral normal emissivity) and CCT-S2 (thermal conductivity) – and indicated that the CCT-S3 (thermal diffusivity) Draft B and CMCs had been submitted for review.

The group had discussed strategy at its meeting. They have been active in providing guidance for CMC review, *CMC review protocol for thermal diffusivity measurements, Part 1: solid materials by the flash method* (to be published) and *CMC review protocol for infrared spectral emissivity measurements, Part 1: normal emissivity (emittance)* (in progress). They also discussed potential next comparisons and had converged towards the suggestion to compare the determination of thermal expansion of monocrystalline silicon and Sitall CO-115M[1] for the temperature range from 273.15 K to 773.15 K. NIM, NMIJ AIST and VNIIM have standards for absolute measurements. LNE, NPL and UME, who carry out relative measurements, may link to this same comparison.

The comparison activities in the RMOs for thermophysical quantities were displayed. APMP had been active in supplementary comparisons of thermal diffusivity and thermal conductivity. COOMET had activities on bomb calorimetry involving six institutes and measurements within the frame of a gas calorimetry comparison were about to start. EURAMET had several ongoing projects. One of the collaborations concerns emissivity measurements of reflective insulation materials. A second project concentrates on the optimization of industrial processes through improved metrology of thermophysical properties.

The online communication was unfortunately interrupted near the end of the presentation.

3 Report from TG-GoTh, Rod White (MSL)

Dr R. White reported from the meeting of the Task Group for Guides on Thermometry who met in December 2020 [CCT/20-81]. He recalled the terms of reference, focused on the revision of "*Techniques for Approximating the International Temperature Scale of 1990*" https://www.bipm.org/utils/common/pdf/ITS-90/ITS-90-Techniques-for-Approximating.pdf .

The group communicates with ease via e-mail and met earlier at the TEMPMEKO 2019 conference in China. Two guides of secondary thermometry have been published: "*Thermistor Thermometry*" https://www.bipm.org/utils/common/pdf/ITS-90/Guide-SecTh-Thermistor-Thermometry.pdf and "*Specialized Fixed Points above 0 °C*" https://www.bipm.org/utils/common/pdf/ITS-90/Specialized-FPs-above-0C.pdf .

A third guide, "*Guidance on Thermocouple thermometry Part 1 (General usage)*", will be posted online before the end of February 2021 and be open for comments until 30 March 2021. A draft of "*Guidance on Thermocouple thermometry Part 2 (Reference thermocouples and calibration)*" is 50 % complete. It notably treats ambiguities about annealing Type R and S thermocouples, reporting of the calibration state and the uncertainty budget. An additional guide on industrial platinum resistance thermometry is almost completed, and may be ready for CCT approval in about two months.

A sixth guide on industrial radiation thermometry is about to be initiated, led by Dr M. Sadli (LNE-LCM/Cnam), as a task group of CCT WG NCTh. The author group is to be determined.

Dr R. White mentioned an issue related to the document "*Uncertainties in the realization of ITS-90 metal freezing-points using sealed cells*" https://www.bipm.org/utils/common/pdf/ITS-90/Guide_ITS-90_2_4_MetalFixedPoints_Appendix-1_2018.pdf, drafted by Dr R. White (MSL)

[1] Crystalline glass-ceramic with ultra-low coefficient of thermal expansion

et al. and published as the Appendix 1 to "*Metal fixed points for contact thermometry*" https://www.bipm.org/utils/common/pdf/ITS-90/Guide_ITS-90_2_4_MetalFixedPoints_2018.pdf within the frame of *Guide to the Realization of the ITS-90* https://www.bipm.org/en/committees/cc/cct/publications-cc.html (see Minutes of the 29th CCT meeting, Session 4, Section 3). He recalled that the report issued by the Task Group for Sealed Metal Freezing Point cells (closed in 2017 after having met the objectives) was based on comparison of world-class NMIs and included a recommendation for calibration and verification for lowest uncertainties [CCT/17-20]. However, there was no guidance for use and uncertainty evaluation (for example, due to non-ideal thermal environment). As a result, some guidance needs to be added to the "*Specialized Fixed Points above 0 °C*" guide https://www.bipm.org/utils/common/pdf/ITS-90/Specialized-FPs-above-0C.pdf for sealed metal fixed point cells.

