

Bureau International des Poids et Mesures

Consultative Committee for Units (CCU)

Report of the 24th meeting
(8-9 October 2019)

to the International Committee for Weights and Measures



Comité international des poids et mesures

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR UNITS

as of 8 October 2019

President

Prof. J. Ullrich, President of the PTB, Vice-President of the CIPM

Executive Secretary

Dr E. de Mirandés, International Bureau of Weights and Measures [BIPM]

Members

Centro Español de Metrología [CEM], Madrid

Federal Agency on Technical Regulating and Metrology [Rosstandart], Moscow

Federal Institute of Metrology METAS [METAS], Bern-Wabern

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

Laboratoire National de Métrologie et d'Essais [LNE], Paris

National Institute of Metrology [NIM], Beijing

National Institute of Standards and Technology [NIST], Gaithersburg

National Metrology Institute of Japan, [NMIJ/AIST], Tsukuba

National Physical Laboratory [NPL], Teddington

National Research Council of Canada [NRC], Ottawa

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig

Prof. M. Himbert, personal member

Dr T.J. Quinn CBE FRS, personal member

Prof. I.M. Mills, OBE FRS, honorary member

The Director of the International Bureau of Weights and Measures [BIPM], *ex officio* member

Liaisons

Commission internationale de l'éclairage [CIE]

Committee on Data for Science and Technology [CODATA Task Group on Fundamental Constants]

International Astronomical Union [IAU]

International Commission on Radiation Units and Measurements [ICRU]

International Electrotechnical Commission [IEC]

International Federation of Clinical Chemistry and Laboratory Medicine [IFCC]

International Organization for Standardization [ISO]

International Organization of Legal Metrology [OIML]

International Union of Pure and Applied Chemistry [IUPAC]

International Union of Pure and Applied Physics [IUPAP]

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

The twenty-fourth meeting of the Consultative Committee for Units (CCU) took place at the International Bureau of Weights and Measures (BIPM), Pavillon de Breteuil, Sèvres, from 8 to 9 October 2019.

The following delegates from member institutes were present: S. Bize (LNE-SYRTE), M. Brown (NRC), R.J.C. Brown (NPL), S. Eichstädt (PTB), F. Fang (NIM), N. Fischer (LNE), D. Flater (NIST), K. Fujii (NMIJ/AIST), K. Hosaka (NMIJ/AIST), J. Kronjaeger (NPL), M. Krystek (PTB), T. Li (NIM), H. Margolis (NPL), M.J.T. Milton (BIPM Director), F. Piquemal (LNE), E. Prieto Esteban (CEM), A. Steele (NRC/CIPM member), J. Stenger (PTB), E. Tiesinga (NIST), J. Ullrich (CIPM/CCU President), L.F. Vitushkin (Rosstandart), B. Wood (NRC), D.-H. Yu (KRISS), I. Yang (KRISS), J. Zhang (NIM).

Liaisons: P. Blattner (CIE), D. Burns (ICRU), N. Capitaine (IAU), P. Gillery (IFCC), R. Lapuh (OIML), D. Newell (CODATA-TGFC), K. Pachucki (CODATA-TGFC), L. Pendrill (ISO), P. Sebellin (IEC), E. Shirley (IUPAP), J. Stohner (IUPAC).

CIPM members and Consultative Committees Presidents: N. Dimarcq (CIPM/CCTF President), P. Neyezhnikov (CIPM), P. Richard (CIPM/CCM President), F. Bulygin (CIPM).

Personal members: M. Himbert (LNE-Cnam), T.J. Quinn (BIPM Emeritus Director).

Representatives of Institutes from Member States invited to attend as Observers: E. Massa (INRIM).

Invited guests: E.F. Arias (LNE-SYRTE), R. Beard (ITU-R), C. Bordé (Académie des Sciences / CNRS), C. Boucher (IUGG), H. Holden (IMU), S. Karshenboim (Max-Planck-Institut für Quantenoptik).

Also present from the BIPM: R. Davis, H. Fang (CCM Executive Secretary), S. Judge (CCRI Executive Secretary), G. Panfilo (CCAUV Executive Secretary), S. Picard (CCT Executive Secretary and KCDB Coordinator), M. Stock (CEM Executive Secretary).

Sent regrets: B. Jeckelmann (METAS), P. Mohr (NIST), E. de Mirandés (CCU Executive Secretary), I.M. Mills (honorary member).

Guests attending the CCU half-day meeting on the second on Wednesday 9 October 2019 afternoon: D. Calonico (INRIM, chair of CCTF-WGATFT), L. Erard (former CCTF President), M. Gertsvoelf (NRC, chair of CCTF-WGTAI), J. Gonçalves (BIPM), Y. Hanado (NICT, chair of CCTF-WG-ALGO, on secondment at the BIPM), A. Harmegnies (BIPM), F. Meynadier (BIPM), N. Newbury (NIST), G. Petit (BIPM), P.E. Pottie (LNE-SYRTE), L. Tisserand (BIPM), V. Zhang (NIST, chair of CCTF-WGTWSTFT).

1.1 *Welcoming remarks and introduction*

The CCU President, Prof. J. Ullrich, opened the meeting at 9 am. He welcomed all members, liaisons and personal members. Prof. Ullrich noted that this was the first CCU meeting following the revision of the SI and thanked everyone for their efforts in keeping to the required deadlines and timescales so that all arrangements could run to plan. He thanked especially the editing team of the SI Brochure.

Prof. Ullrich noted that the recent CGPM had been a historic event and it had been excellent to see such extensive global cooperation in action. He remarked that the metrology community should be very proud of all that it had achieved in order to make redefinition of the SI possible.

1.2 *Welcome from the BIPM Director*

The Director of the BIPM, Dr M. Milton, welcomed participants to the BIPM and to the CCU meeting. He also thanked participants for all that had been done to achieve redefinition of the SI. Dr Milton remarked that this was the beginning of a new era for the CCU. Dr Milton also thanked Dr M. Stock for stepping in as CCU Executive Secretary whilst Dr E. de Mirandés was away from the BIPM.

At this stage Prof. Ullrich initiated a round table self-introduction of all participants.

1.3 *Approval of the agenda*

Prof. Ullrich recommended approval of the agenda noting that under any other business there would be discussion of INRIM's application for membership of the CCU and NSC-IM's application for ongoing observer status of the CCU. Prof. Ullrich also noted that a further discussion of a proposed CCU working group on terminology, expected to be initiated during point 7 on the agenda, may be reopened under this item. With these amendments the agenda was approved.

1.4 *Appointment of a rapporteur*

Prof. Ullrich proposed Dr R. J. C. Brown as the rapporteur for the meeting, thanking him for his report of the 23rd CCU meeting; Dr Brown agreed.

1.5 *Update from the CIPM*

Prof. Ullrich provided participants with an update on activities within the CIPM. The most notable point had been approval of Resolution 1 at the recent CGPM, approving the revision of the SI. The CGPM had also seen the election of new CIPM members. At this point Prof. Ullrich thanked Dr B. Inglis for his presidency of the CIPM from 2010 to 2019.

Prof. Ullrich also acknowledged the work of the CIPM Task Group for Promotion of the SI, especially Mrs F. Auty (NPL). Whilst the group had now been closed, its work having been completed, Prof. Ullrich stated that the individuals involved had nonetheless been encouraged to continue with their efforts in publicizing the SI.