He also recalled that the work on establishing an online database for secondary fixed points had not progressed.

Dr R. White informed that he has now retired from MSL (New Zealand) but will continue to contribute to current activities. He also outlined how the future group on guides will be organized (cf. Section 6.1 below).

Dr R. White thanked all his colleagues, present and former members and Dr S. Picard who had contributed to the realization of the guides.

Dr M. Sadli said it was his pleasure to lead the author group on industrial radiation thermometry, and would do his best to ensure that this guide would be completed on a short time frame.

4 Report from WG-SP, Yuning Duan (NIM)

Dr Y. Duan presented the outcome of the Working Group for Strategic Planning that met on 26 January 2021 [CCT/20-80]. Dr G. Machin (NPL) had been tasked as *rapporteur* and had provided the report [CCT/20-77].

The WG-SP supported the request expressed by WG-Hu to carry out a repeat of CCT-K6. They considered it possible to start preparing the exercise while the reporting was concluded for CCT-K8.

The future of TG-GoTh was discussed. Since Dr R. White stepped down as Chair of TG-GoTh, the WG suggested that TG-GoTh be closed down and replaced by smaller author groups. Each relevant activity would be spun-out to the related WG which would then create a TG when a particular guide was needed. A coordinator would survey the work of the Task Groups and make sure that the revision was completed. Dr J. Pearce, active member of TG-GoTh, had been asked by WG-SP to carry out that role and had accepted to do so.

The TG-CTh-ET had carried out their objectives as planned during their first cycle from 2017 to 2020. The group, supported by several CCT delegates, suggested to start a new cycle with updated Terms of Reference. The WG-SP supported this initiative and encouraged TG-CTh-ET to include expertise on fibre optic technology from the PR community.

A new TG for Air Temperature had been proposed by WG-Env and will be discussed at a separate agenda point (cf. Section 6.2 below).

The draft recommendation on measurements above 400 K that had been discussed by WG-CTh was discussed by CCT delegates in January. The draft had converged to include a single recommendation will be discussed in a separate agenda point (cf. Section 5 below). It was distributed to the CCT delegates before the fifth session.

The CCT Strategic Plan needs to be revised, based on a 4-year cycle. Dr G. Machin (NPL) has been invited by Dr Y. Duan to coordinate the revision and liaise with the other WG and TG chairs. This revision will take place in the first half of 2021, in view of the coming 2022 CGPM meeting.

Dr Y. Duan presented the approach for the next CCT meeting. He considered the world situation still problematic with regards to the Covid-19 pandemic and that a face-to-face meeting would be unlikely to be held for the next one or two years. He proposed to hold the 30th Meeting of the CCT as 2 online sessions in early 2022. Future meetings could also give access to virtual laboratory visits to give insight into laboratory work while being prevented to travel.

He indicated that NMI activity reporting is not consistent. Based on a suggestion made at the WG-SP meeting, a template will be drafted and distributed to all delegates before each coming meeting, which they will fill out with the relevant activities engaged by their respective NMIs.

Dr G. Machin (NPL) indicated that he will soon contact the WG Chairs for input on refreshing the CCT Strategic Plan.

5 Recommendation from the CCT to the CIPM

Dr C. Gaiser (PTB) displayed the first revised version of 25 January 2021 and summarized the modifications that had been made. Part of the initial recommendation was included as a ‘noting that’ subject, and the primary thermometry and ITS-90 part had been merged, resulting in one single recommendation. He then displayed the present 2nd revised version of 29 January [CCT/20-48rev].

He thanked Dr P. Rourke (NRC) and Dr G. Machin (NPL) for their contribution.

Dr S. Picard indicated that the most recent revised version had been communicated to the CCT delegates before the 5th session so that all delegates could become aware of the new version.

Dr G. Machin (NPL) thanked Dr P. Rourke (NRC) and other colleagues for their work on the recommendation. He considered it as well expressed and hoped that the other delegates would share his opinion.

Dr Y. Duan asked the CCT delegates if they had any further comments on the Recommendation, and subsequently asked for a vote by hand raising. The CCT approved the recommendation. Dr Y. Duan thanked the small team for their work on the recommendation, and expressed his approval that despite the difficult time due to the pandemic, the CCT has still been able to make this important recommendation.