Prof. Ullrich highlighted the new CC Presidents and the new chairs of CIPM WGs that had been appointed. In particular Prof. Ullrich highlighted that a new CIPM WG on 'unit' had been formed. The chair (Prof. Ullrich) had been asked to propose terms of reference for the group to the next meeting of the CIPM. Prof. Ullrich stated that he expected the group to deal in particular with the definition of 'unit' in the SI Brochure, but also that its remit might broaden to discuss other important metrology terms, especially those used in legislation. Prof. Ullrich mentioned again that, related to this, a new CCU-WG on 'terminology' would be discussed under any other business.

Prof. Ullrich recalled that the CIPM had decided to adopt the same definition of consensus for decision making that was used in the ISO/IEC Directives ¹, namely, "General agreement,

¹ ISO/IEC Directives , Part 1, Consolidated ISO Supplement – Procedures specific to ISO, 2019

characterized by the absence of sustained opposition to substantial issues by any important part of the concerned interests and by a process that involves seeking to take into account the views of all parties concerned and to reconcile any conflicting arguments. Consensus need not imply unanimity.” Prof. Ullrich stated that CIPM-D-01 had been updated accordingly. If no consensus is reached then the CC President should report this back to the CIPM. Prof. Ullrich also noted the intention for CIPM-D-01 to be updated so as not to make any reference to voting taking place.

Prof. Ullrich reported on several CIPM decisions that could be of interest for the CCU, in particular the decision to accept LNE as a member of the CCU, remarking that now the CCU had adopted the same criteria for membership and participation in meetings as all the other CCs.

2. PRESIDENT’S REPORT

Prof. Ullrich began by reviewing the decisions of the 23rd meeting of the CCU. Under Decision 2 he confirmed with Dr D. Newell that the measurement of the Boltzmann constant k by the Russian research group had not been included in the final CODATA adjustment since it had been submitted too late (it was noted that it would have made no material difference to the final numerical value anyway).

Prof. Ullrich noted that the change to liaison status has been communicated to those CCU participants who were affected but commented that in reality there was little working difference between membership and liaison status, especially since references to voting were to be removed from CIPM-D-01. At this stage Dr D. Flater remarked that voting is the mechanism by which consensus is measured and so he did not see the advantage in ruling out voting. Prof. Ullrich replied that the nature of the CCs was consultative and not necessarily decision making, the aim being to canvass opinions from participants. If there was no consensus amongst participants then this would be reported to the CIPM.

Prof. Ullrich then noted some late changes that had been made to the draft of the 9th SI Brochure prior to publication. The main change related to the decision by the CCU (via an e-mail vote) was to revert to the text used in the 8th SI Brochure to explain the concept of unit. Prof. Ullrich stated that this issue had prompted the CIPM to initiate its task group on unit, which first met in June 2019, with the initial recommendation that the CCU should create its own working group on terminology. At this stage Dr RJC Brown asked what the interaction of such a working group would be with the JCGM-WG2 on the VIM. Prof. Ullrich replied that from his perspective the working group would provide the CIPM with a more concise and direct view of the issues from a CC perspective. Dr S. Karshenboim and Mr P. Sebellin were unclear as to the order of precedence of these groups and whether decisions made by the CCU working group could be directly incorporated into the SI Brochure or whether these first needed to be agreed with JCGM-WG2. Prof. Ullrich was of the view that the first step was for the working group to bring a consensus to the CIPM, this would then be taken to the JCGM-WG2 for agreement, and then it could be included in the SI Brochure.

Other comments on the draft 9th SI Brochure had been received at a late stage. Not all of these were accepted. However, a few minor errors were noted, mostly carryovers from the 8th SI Brochure. In particular the change of description of the Avogadro constant from a conversion factor to a proportionality constant was significant. A further comment concerning the definition of the elementary charge was being considered in more depth by the CCU Working Group on Strategy.

Prof. Ullrich reported of the reconstitution of the CCU Working Group on Strategy, stating that the group had met in January 2018 and in January 2019. They had already been very effective in helping to prepare the agenda for the current CCU meeting. The CCU approved the terms of reference for the CCU Working Group on Strategy with no further comments. Prof. Ullrich noted that if anyone, upon further reflection, had other comments the topic would be revisited under point 11.

3. CODATA TGFC REPORT ON THE 2018 CODATA ADJUSTMENT

Dr Newell presented the first adjustment since the SI revision. He noted the change in the adjusted variables. Since the Planck and molar gas constants, h and R , are no longer adjusted, the muonic-Deuterium and muonic-Hydrogen Lamb shift variables have been introduced in their place. Dr Newell showed that many constants now have exact numerical values. He explained the variance weighted least squares procedure that treats uncertainties of, and correlations among, input data and explained that uncertainties in theoretical models are now included as additional data. No data had been removed, but several expansion factors have been used to deal with discrepant data. It was noted that there was new data available for the gravitational constant, G , plus a re-evaluation of an existing data point. This had yielded a new value for G with a relative uncertainty of 2.2×10^{-5} . New data was also available for the fine structure constant, α , and the latest CODATA value had a fractional uncertainty of 1.5×10^{-10} . Dr Newell remarked how dramatically the relative uncertainty of α had decreased over time, observing its own ‘Moore’s Law’.

Dr Newell continued to explain that for the first time the CODATA adjustment had included the experimental measurements of the 2s to 2p transition frequency (Lamb shift) for muonic hydrogen and deuterium. It was noted that this data constrains the value of the proton radius. Furthermore, new measurement and theoretical data for hydrogen and deuterium spectroscopy had also helped to provide new determinations of the Rydberg constant, R_∞ . Dr Newell elaborated that this seemed to have provided a solution to the proton radius puzzle – the discrepancy between proton radius measurement obtained from muonic-H and regular H-spectroscopy. With the inclusion of the new muonic data the values for the Rydberg constant and proton radius are less correlated. The Rydberg constant was now known with relative uncertainty of 1.9×10^{-12} and the radius of the proton was 0.8414(19) fm.

Dr Newell concluded by stating that the CODATA TGFC felt it was very important for specific constants to clearly state what units were being used for their expression (for instance the Planck constant and the reduced Planck constant), and in some cases this meant elaboration of the unit meaning in a footnote (for instance for the Rydberg constant and Compton wavelength) to avoid misunderstanding. Dr RJC Brown commented that this extra information and a full description of the quantity being expressed is very useful for users.

4. REPORTS FROM THE CONSULTATIVE COMMITTEES

4.1 *Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM)*

Dr RJC Brown reported on behalf of the CCQM President, Dr Sang-Ryoul Park. The main activities relevant to the CCU since the last meeting had been undertaken by the CCQM *ad hoc* Working Group on the Mole. The working group had the remit to: draft a *mise-en-pratique* for the realization

of the mole, respond to the CCU draft of the 9th SI Brochure, engage with IUPAC activities, discuss and draft a new definition of the mole considering the opinions of the relevant stakeholders, and create awareness of redefinition of the mole. Dr RJC Brown explained the close cooperation between the CCQM and IUPAC in coming to an agreement on the wording for the definition of the mole in the revised SI. The final definition had been agreed by the CCQM at its April 2018 meeting. The working group had then turned its attention to revision of the *mise-en-pratique* which had required: incorporation of the Avogadro experiment, coordination with the CCM (considering the *mise-en-pratique* of the kilogram), ensuring continuity with the existing *mise-en-pratique*, adding guidance for dealing with small numbers of entities, and ensuring continuity with the previous definition (in particular explaining the newly acquired uncertainty in the molar mass constant). The new *mise-en-pratique* was approved by the CCQM at their April 2019 meeting. Dr RJC Brown went on to explain that the working group has subsequently been engaged in dissemination of the new definition through a variety of peer-reviewed papers, trade journal articles, presentations, webinars and website material with the aim of reaching the widest possible base of stakeholders. Dr RJC Brown concluded by mentioning two other CCQM activities of relevance to the CCU. Firstly, the work the CCQM is doing to remove the traceability exception in the CIPM MRA on isotope ratio measurements (which are currently traceable to internationally agreed references). Secondly, the review paper that the CCQM published on method-defined measurands. This paper defines requirements to be met for these measurands to be eligible for CMC claims and, importantly, concludes that results expressed in SI units with metrologically valid methods may be considered SI traceable (including counting quantities). Dr P. Blattner asked whether the mole could be used with photons. Dr RJC Brown said that it could since the photons would be considered as elementary entities. Prof. J. Stohner agreed, citing the practical example of photochemical reactions.