6 Working Group and Task Group issues

6.1 Dissolution of TG-GoTh and Creation of 4 new Task Groups for Guides on thermometry

The dissolution of TG-GoTh was approved by the CCT.

The creation of smaller author groups in the form of TGs for guidance on secondary thermometry, coordinated by Dr J. Pearce (NPL) was approved by the CCT [CCT/20-75]. The membership will be decided via e-mail. Each person who joins one of these TGs should contribute to the draft of the guidance document being prepared by that TG.

6.2 Proposal for the creation of a new Task Group for Air temperature

Dr A. Merlone (INRIM) presented the proposal for a TG dedicated to air temperature measurements. Air temperature measurements are important not only for the environment, but also in dimensional metrology and industry. He presented a draft proposal for the objectives – to propose a practical definition for air temperature, to advise on evaluating uncertainty in air temperature measurements and to develop guidelines for the calibration of thermometers in air [CCT/20-74].

Parts of these objectives are the subject of EURAMET activities but Dr A. Merlone requests a coherent approach amongst the RMOs. He informed that these issues are also incorporated in the CCT Strategic Plan. He recommended co-opting members from TG-CTh-ET and the dimensional metrology community.

Dr Y. Duan commented on the importance of trustworthy air temperature measurements.

Dr S. Picard suggested that this task group include representation from all RMOs, and asked for the timeline of the objectives. Dr A. Merlone estimated that 2 to 3 years would be needed to draft the guidelines, which also will involve technical work and investigations.

Dr Y. Duan clarified that this group will be under the umbrella of WG-Env.

Dr S. Picard asked to what extent the guide will be different from the EURAMET work.

Dr A. Merlone replied that there are presently no existing guidelines. The calibration issue is one aspect, and the uncertainty is another part. Since there are no guidelines, it is important to collect how other institutes solve these problems, and the more participants there are the more ideas will be able to inform the guidelines.

Dr Y. Duan observed that many institutes of the CCT were interested to participate. The CCT approved the creation of TG-Env-AirT.

6.3 Approval of a repeat of CCT-K6

Dr S. Bell (NPL) presented the background for a repeat of CCT-K6 – a key comparison of frost and dew point from -50 °C to +20 °C. The original CCT-K6 had 10 participants and measurements ended in 2009, with the report being issued in 2015. She also highlighted CCT-K8, which is presently being completed, that covers dew points above 20 °C; and mentioned that frost points below -50 °C can be covered by supplementary comparisons.

The travelling standard is to be determined by the Pilot (not yet identified) and participants. The revised guidance in CIPM MRA G-11 will be followed and changes from the previous protocol will be considered to improve the speed and effectiveness of the comparison.

The WG-Hu have expressed their wish to avoid overlap, in time, of measurements for the repeat of CCT-K6 with other comparisons.

Dr S. Bell also drew attention to the related problem with the present version of the CMC review protocol for humidity that requires a large number of discrete temperature points and would need a longer comparison exercise if not revised. The comparison will be coordinated alongside a review of, and alignment with, the CMC review protocols.

Dr S. Picard invited the delegates to indicate their interest to participate in the repeat comparison (via the online meeting chat facility), and observed some fifteen institutes showing their interest.

Dr Y. Duan concluded that there was a large interest. The CCT approved the request to carry out the repeat of CCT-K6.

6.4 Approval of the revised ToR for WG-NCTh

Dr G. Machin (NPL) presented the revised terms of reference for the WG-NCTh [CCT/20-71]. It represents a small update and reflects some of the new activities. Notably, the work towards guidance on industrial radiation thermometry has been included, and Dr G. Machin thanked Dr M. Sadli (LNE-LCM/Cnam) for agreeing to lead this work.

The new activities on body temperature measurement have also been included.

Dr Y. Duan commented that the development of guidance of body temperature measurements, one of the new objectives of the group, is very important and useful for society.

The CCT approved the new terms of reference for WG-NCTh.

Dr Y. Duan commented on the increased workload for Dr G. Machin. Dr G. Machin thanked Dr. Y. Duan and expressed that this work is a real pleasure and a great honour.