4.2 *Consultative Committee for Mass and Related Quantities (CCM)*

Dr P. Richard, President of the CCM, provided an update. He started by highlighting the CCM-CCU roadmap to redefinition of the SI which was now complete. He thanked everyone for their help in meeting the deadlines on the plan. Dr Richard noted that the April 2018 CCM had approved the final version of the *mise-en-pratique* for the kilogram, and that the May 2019 meeting of the CCM had produced a detailed note on the dissemination process after redefinition of the kilogram and approved the creation of a single working group for mass. Dr Richard continued, reporting that the BIPM had prepared a note on the impact of the redefinition of the kilogram on BIPM mass calibration uncertainties. The first key comparison of realization experiments will start soon and is expected to be finished in April 2020. Dr Richard congratulated the BIPM for the excellent recent results obtained with their Kibble balance.

4.3 *Consultative Committee for Electricity and Magnetism (CCEM)*

Dr Stock presented on behalf of the CCEM President, Dr G. Rietveld. He reminded participants of the change to electrical metrology upon revision of the SI, noting that quantum electrical standards had now been 'brought into the SI'. He explained the small step changes that had resulted to voltage (+0.1 ppm) and resistance (+0.02 ppm) values. The CCEM had produced two important guidance documents, one on the *mise en pratique* for the ampere and one on implementation guidelines for the revised SI. Dr Stock concluded by reporting that two CCEM working groups had been closed now that redefinition was achieved: the CCEM Working Group on Proposed Modification to the SI (which prepared guidance documents) and the CCEM Working Group on Electrical Methods to Monitor the Stability of the Kilogram (which oversaw and coordinated the development of Kibble balances). He noted that the Kibble balances are now under the responsibility of the CCM, but that the electrical community retains an important role as a service provider for the Kibble balance community.

Dr E. Shirley asked whether the size of the electronvolt had changed. Dr R. Davis noted that the electronvolt, which of course is not an SI unit, now has exact conversion to joules but that in any event users had never worried about this uncertainty prior to redefinition.

4.4 *Consultative Committee for Thermometry (CCT)*

Dr S. Picard presented on behalf of CCT president Dr Y. Duan. It was noted that at the point of redefinition the triple point of water had acquired a new uncertainty. The CCT had produced a *mise-en-pratique* with several primary thermometry methods for realization specified (acoustic gas thermometry, radiometric thermometry, polarizing gas thermometry, Johnson noise thermometry). However, it was important to note that the ITS-90 scale continued to be used and was still valid and in Dr Picard's opinion this would continue to be the case for the next 10 years. Present activities in the CCT were aimed at developing further these primary methods. Dr Picard also noted that the recent ban on the transport of mercury caused a problem for one of the fixed points of ITS-90 and also for extrapolation between fixed points. Dr Picard concluded by stating that the education around the new definition was a priority since this was much more abstract than the old definition. Prof. Ullrich asked whether, if traceability was required, one would now need to apply extra uncertainty to a measurement based on ITS-90. Dr Davis replied that in fact there were no changes to the uncertainty of the fixed points apart from at the triple point of water, which now has an uncertainty in the SI, but not in the ITS-90.

4.5 *Consultative Committee for Time and Frequency (CCTF)*

Dr N. Dimarcq, President of the CCTF, reported on the thematic organization of the CCTF working groups and the major topics currently under consideration. These major topics are: redefinition of the second, increasing the role of secondary frequency standards in the construction of atomic time scales and the emergence of optical time scales, leap seconds, promotion of the benefit of UTC to the international scientific and industrial communities, and GNSS time scales and traceability to UTC. Dr Dimarcq reviewed the number of primary and secondary frequency standards reporting to the BIPM.

Dr Dimarcq highlighted the complimentary roles that the CCU and CCTF would have to play in any future redefinition of the second, in particular in recognizing the possible effect on other units. Dr Dimarcq concluded by highlighting his statement to the CCU on the role of relativity in time and frequency metrology. He stated that it is properly managed in scientific and industrial applications and the present implementations of special and general relativity are compatible with uncertainties of 1×10^{-18} (relative) in frequency (for clocks) and 1 ps in time (for time transfer), assuming some key parameters (gravity potential, velocity) are known at an adequate uncertainty level. The validity beyond this level has still to be studied and the improvements on the theoretical sides will be linked to the improvements in clocks and transfer techniques. Dr Shirley asked about the effect of a redefinition of the second on other units, mentioning that now we use fundamental constants for definitions, what was the real consequence. Dr Dimarcq replied that any effect would be very small as the second was realized with a much lower uncertainty than any of the other units. Prof. Ullrich noted that the effect of special relativity had come up in the CCU WG on Strategy with reference to experiments performed over macroscopic distances using interferometers, such that the local approximation to general relativity does not hold anymore.

4.6 *Consultative Committee for Ionizing Radiation (CCRI)*

The CCRI Executive Secretary, Dr S. Judge, reported on behalf of the CCRI and CIPM President, Dr W. Louw. He began by explaining the complex arrangements for controlling quantities and units in ionizing radiation, highlighting the advisory role of the International Commission on Radiological

Protection (ICRP), the recommendations received from the International Commission on Radiation Units and Measurement (ICRU), and the implementation by the CCRI of decisions of the CGPM and CIPM. He continued, mentioning that the recent introduction of ICRU 90 had been the most significant change in ionizing radiation in many years. This had provided new data that impacted primary standards and other changes to standards and uncertainties. Importantly the CCRI had coordinated the implementation of the report in order to maintain a harmonized international system. Dr Judge highlighted the very active programme of comparisons within the CCRI, matched only in number by the CCQM. Work to improve the efficiency of these processes had concentrated on faster procedures for receiving reports, consensus on an approach for interpreting CMCs and a new streamlined meeting structure. This work included a new user community-focused strategy including novel exercises such as comparisons of raw data and how it is analysed. Dr Judge went on to explain that radionuclide metrology relied on ionization chambers and that a new CCRI-CCEM collaboration was aimed at supporting the development of innovative new technology and instrumentation in this area. Dr Judge concluded that one of the main challenges for CCRI lay in the area of radiation dose measurement for radiopharmaceutical therapy and a new working group had been established to address these issues.

4.7 *Consultative Committee for Photometry and Radiometry (CCPR)*

Dr Blattner reported on behalf of the CCPR President, Dr M. Rastello. He highlighted the new wording of the candela definition and also how the new defining constant, K_{cd} , provided an important link between a number of photometric and radiometric quantities. Dr Blattner also mentioned that there was a newly agreed human visual response function for mesopic vision.

It was noted that the revision of the SI had no discernible effect on radiometric measurements because the best uncertainties achieved in radiometric measurement were far higher than those associated with redefinition. One important effect had been the impact on CIE standard Illuminant A. This is defined via an ideal blackbody radiator with a specific temperature. To keep the spectral distribution unchanged the distribution temperature has to be changed each time the values of h , c and k change. The previous value, based on ITS-90, resulted in a temperature rounded to 2856 K. In the revised SI the value shifted by -46 mK, resulting in a temperature that would be rounded to 2855 K. (The uncertainty of the distribution of temperature measurements is about 5 to 10 K). The CIE now recommends a definitive value of 2855.5 K for the practical realization of Illuminant A. Dr Blattner concluded by highlighting possible new traceability routes for optical power linked directly to the kilogram using photon momentum and noted that some devices to test this idea had already been constructed.

Opening the discussion Dr Shirley asked whether the Illuminant A temperature change would affect the photometric industry. Dr Blattner replied that it would not because the distribution function had not changed, but that it was important to check what values of h and k were being used. Dr Milton clarified that the problem related to the change in the term hc/k in the equation governing the relative spectral distribution. Dr Steele highlighted that whilst ITS-90 is still being used by the thermometry community, the CCPR and CIE are moving towards traceability based on thermodynamic temperature. Referring to the possible new traceability routes for optical power Dr Newell remarked that it was probably best to measure force rather than mass, allowing the use of a Kibble balance for optical measurement in space. Dr K. Fujii asked whether these new methods of realization featured in the CCPR's *mise-en-pratique*. Dr Blattner replied that they did not, but this was a possibility for the future.

4.8 *Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV)*

Dr G. Panfilo presented on behalf of Dr T. Usuda, President of the CCAUV. The most notable issue had been the revision of the ISO 80000 series, in particular the parts relevant for the CCAUV: Part 8 (Acoustics), Part 3 (Space and Time, where the decibel and neper are defined amongst others) and Part 1 (Quantities and Units, which mainly gives the basic definitions for quantities; to a lesser extent units, where it mostly follows the VIM and the SI brochure). The FDIS of Part 8 had been rejected mainly because of the introduction of the units of neper into the formulae for levels of quantities, rather than decibels. As a result a joint task force was formed by ISO TC12 to enable wider consultation. A second FDIS was created by the task force and will have a further ballot within ISO and IEC. The 12th CCAUV meeting agreed to support the new FDIS and that members would also encourage support within their own national committees. One action from the CCAUV meeting had been to raise with the CCU the need for systematic communication with ISO TC12 for the future revision of relevant standards for units. It was noted that the BIPM already receives formal invitations to attend from ISO TC 12 and IEC TC 25. Dr Milton acknowledged this but stated that no one from amongst the BIPM staff was available to attend currently and wondered whether the CCU would like to send someone in order to respond to the invitation.

Prof. L. Pendrill remarked that the ISO 80000 revision process had increased liaison with the relevant committees and had highlighted the fact that the end user needs clear guidance on these topics. Dr M. Krystek added that logarithmic units are no longer in ISO 80000 Part 3, but these will be included instead in a new document under IEC TC25. Dr Steele proposed that many of these liaisons should be managed via the CIPM and CCU to ensure proper representation when liaising with third parties such as ISO and IEC and so as to know as soon as possible what is required, and that this was a topic for the CCU WG on Strategy. Prof. Ullrich agreed that this was a suitable topic for the CCU WG on Strategy.

4.9 *Consultative Committee for Length (CCL)*

Dr Panfilo presented on behalf of Dr I. Castelazo, President of the CCL. The main highlights had been the publication of the *mise-en-pratique* for the primary methods for the practical realization of the metre and the secondary methods for the practical realization of the metre in the domain of dimensional nanometrology using silicon lattice measurements. The CCL had also published an update to its strategy document and its guidance documents for CMCs after the last meeting held in 2018. Dr Panfilo mentioned that the “recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second” had been published on the BIPM website.

Mr E. Massa observed that the value of the silicon lattice spacing is an important input data for other experiments and the evaluation of the expected value is part of the work of the CODATA TGFC. Dr Newell replied that natural silicon lattice spacing has a relative uncertainty of 1.22×10^{-8} , but that if Mr Massa was referring to enriched silicon then this would be lower. Dr Karshenboim added that for these secondary methods the CCU and CCL should be clear and specific about what it is requested from CODATA TGFC, especially what they consider the natural abundance of silicon to be for the purpose of these secondary methods, since this can vary. Mr Massa agreed but also stated that the measurement of other parameters such as impurities was also of great importance. Dr B. Wood re-emphasized that the CCL should liaise with the CODATA TGFC to ensure their requirements are known and what values should be used, since during the last CODATA least squares adjustment many of these quantities had almost failed to be included.

5. COMMENTS ON WRITTEN REPORTS FROM OTHER ORGANIZATIONS AND INSTITUTIONS

Prof. Ullrich thanked the organizations and institutions that had provided their written reports in advance of the meeting and remarked that the content had been very useful and informative. There were no further questions or discussions on these written reports.

6. QUESTIONNAIRE FOR CCU MEMBERS AND STAKEHOLDERS ON THE IMPLEMENTATION OF THE NEW DEFINITIONS OF THE SI

Prof. Ullrich explained that the CCU now wished to gather information and feedback from National Metrology Institutes, liaison organizations and academic institutions on the way the revision was introduced, on the communication strategy, on the implementation as well as on experiences with innovations triggered by the revised SI. The outcome of this survey will be considered in planning the future BIPM communication strategy, in defining new directions that potentially should be followed by the BIPM, as well as planning for the redefinition of the second. This questionnaire consisted of three parts. Part A is dedicated to National Metrology Institutes, Part B to liaison organizations of the CCU and Part C to academic institutions. Prof. Ullrich invited comments on the proposed questionnaire.

Dr RJC Brown began by asking how it would be distributed, continuing that contacts at NMIs, DIs and liaisons were clear but that the plan for contacting academia was not so clear. Prof. Ullrich agreed this was a good question and this had not yet been fully resolved. He suggested that perhaps these could be reached successfully through liaisons with IUPAC and IUPAP in the first instance. In response to Dr Karshenboim asking why NMIs should have any problems with implementation since they are in charge of the process, Prof. Ullrich added that there should probably be an additional question to ask about legal implementation of the changes within each country.

Returning to the discussion about contacting academic institutions, Dr Milton asked what the motivation had been for engaging with academia directly, proposing that this was best dealt with through IUPAC and IUPAP. Dr Shirley saw value in asking the IUPAP C2 committee to be involved in this process, although Dr Krystek was concerned that there was not enough current activity in the IUPAP C2 committee to drive this forward in a timely manner. Dr Steele felt that this was an opportunity for colleagues previously involved in the CIPM Task Group on the Promotion of the SI to get involved, especially since many of these questions felt like they could be aimed more at the high school and secondary school level. He went on to suggest that there was a grouping of national scientific academies who could be engaged with as part of this process, and also that some engagement with policy and regulatory decision makers was also important. Prof. Stohner remarked that from experience, when contacting the national scientific academies about the redefinition of the mole the flow through to chemical societies, and therefore the response, had been very poor. Dr Steele identified that one of the main problems seemed to be that arrangements varied between countries. He proposed that a solution might be to take the questions on NMI/DI and liaison engagement forward and bring up the topic of engagement with academia at the forthcoming NMI Directors meeting in order to seek guidance. Prof. Pendrill proposed widening the stakeholder recipients of part C and that liaisons to the CCU might be able to help with this. ISO had a large stakeholder base that could be engaged as part of the discussions with academia. Mr Sebellin suggested similarly that IEC could ask members to reach out to universities at a national level.