6.5 Approval of a new activity cycle of TG-CTh-ET and revised tasks

Dr S. Picard indicated that the TG for Emerging Technologies successfully fulfilled all their objectives within the planned time frame. Dr Z. Ahmed (NIST) requested that TG-CTh-ET be renewed for another cycle in order to continue its work under the same overarching Terms of

Reference, but with updated tasks [CCT/20-73rev]. He highlighted a big change for the upcoming cycle: a new task regarding best practices for calculating figures of merit for emerging technologies, since different groups are evaluating the merit of new thermometry technologies in different ways, making it difficult to compare amongst them. The objectives will be to guide which data to report, how to calculate it and which representation will be useful; to establish homogeneity when reporting new technologies and instruments, often developed directly at the institutes, so that the methods and results can be understood by everyone. The TG seeks to promote fair and open communication between all researchers. There is also a task to review and report on emergent technologies specifically for primary thermometry.

Dr Z. Ahmed was happy to announce that the TG had proposed to write a review paper on emergent technologies for thermometry. This has been presented to several metrology journals: *Measurement Science and Technology* has accepted the offer to write a review article and suggested some modifications. The TG will put together a team to write this review paper.

The CCT approved the new cycle and tasks for TG-CTh-ET.

6.7 Update of WG and TG Chairs

Dr Y. Duan has reviewed the Chair positions for the working and task groups. The present Chairs will remain for a new term, except Dr R. White (MSL) who will step down as Chair of TG-GoTh.

7 CCT memberships

Dr Y. Duan invited Dr Å.E. Falnes Olsen, Justervesenet (Norway), to give a presentation to support their request for full membership of the CCT [CCT/20-78, 79 and 82].

Dr Å.E. Falnes Olsen has worked within the thermometry department of Justervesenet (JV) for almost a decade and has mostly worked with radiation thermometry. JV is the NMI of Norway and has around 30 staff members working in seven different areas on national standards. It is in charge of disseminating the SI to national clients, supporting traceability for legal metrology, and also carries out research and development.

There are five full-time employees in the thermometry department. There is a primary standard lab with fixed points from Ar to Ag and Cu. There is also a secondary standard lab covering a temperature range from -196 °C to 1200 °C. JV has activities for contact and non-contact thermometry, and for humidity. The humidity laboratory is presently being upgraded and JV thermometry staff are constructing their own new dew point generator. The JV thermometry department issues around 160 calibration certificates annually.

Dr Å.E. Falnes Olsen reviewed the EURAMET key, supplementary and European comparisons in which JV has participated, and noted that they have acted as pilot and/or coordinator for some. He also listed European research and development projects in which JV is active. He displayed their motivation for requesting to become member of the CCT, where JV wish to contribute in

developing i) industrially relevant thermometry at a global level; ii) environmentally relevant standards, techniques and recommendations; and iii) the framework of international equivalence.

Dr Y. Duan thanked Dr Å.E. Falnes Olsen and asked for the list of publications that was then displayed [CCT/20-78].

Dr Y. Duan invited comments from the delegates.

Dr P. Rourke (NRC) recalled the previous requests to become member and observer from NSC IM (Ukraine) and SCL (Hong Kong, China) and asked why JV wishes to jump straight to member status rather than starting as an observer. He considered the presentation of Dr Å.E. Falnes Olsen to be strong but asked for clarification on the distinction of where to start when joining the CCT.

Dr Å.E. Falnes Olsen emphasized that JV is eager to get involved in the CCT in order to contribute and not only observe. He related that he can understand if there is a two-stage process involved in joining the CCT, but that their reason for applying for membership is that they intend to get involved and work.

Dr A. Merlone (INRIM) commented that he would welcome a membership of JV, appreciating their previous contribution, so that they can immediately start working.

Dr Y. Duan indicated that the delegates will be contacted by e-mail for feedback on the request to grant CCT member status to JV.

8 Next CCT meeting

Dr Y. Duan announced that the CCT meetings, as well as the WG and TG meetings, will continue online until the epidemic situation has improved worldwide. WGs and TGs may meet when necessary and will get meeting arrangement support from the BIPM.

He proposed to the CCT that the 30th meeting of the CCT will be organized via 2 online sessions in the beginning of 2022, in order to be able to report the most up to date progress to the CGPM meeting in the second half of 2022. Exact dates will be communicated later. The Strategic Planning WG will also meet at that occasion. There may also be a possibility for a “cyber” visit of some laboratories.