Prof. P. Gillery added that it would be easy for the IFCC to distribute such a survey and obtain feedback from members, many of whom had direct interaction with end users. Dr Shirley remarked that the discussion had highlighted a general disconnect between NMIs/DIs and the academic community and CCU should think about how to improve the situation. Dr Karshenboim was of the opinion that academics did not engage with these processes because, in general, they did not worry about, nor were very interested in, the definitions or realizations of units.

Prof. Ullrich brought the discussion to a close noting that he would take the question of how to engage with academia and with OIML concerning legal implementation to the forthcoming CIPM meeting, and would discuss the distribution amongst NMIs and DIs at the NMI Directors meeting. He also invited liaisons to consider how they could help engagement with the academic sector.

7. DISCUSSION ON THE DEFINITION OF THE TERM “UNIT”

Prof. Ullrich introduced the topic by stating that this followed on from the earlier discussions around changes to the SI Brochure. Four presentations had been offered by participants.

Prof. Pendrill began by highlighting the current work in ISO TC12 to revise the ISO 80000 series of standards. He saw this as a coordinated effort between ISO TC12, the CCU and JCGM-WG2 on the VIM, between whom there had been tripartite exchanges. Prof. Pendrill displayed some of the comments received from members who had objected to the change in the definition of unit, specifically that no rationale had been offered in the Technical Committee for redefining unit as the value of a quantity. Prof. Pendrill noted the timeline of the issue, highlighting that ISO TC 12 had made the decision early in 2018 (supported by 12 in favour, 1 against and 4 abstentions) to revert back to referring to units as quantities. In addition, this change was subsequently carried out when the 9th SI Brochure reverted back to the text of the 8th SI Brochure following a CCU electronic ballot later in 2018. Prof. Ullrich did not agree that there had been no rationale or explanation for the change, arguing that an open and transparent process had been followed.

Dr RJC Brown presented the NPL position. He began, notwithstanding earlier discussions about a CCU WG on terminology, that it was NPL’s opinion that the definitions of units are owned by the CCU, but that definitions of terms are owned by JCGM-WG2 (even the term ‘unit’). He remarked that last year when the CCU had held their electronic vote, the current position was supported 16-4 and that a clear consensus would be needed to change this. Dr RJC Brown considered that few if any scientific papers supported units as values of quantities, whereas well-argued papers support units as quantities (of objects). Dr RJC Brown acknowledged that much of the problem arose from the very subtle differences between the meaning of ‘terms’, ‘concepts’ and ‘objects’ and also the philosophical difference between definition, expression and explanation. Dr RJC Brown believed that the current definition maintained the important distinction between empirical knowledge about quantities of objects and mathematic knowledge about values of quantities; and that if units are considered as ‘values of quantities’ a circularity would arise. In conclusion Dr RJC Brown said that the NPL supported the *status quo*, or as a compromise a clarification of the SI Brochure, as suggested in L. Mari *et al* in their recent paper ‘Measurement units as quantities of objects or values of quantities: a discussion’ in *Metrologia* (2018, **55**(5), p716) on the subject.

Dr J. Stenger presented the PTB position. He began by comparing the proposed text of the 9th SI Brochure before it was changed back, and the text of the 9th SI Brochure as it now is. Dr Stenger stated that there was not a comprehensive discussion on this topic at the time because of the large number of other changes made to the SI Brochure at the same time. He argued that the current text introduces a logical contradiction, equivalent to stating, “a quantity is a value of a quantity”, within

the same sentence. Dr Stenger was of the opinion that the term “unit” should be owned by the BIPM, and not the VIM, because of BIPM’s involvement in units themselves. He thought this was probably the case for other key metrological terms too. Dr Stenger concluded with a suggestion that since the SI Brochure is not just for metrologists but for all those interested in the SI, the BIPM should launch a survey to ask which of the sentences describing unit is logical and clear. The survey should not refer to the history of the area or specific supporters of either side.

Dr Krystek stated that in the revised SI all defining constants are ‘quantity values’ according to the definition in the VIM and that all base units now are defined by using products and quotients of these defining constants. Thus, according to the rules of mathematics, all units have to be ‘quantity values’. He added that this is even more obvious after adding the number 1 in front of each base unit in its respective defining equation, as required by METAS some meetings ago. Therefore, today the SI brochure is logically inconsistent after reverting to the status of the 8th edition.

Dr E. Tiesinga presented on behalf of NIST. He began by proposing an improvement to the definition of unit, corresponding to a shortening/removal of the last sentence(s) in the current version of the 9th SI Brochure: “The value of a quantity is generally expressed as the product of a number and a unit. The unit is a particular example of the quantity concerned, which is used as a reference.” Dr Tiesinga reminded participants that the SI Brochure is not intended to be a complete dictionary: rigorous, formal definition of terms often require more words and do not fit into concise sentences. He concluded with a few examples of usage highlighting the normal usage of ‘quantity’ and ‘value of a quantity’, often within the same equality. He also considered as an open question whether the SI redefinition had made a difference to these philosophical considerations.

Prof. Ullrich initiated a discussion on the topic. He stated his proposal for reaching consensus: suggesting that there should now be an open scientific discussion where personal views could be aired. The output of this discussion would point to the best way forward for a resolution of the issue.

Thus began a lengthy, and at times fractious, discussion of the topics concerned with the views expressed not indicating any movement towards consensus. Mr Sebellin began by stating his view that the VIM controls definitions and is the forum to establish a coherent position. Prof. Ullrich was concerned that only one member of the JCGM-WG2 (VIM) was formally representing the views of the Metre Convention, adding that the CIPM still needed to come to consensus about the ownership of these issues. Dr Steele agreed that it was a good idea to seek informed opinion, and that this meeting report would serve as a good starting point to gain the views of other institutes. Dr Blattner was concerned not only about the definition of unit but also how we explain the realization of a unit. Dr Stenger replied that realization is simply the materialized reference of the unit, and he was not sure it was relevant to this current discussion. Dr RJC Brown drew participants’ attention back to the paper by L. Mari² *et al* in *Metrologia*. Whilst the paper favoured the description of unit as a quantity it recognized why confusion could occur and gave a very detailed background to the arguments. Dr RJC Brown strongly recommended consideration of the compromise text proposed at the end of the paper for consideration: “The quantity Q of an object a (for example a phenomenon, a body, or a substance), Q_a , is generally expressed as the product of a number $\{Q\}$ and a unit $[Q]$. The unit $[Q]$ is an example of the quantity Q which is used as a reference, and the number $\{Q\}$ is the ratio of the quantity Q_a to the unit $[Q]$ ”. Dr RJC Brown highlighted the concept of ‘quantity of an object’, which would help to bridge the gap between empirical knowledge about quantities of objects and mathematic knowledge about values of quantities, which he proposed was the current source of disagreement and misunderstanding in the CCU.

Dr M. Himbert stated that some issues were language related, in particular ‘value of a quantity’ was never used in French and ‘magnitude’ was also not used often in French in a similar way to its use in English. Magnitude may be expressed as a number and a reference in English but a similar expression

² Luca Mari *et al* 2018 *Metrologia* 55 716

in French is not possible. This makes the communication of concepts between languages particularly difficult. Prof. Ullrich agreed stating that the English and French versions of the VIM were not coherent on this topic and this also remains a problem. Dr Stock felt that the disagreement was more fundamental and related to understanding of quantity. He gave the example that some in the room thought that the speed of light was a quantity whilst others felt this was the value of a quantity. Dr RJC Brown stated that this could depend on the exact context of its usage and expression, referring again to the different cases explained in the paper by L. Mari. Dr T. Quinn thought that such definitions must reflect normal usage as closely as possible. He was in favour of reverting to a description of unit as the value of a quantity, as was Dr Krystek who said that in the past the term ‘quantity’ usually was unconsciously used with the meaning of what we today call ‘quantity value’, which did not exist until it was introduced by the VIM. Dr Quinn added that he had been a member of the VIM committee when the definition for quantity value was introduced and had objected at the time because it went against ordinary usage. Prof. Pendrill felt that if the work of the VIM was being discussed then a VIM representative ought to be present. Dr Krystek added that Julius Wallot, when introducing the ‘quantity calculus’, understood ‘quantity’ in the way ‘quantity value’ is defined in the VIM today. Dr Krystek elucidated that considering the equation $Q = \{Q\}[Q]$ it follows from mathematical logic that if the left-hand side represents a quantity value then the unit is a specific example for a value of a quantity. If, however, and that would be feasible as well, the left-hand part specifies a quantity, then the unit is a specific example of a quantity, but with the historical meaning used by Wallot. If the preference is that ‘unit’ is a ‘quantity’, the term ‘quantity value’ is dispensable and the definition of ‘quantity’ in the VIM must be changed accordingly. Otherwise it must be admitted that ‘unit’ is a ‘quantity value’ and the definition of ‘unit’ in the VIM needs to be changed accordingly. Both would be feasible, but one has to decide one way or the other.

Dr Flater noted that ‘quantity’ has multiple meanings in different contexts and that this was part of the problem. He also believed that in French ‘grandeur’ was selected specifically to allow a similarly ambiguous meaning. Dr E. Prieto Esteban stated a similar issue existed in Spanish. He also stated his opinion that it was not possible to separate number from unit (i.e. 1 Ω , 1 V, etc) because it was a reference property. Dr Stenger suggested a footnote to the text of the SI Brochure explaining that there may be different terminology and interpretations that are language dependent.

Prof. Pendrill stated that the CCU should keep to the meaning of Q, for quantity, in the equation $Q = \{Q\}[Q]$ as used originally by Maxwell. Dr Krystek disagreed that Maxwell used this equation, always quoted as ‘Maxwell’s equation’, but who had never written it. Instead it came from Julius Wallot, the originator of the quantity calculus, and its content was also used by him in a German standard in 1931. He further claimed that the current VIM definition was not in line with the equation in any case. Prof. Pendrill replied that Maxwell wrote very clearly in English what was intended by this equation – writing for instance in the 1873 transactions: ‘If l is the numerical value of a length, it is understood to be expressed in terms of the concrete unit $[L]$, so that the actual length would be fully expressed by $l [L]$ ’ – and this should be what was used. Dr Krystek answered that he knows what Maxwell has written, but that Maxwell never defined the term quantity and thus we cannot not know what he really meant. Drs Krystek and Quinn each felt that the original meaning of ‘quantity’ was number and reference.

Changing the direction of the discussion Prof. Ullrich asked how this current discussion impinged on the fundamental constant approach in the revised SI. Prof. Pendrill pondered whether there was a case for changing our concept of unit based on the revised SI. Dr Milton read from the previous CGPM resolutions where units had been defined, for example, the declaration of the 3rd CGPM (1901) that “The kilogram is the unit of mass; it is equal to the mass of the IPK”; yet the same declaration also stated that “the value adopted in the International Service of Weights and Measures for the standard acceleration due to gravity is $980.665 \text{ cm/s}^{-2}$ ”. He speculated that these examples did not use consistent language, and that the new defining constants could be considered to be either quantities or

values of quantities. Dr Quinn felt the arguments were no different in the revised SI to those that had existed prior to redefinition. Dr Flater stated that NIST had done some work to attempt to produce a definition of unit without using terms with debated meaning. One attempt read: “In the SI, a measurement unit is a product of powers of the defining constants and of numerical constants, which can be realized in practice to serve as a reference for quantities of the same dimension.” Dr Flater added that practical realizability might not be essential to the definition and that “same kind” might be more appropriate than “same dimension”. However this definition still used ‘quantity’ which also seemed to be in dispute. Dr Krystek stated that the result of the product described was obviously a quantity value. Trying to summarize the problem, Dr Flater remarked that in mathematics an equation $A=A$ is acceptable and necessarily true, while in terminology work a definition of analogous form is forbidden since it is circular, but the contested text of the SI Brochure is neither a mathematical equation nor a formal term definition. It is simply a narrative which introduces concepts as much as is necessary for the brochure to do its job. They are not required to be as precise as a terminology standard. Dr Krystek stated that his argument was the same as Dr Flater’s but the conclusion is different. He went on to say that ‘1’ was put in front of the unit in each unit definition equation in the SI Brochure to make it a quantity value, not a quantity. Dr Shirley added that for any given expression, 4.7 kg as an example, some will say this is a quantity and some will say this is the value of a quantity. Dr RJC Brown stated that this depends on the level of abstraction to which the reference is being made. Dr Krystek thought this was similar to angle. In his opinion it was a geometrical figure. However if we then need to talk about its magnitude we need to go into more depth and discuss units, and then the radian is introduced. Returning to the real effects of this debate Dr Flater said that he did not think the wording of unit in the SI Brochure would affect the services delivered by NMIs to customers. Dr Stenger replied that the wording in the SI Brochure was not meant to tell people how to talk in everyday life but it still must be scientifically clear to explain what a unit is. Dr Davis reminded participants that one of the original requirements for the SI Brochure was to help people convert between different units, for instance in the electrical area where this is more challenging. Dr Quinn agreed that the SI Brochure was originally set up to explain how to use the unit definitions, not to explain fundamental physics.

Dr Blattner agreed that there were fundamental differences in the understanding of simple terms, for instance he did not regard ‘2.3 m’ as the multiplication of the two terms. Dr Krystek objected to this stating that it was essential to accept quantity calculus to enable the SI to work – it was introduced originally to resolve difficult problems in electrotechnical work. Dr Krystek went on to say that there is not a one-to-one correspondence between quantities and units (there are more quantities than there are units, for instance speed and rainfall rate both have units m/s) and this was why a unit could never be a quantity. Dr RJC Brown agreed there are more quantities than there are units but did not agree that this led to the conclusion that a unit could never be a quantity.

Dr Karshenboim did not think the arguments would make any further progress until written formulations were discussed. Prof. Pendrill added that while there was the JCGM-WG1 on the GUM producing guidance about uncertainty, there was not a similar committee producing guidance about measurement: the VIM is just a terminology guide. Dr Steele was worried about the danger of producing conflicting documents, arguing that perhaps the SI Brochure was not the place to make a normative pronouncement of this definition and proposing that the wording makes very little difference so long as the context is clear. Dr Steele further noted that the ISO 80000 series of standards was quoted by most regulatory authorities and the VIM was the right place to feed into this process, not the SI Brochure. Dr Krystek observed that ISO TC12 started editing their standards in order to bring across the decisions of the CCU and then these decisions were subsequently reversed.