Dr A. Merlone (INRIM) asked if the opportunity for hybrid meetings could be considered in the post-pandemic future, *ie.* people who are available for travel would be on site at the BIPM, and others may join online.

Dr M. Milton thanked Dr A. Merlone for this question. He informed that the CIPM, and the CIPM President in particular, are considering this idea, but need to be careful on how meeting participation might be affected. It is not desirable, for example, to have meetings where only members from Europe are on site in Paris, while all others from the rest of the world are relegated to participating online. Nevertheless, the CIPM are considering these topics and doing their best to progress the agenda.

Dr Y. Duan informed that his term as CIPM member will end in 2022 and he would much like to meet in person before his term ends, where a hybrid meeting might allow colleagues to meet face to face. However, this is presently unlikely due to the ongoing pandemic.

9 AOB

Dr S. Picard informed that if no objection had been received by the end of the week, the working documents would be made openly accessible.

Dr Y. Duan thanked Dr I. Yang (KRISS) for having completed the minutes of the previous session.

Dr Y. Duan thanked Dr R. White (MSL) for his work and constructive contribution over the years. The CCT delegates and experts joined the CCT President in applause.

Dr Y. Duan called on Dr J.-R. Filtz, who was again connected, and congratulated him for the results of the TG and his work. Dr J.-R. Filtz thanked Dr Y. Duan for his support. He apologized for the earlier problems with the connection, giving rise to some jokes, and the session ended in laughter.

10 Scientific presentation, Andrea Peruzzi (NRC)

Dr A. Peruzzi (NRC) presented "Time evolution of the thermodynamic temperature scale" [CCT/20-56], a reflection on the historical development of the concept of temperature and its measurement scales.

He began by noting that the BIPM website does not have a definition of thermodynamic temperature itself, only how the SI unit is defined and realized. Dr A. Peruzzi outlined different approaches to defining thermodynamic temperature, falling within the categories of phenomenological, axiomatic and microscopic.

Dr A. Peruzzi explained measurement theory and then used this to describe the evolutionary path of temperature scales: first a nominal scale (snow is cold, fire is hot), then ordinal scales (the Fahrenheit scale of 1724 and the Celsius mercury-based Centigrade scale of 1741), then interval scales (Thomson's initial 1848 proposal, the modern Celsius scale and the modern Fahrenheit scale), and then finally a rational scale (Thomson's final 1854 Kelvin thermodynamic scale). He expressed that the more humans learnt about the true nature of temperature, the more our scales have been able to encode this understanding in the numbers we use to measure it.

He noted that measurement scales assign numbers to a quantity, but that care must be taken since not all mathematical operations are meaningful: the operations allowed are different for different kinds of scale. For example, the modern Celsius scale is an interval scale, and it does not make sense to say that 18 °C in Paris is two times 9 °C in Moscow; but on the other hand, temperature differences are meaningful and can be compared, and transformations between °C and °F are allowed. For a rational scale like the Kelvin thermodynamic scale, both temperature differences and temperature ratios are meaningful, and transformations that uniformly re-scale the size of the unit are allowed.

Dr A. Peruzzi went on to describe the evolution of the thermodynamic temperature scale over the past 100 years. He explained that before 1927, the unit of thermodynamic temperature was defined by fixing a 100 °C temperature difference between the ice and steam points, but in 1927 there existed three scales with identical units: the Thermodynamic Celsius Scale t and the ITS-27 t_{27}

(ice point 0 °C, steam point 100 °C), and the Thermodynamic Kelvin Scale *T* (100 K difference between ice and steam points). He related that in 1948, the CGPM accepted the principle of a thermodynamic temperature scale having a single fixed point provided by the triple point of water (TPW); it was already clear that TPW was 0.01 °C above the ice point and so would take a value of 0.01 °C in the Thermodynamic Celsius Scale, but it was not yet known with sufficient accuracy what numerical value should be attributed to absolute zero in this scale (or equivalently what should be the ice point value in the Thermodynamic Kelvin Scale). Dr A. Peruzzi pointed to the CCT session of 1954, in which this question was resolved by setting 273.15 K at the ice point and keeping the ice and steam points at 0 °C and 100 °C by convention: this created a new thermodynamic temperature scale. However, he showed that 1976 measurements by Guildner and Edsinger revealed that the size of the kelvin in the new thermodynamic scale was larger than the size of the kelvin in the old thermodynamic scale. Finally, he reminded that starting from the 2019 revision of the SI, the thermodynamic temperature of TPW remains 273.16 K but no longer by definition: since the kelvin is now defined by the fixed value of the Boltzmann constant, T_{TPW} is now a measured temperature which has an uncertainty and could change in the future (without affecting the definition of the thermodynamic temperature scale) if better measurements are performed.