Returning to the equations in the SI Brochure where the units are defined Prof. Ullrich was worried that there was now an inconsistency because units were defined as ‘1 m’, ‘1 kg’ etc. Dr Steele did not think this caused any harm and asked how this could lead to any confusion. Dr Krystek stated that the

best way to be consistent is to follow the logic of mathematics, and that the SI Brochure should be logically correct. One option could be to delete entirely from the SI Brochure any points of contention. Dr Stenger thought the equations were fit for purpose but better explanatory text to describe them was needed. Dr Newell reminded participants that this was what NIST had tried to do to make the definition of unit understandable and simple, but that it was not a simple task. Dr Steele observed that whilst the VIM and ISO 80000 standards are designed to be entirely self-consistent and clear, we must acknowledge that there are other places where things are not as clear and that this arises from the context dependent usages of these words, for instance in the SI Brochure. Dr Krystek stated that German DIN standards always start from the point of view of what is logically correct and then step back from this to decide what is practical. Dr Shirley thought that this implied the starting point for the definition of unit being a mathematical one. Dr R. Lapuh did not see any problem with the current mathematical approach since he thought this was well understood but noted that the equation used had three symbols, but that the current discussion was about the meaning of four terms (unit, number, quantity, quantity value) and this would make a resolution difficult.

Dr RJC Brown thought there was a fundamental difference between ‘a definition’ and ‘an explanation’, which was not being fully appreciated in the discussion and did not expect that a resolution to these issues would be found overnight. Dr Shirley thought that more research was needed into the literature on these topics. Dr Steele reflected that there had been a big effort to make the SI Brochure much shorter in the 9th Edition and perhaps the community was now realizing that some information needs to be put back in.

Dr Ullrich concluded the discussion with the proposal to set up a CCU working group on this topic to perform more in-depth research and consideration. The working group would produce a proposal in a year’s time which would be circulated to participants in order for them to obtain the official views of their organizations, ready for a further discussion at the next CCU meeting.

8. DISCUSSION ON ANGLES AND DIMENSIONLESS QUANTITIES

Prof. Ullrich introduced the topic, which he described as another ‘leftover’ from the revision of the SI that the CCU had debated before on several occasions, and invited contributions from participants who had prepared presentations on the topic.

Dr Flater began, specifically addressing the unit one. Many measurements must be traceable to the SI in regulations and the presence of the unit one in the SI answered much of this regulatory burden. He proposed that counting involves identification of entities intended to be counted, so as to exclude all others from the count, and the enumeration as a separate concern. He argued that units and standards required for identification and enumeration are not part of the SI. (Although in some cases, such as for the becquerel, a specialized unit explains what is being counted). Dr Flater made the case that a quantity, one ‘something’ is not the same as a mathematical number one and proposed the introduction of extended units to distinguish kinds of quantities that he considered to be outside the scope of the SI. In such a case he proposed that the unit of the count should identify the kind of items being counted. Dr Flater raised the example of the expression of a number of ‘bytes’ where trying to avoid extended units is pointless. Concerning ratios of quantities of the same kind Dr Flater conceded that simplifying these expressions to a number makes things less clear and that preserving the nature of the ratio (for example mg/kg) was preferred and also allowed by the SI brochure. Dr Flater went further, out of concern that mg/kg could simply be read as 10^{-6} , stating that NIST were considering the implications of proposals to use terms such as mg(Si)/kg(sample).

Dr RJC Brown followed with the NPL position on both angle and dimensionless quantities. He stated that there was no single correct way to treat angle, and the previous status of radian and steradian as supplementary units was testament to this. Dr RJC Brown cautioned that when considering such significant changes to the SI, quoting the previous CCU president Prof. I. Mills, who stated that it is pointless to make changes that will simply be ignored. Further, Dr RJC Brown warned that it was dangerous to make compulsory changes that would cause confusion if partially implemented. Dr RJC Brown continued, laying out the range of philosophies that existed within the angle debate from those who consider angle inherently dimensionless to those who considered angle inherently dimensioned. Somewhere in the middle were those who considered angle conventionally dimensioned. Dr RJC Brown thought that the current treatment in the SI sat somewhere between inherently dimensionless and conventionally dimensioned. He explained that the source of the confusion had recently been explained in papers published by the NPL and in particular work by Dr P. Quincey. These had explained that the coherent equation for angle in the SI is not unit-independent in that it requires the use of radian. The most general unit-independent equation (called a ‘complete equation’ in older literature) involves an additional constant representing a specific quantity of angle. This unit-independent equation gives no implicit indication of the dimension of angle – this is conferred by our choice of units. Dr RJC Brown proposed therefore that the status of angle in the SI is probably best described as conventionally dimensionless, where this additional constant is set equal to 1. In light of this Dr RJC Brown then reviewed the options for the treatments of angle within the SI concluding that the current treatment within the SI, as conventionally dimensionless, was the most pragmatic solution. Either doing away with radian entirely, or giving angle its own dimension would be too confusing and require too much upheaval to the current equations used. However Dr RJC Brown did suggest that there were a number of implementations that were consistent with the approach in the current SI, ranging from maintaining the *status quo* to reintroducing supplementary units. The NPL preferred a middle ground, which would involve editing the text of the SI Brochure to provide clarity on the status of angle. This should highlight the importance of a clear description of the quantity being measured, which is essential for the understanding of quantities to be interpreted by humans, the explicit use of the unit radian when appropriate to avoid confusion, and local implementation of the complete equation approach to solve the problems in software and other problematic applications. Turning his attention to dimensionless quantities (or quantities with the dimension number) Dr RJC Brown was again clear that the solution must be based on a clear description of the quantity being measured and the use of explicit units where possible (such as mol/mol etc). He was against the invention in the SI of new special names for ‘counting units’ as this mixed the description of units and quantities. Such an approach would need clear rules for usage and the precise definitions of names for units and when they could be used. This would be unlike any other current area of the SI. It would also invite other bad practices that mixed quantities and units. Dr RJC Brown was clear that counts are traceable to the SI – their method-defined nature does not prevent this as stated in the recent CCQM report on method-defined measurands. He agreed with NIST that ‘counting units’ are likely to appear in local implementation, downstream of the SI, and he stated that this was the correct place for their consideration, not in the SI. Dr RJC Brown concluded by explaining that the use of units such as mg/kg, mL/L and mol/mol is encouraged and widely accepted in chemistry and so units that mixed quantities and units such as kg(O) and kg(N) should be strongly resisted. By analogy he said that no one would consider using m(l), m(w), m(h), m(r), m(λ) to distinguish length, width, height, radius and wavelength.

The next presentation was from Prof. H. Holden, Secretary General of the International Mathematical Union (IMU). Prof. Holden introduced the IMU stating that it would celebrate its centenary in 2020 and was responsible for awarding the Fields Medal every four years at the International Congress of Mathematicians. He continued that in mathematics angle is simply defined as the ratio of arc length to radius. This definition makes the magnitude of an angle dimensionless, a pure number. However Prof. Holden conceded that the statement ‘this angle is 0.45’ is ambiguous and the way around this

was to introduce the concept of radians or degrees. This, he said, was a social problem, not a scientific problem.