Dr A. Peruzzi concluded by summarizing what has changed since the redefinition of the kelvin in 2019. He noted that the type of thermodynamic scale remains unchanged, as it is still a rational scale, but that now the value of TPW can change without affecting the size of the kelvin. He explained that the redefinition changed the size of the unit by 2 µK at TPW and 9 µK at the Ag fixed point, but that these changes are imperceptibly small. And he reassured that the meaning of temperature remains basically unchanged: that classical thermodynamic temperature and statistical thermodynamic temperature, which are formally equivalent, represent the average thermal energy per degree of freedom in the system.

Dr A. Peruzzi thanked Dr R. White (MSL) and Dr R. Rusby (NPL) for interesting discussions and correspondence that informed his presentation.

Dr Y. Duan thanked Dr A. Peruzzi for having reminded CCT colleagues about the evolution of temperature scales and thermodynamic temperature measurement. He invited questions and comments.

Dr H. Yoon (NIST) referred to the history. He observed that it is difficult to predict the future but, nevertheless, asked Dr A. Peruzzi what he believed would happen to the temperature scale.

Dr A. Peruzzi agreed that predicting the future is difficult, and that is why he had deliberately avoided this subject in his presentation. He referred to the excellent presentations given at earlier sessions by his CCT colleagues. However, Dr A. Peruzzi shared his own opinion, that the ITS-90 or another International Temperature Scale (depending on what the CCT will decide to do) will still be used for decades in the middle temperature range. He expected that thermodynamic temperature measurement will become increasingly practical, but he does not expect this to happen in the short term. Therefore, he believes it will take decades, not just a few years, for direct dissemination of thermodynamic temperature to completely replace defined scales.

Dr G. Machin (NPL) thanked Dr A. Peruzzi for his talk which he enjoyed a lot. He commented about Thomson's 1854 formulation, that Thomson was almost immediately forced to abandon the Carnot approach used for his earlier proposal of 1848 because it did not conserve energy. By discussions with Joule, Thomson realized that he had to conserve energy to make it really work, and this led to his final proposal of 1854.

Dr A. Peruzzi agreed that at the start Thomson was driven by the Carnot theory until 1848, when he began to become influenced by Joule. Dr A. Peruzzi realized that Thomson walked a twisted path to reach his final formulation for thermodynamic temperature and expressed that he had enjoyed reading the original works by Thomson. He also mentioned a recent discussion on the topic with Dr R. White (MSL).

Dr A. Merlone (INRIM) thanked Dr A. Peruzzi and desired that the recording would be made available afterwards. He asked if Dr A. Peruzzi believed that temperature really exists.

Dr A. Peruzzi does, and referred to the mathematical theory that he had displayed earlier in his talk.

Dr A. Merlone explained that his original provocation was not on the term "temperature" but rather on the term "belief." He compared with length as a proportion of space and mass as an amount of material, but for temperature it is more abstract and harder for people to understand the link between high level science and practical applications. He reminded of his earlier point about the lack of a definition of air temperature (cf. Section 6.2 above) and noted that every time we measure temperature, we actually measure something else.

Dr A. Peruzzi commented that you do not measure temperature directly, but you always measure something else that is related to temperature.

Dr D. Zvizdic (DZM/FSB-LPM) said that Thomson was the first person to define an absolute zero and that the definition appears paradoxical at first glance: he said it is the temperature of the reservoir to which an ideal Carnot process cannot deliver any heat. Dr D. Zvizdic explained that Thomson reasoned that the next highest reservoir had so little energy that it would all be converted to mechanical work by the ideal Carnot process, leaving no heat or energy left to pass to the reservoir at absolute zero, and that Thomson importantly concluded that absolute zero can never be reached because of that.

Dr Z. Ahmed (NIST) thanked Dr A. Peruzzi for the wonderful talk. He wondered how temperature can be defined at a nano-scale, reaching an increasingly finer structure.

Dr A. Peruzzi considered that when reaching ultra-low temperatures, you have to distinguish between the temperatures of each part – for example, the temperature of the electrons, the temperature of the nucleus, the temperature of the phonons – and temperature is no longer a microscopic quantity. So then it becomes difficult to say which one is the "real" temperature.

Dr Y. Duan assured that the talks will be made available on the CCT web.

11 Closure of the 29th meeting of the CCT

Dr Y. Duan thanked Dr S. Picard for her excellent support of the CCT, its WGs and its TGs, and the organization of the many meetings. He thanked the rapporteurs for their support, and the invited speakers of the five sessions for their interesting talks.

Dr Y. Duan finally thanked the CCT participants for having contributed to making the 29th Meeting of the CCT successful, and declared the meeting closed.

He said that the Chinese New Year will soon start, which is the year of the ox – a strong year. He wished all participants and the world an end of the pandemic crisis to allow in-person meetings again soon. Dr Y. Duan wished a successful and happy new year to all.

12 Actions and Decisions

The following actions were identified during the session:

Actions:

CCT29/A1. S. Picard to contact the delegates on the request from Justervesenet (Norway) to become a member of the CCT.

CCT29/A2. S. Picard to make the five scientific talks available after approval by the speakers.

Decisions:

CCT29/D1. The recommendation CCT T 1 of 2021 was approved by the CCT.

CCT29/D2. To dissolve the TG-GoTh.

CCT29/D3. To create smaller author groups in form of TGs for guidance on secondary thermometry, coordinated by Dr J. Pearce (NPL).

CCT29/D4. To create a new Task Group for air temperature measurements, linked to the WG-Env.

CCT29/D5. To carry out a repeat of CCT-K6.

CCT29/D6. The revised terms of reference of WG-NCTh were approved.

CCT29/D7. To renew a cycle for TG-CTh-ET.

CCT29/D8. The revised tasks of TG-CTh-ET were approved.

Dr P. Rourke, Rapporteur
February 2021

RECOMMENDATION OF THE CONSULTATIVE COMMITTEE FOR THERMOMETRY SUBMITTED TO THE INTERNATIONAL COMMITTEE FOR WEIGHTS AND MEASURES

RECOMMENDATION T 1 (2021)

Requirement for new determinations of thermodynamic temperature above 400 K

The Consultative Committee for Thermometry (CCT), at its 29th meeting in 2020/2021,

recalling

• the CCT Declaration on the 27th meeting in 2014 "Requirement for new determinations of thermodynamic temperature",

• the CCT Recommendation to the CIPM in 2017 "For a new definition of the kelvin in 2018", CCT T 2 (2017);

welcoming

• the Resolution 1 (2018) of the CGPM "On the revision of the International System of Units (SI)", which now links the unit of temperature to the Boltzmann constant;

considering

• the discussions held at the 27th, and 28th meetings of the CCT in 2014 and 2017,

• that experimental progress has allowed the development of a *Mise en Pratique* for the realization of the kelvin (*MeP*-K), which has been extended to cover direct measurement of thermodynamic temperature, T, after the redefinition of the kelvin;

noting that

• Resolution 1 (2018) of the CGPM stated "that member state NMIs take full advantage of the opportunities for the realization and dissemination of thermodynamic temperature afforded by the kelvin redefinition and the *MeP*-K",

• in the last years, primary thermometry by acoustic gas thermometry, dielectric-constant gas thermometry, and refractive-index gas thermometry have yielded low uncertainty thermodynamic-temperature data and so improved considerably the knowledge on $T - T_{90}$ below 400 K (T_{90} is the temperature according to the International Temperature Scale of 1990, ITS-90),

• above 400 K, there is a dearth of new accurate measurements of thermodynamic temperature which are urgently required,

• primary thermometry approaches to facilitate implementation of the *MeP*-K by thermodynamic thermometry and to evaluate $T - T_{90}$ in this important temperature region need significant further development;

recommends

• that member state NMIs improve their capabilities in primary thermometry, by various means, above 400 K to improve determination of $T - T_{90}$, accompanied by appropriate research to ensure that International Temperature Scale realization remains fit for purpose, allowing access to lower uncertainty thermodynamic temperature values over a wide range for a broader community.