Dr Stenger presented next on behalf of the PTB. Starting with angle, Dr Stenger was of the opinion that the definition of plane angle is the quotient of two lengths and is therefore a pure number and so the radian cannot be a base unit. Dr Stenger then considered the case where a plane angle was considered independently from a ratio between arc length and radius. He theorized that the construction of a plane angle and the definition of the unit of a plane angle are two different things. The unit radian can be used to describe measurement results of any plane angle. The same argument held for the unit steradian in his opinion. Dr Stenger went further to suggest that the unit radian should not be an SI unit as it is an alias for the number 1. Turning his attention to Hz he stated that confusion was generated in the English version of the 8th SI Brochure, which said: “The SI unit of frequency is given as the hertz, implying the unit cycles per second”. This led to the statement that $\text{Hz} = 1/\text{s} = \text{cycle}/\text{s} = 2\pi \text{ rad}/\text{s}$, and thus $2\pi \text{ rad} = 1$. This potential error is now explained in the 9th SI Brochure. Dr Stenger noted that the French version, “*On appelle l’unité SI de fréquence hertz (un cycle par seconde)*” does not say that cycle is a unit. It just indicates that periodic phenomenon are being considered. Dr Stenger concluded that ‘cycle’ is not a unit, and definitely not an SI unit.

The final presentation on the topic was by Dr P. Mohr, who could not attend the CCU in person, but had provided a pre-recorded presentation. He reported that the consensus of a NIST committee on the topic was that angle should be considered as having an independent dimension and that its base unit should be the radian. It was proposed that the benefit of this treatment is that it would provide a basis for a consistent treatment of angle and phase that avoids the 2π ambiguity. It would also expose hidden dependencies on angles in units for physical quantities and constants. Dr Mohr then compared the radian with the cycle and proceeded to describe a number of other examples where he proposed that the use of radian as a base unit, and its distinction from cycle, would have benefits: circular rotation, periodic functions and the frequency of periodic functions. Dr Mohr then explained how this proposal would deal with trigonometric functions – the quantity in the SI would need to be divided by radians to obtain a pure number suitable for use with trigonometry. In conclusion, Dr Mohr’s recommendations were to change the SI designation of the unit radian for plane angles and phases from being a derived dimensionless unit to being an independent unit (formerly a base unit); recognize cycle as a unit of angle or repeating segment of a periodic function; encourage use of complete units for periodic phenomena, such as Hz, rad/s, rather than 1/s; discourage using names of quantities to imply particular units, and do not allow Hz to be replaced by 1/s.

Starting the discussion Dr Karshenboim stated that care was needed as quantities could imply references other than unit. In this case units are not enough, and additional information needed to be added to the quantity being described. He gave the example of the mole – it was necessary to specify what chemical entities were being referred to. Furthermore, when we have a count, we must define what is being counted. Dr RJC Brown accepted the specific examples Dr Karshenboim used but said that this was a general principle of the expression of results to specify precisely the quantity being expressed and was not specific to chemical measurement. For example ‘the width of the dining room table’. Dr Karshenboim added that it was convenient to use the unit radian so that it could be used with prefixes, such as μrad etc. Dr Krystek asked why we required this special case for angle as opposed to any other dimensionless quantity, for instance refractive index using $(\text{m}/\text{s})/(\text{m}/\text{s})$. Addressing the issue at the heart of the possible confusion about angle Dr Newell mischievously asked how many participants believed that $2\pi=1$? Dr Stock countered that this confusion came purely from a misunderstanding about the correct equations to use for given quantities. Dr Wood replied that this issue had been discussed for years and that most participants must recognize that there was a problem that needed solving. Dr RJC Brown answered that even if angle was implemented as a base quantity, which he did not believe to be the right course of action, it would be impossible to

implement. He stated that most of the issues were found in software, where human interpretation was not possible, and the complete equation approach described earlier was a way to solve this.

Dr Steele was concerned that if angle remained dimensionless it was more challenging for people to convert between unit systems. He thought that the proposed additional statement in 2.2 of the SI Brochure that “the plane right angle is $\pi/2$ rad” would help with this. Dr Krystek did not think the conversion factor argument was valid, mentioning that many other similar units were dimensionless but did not need conversion factors. He further proposed that the definition of π was the ratio of circle’s circumference to its diameter and this did not have anything explicitly to do with angle. Dr Flater thought the problem was more general, stating that if any quantity was canonized within the SI as having no dimension then it was by definition just a number and it needed downstream references to standard methods in order to deal with it. Dr Newell agreed and felt that software needed to know the quantities it was dealing with. As a result Dr Shirley proposed more specification of units in expressions. Dr RJC Brown disagreed stating that it was quantities that were specific and units that were general – this was why there were more quantities than there are units. Dr RJC Brown again proposed the complete equation approach to deal with the software problems that Dr Newell had mentioned. Dr Blattner agreed with Dr RJC Brown, adding that the introduction of the radian as a base unit would have unwelcome effects for photometric quantities, because of the effect of the dimensions of the steradian.

Dr Flater proposed that a change to Section 5 of the SI brochure to allow more flexibility in the use of unit symbols and names would provide a solution. Dr Blattner stated that this was the job of the ISO 80000 series of standards, not the SI brochure, and that the answers still lay in a better description of the quantity being described. Dr Karshenboim did not think that there were significant problems. He considered that the answer was to provide a full description of the quantity being expressed, and also reminded participants that the explicit usage of the radian was recommended when there was a danger of ambiguity. He gave an example, to counter the ‘ $2\pi=1$ ’ statement, that if he wished to measure frequency in half cycles per second this did not mean that ‘ $2=1$ ’. Dr Krystek added that ISO 80000 clearly states that frequency and angular frequency are different quantities, and because in Dr Mohr’s presentation these are treated as the same thing, the contradiction arises. He added that how an event changes in time and how an angle changes in time are different things. Dr Krystek reminded participants that the IEC had done much work to get the CGPM to accept the unit Hz in the 1930s and there was a good reason for this. Dr Stenger added that he did not think the proposal to make radian a base unit would bring any benefits. He agreed that there was a need to solve the angle problem, but that this solution would cause more problems.

Dr Karshenboim asked whether a base unit was also required for steradian. Dr Flater said that the short answer was that they should be treated as angle squared. Returning to Dr RJC Brown’s earlier suggestion of revisiting the concept of supplementary units, Dr Steele asked what had motivated that move away from supplementary units in the first place. Dr Milton, reading from the Resolution 8 of the 20th CGPM (1995), recalled that “the status of the supplementary units in relation to the base units and the derived units gave rise to debate, and that the CIPM, in 1980, having observed that the ambiguous status of the supplementary units compromises the internal coherence of the SI, has in its Recommendation 1 (CI-1980) interpreted the supplementary units, in the SI, as dimensionless derived units.” Dr Davis remarked wryly that supplementary units were added in the first place because no one could decide on their status, rather like now. He added that a paper of Jan de Boer from 1979 discusses that one could have decided to introduce the radian as a base unit by defining the right angle as $\pi/2$ radian but it was decided it was not worth the effort.

Returning to dimensionless quantities in general, Mr Massa stated that he was conformable with using the unit nm/m to express a fractional uncertainty. Dr RJC Brown agreed, adding that he saw such units widely and usefully used in all area of metrology without any confusion.

Bringing to a close what had been another lengthy discussion with little consensus detectable in the views expressed, Prof. Ullrich proposed a way forward. He suggested that participants should discuss these matters within their organizations and return with an official view ready for the next CCU meeting. Prof. Ullrich stated that he would like to know why the views were arrived at and by what mechanism. Returning to the discussion on unit he stated that the approach here would be slightly different. The new CCU WG would provide some recommendations by September 2020, which organizations would then study and then come up with an official organizational view in time for the next CCU meeting. Prof. Ullrich closed day one of the meeting.

9. DISCUSSION ON THE SI IN THE DIGITAL WORLD

Opening the second day of the CCU meeting Prof. Ullrich thanked participants for the previous day's discussions and introduced the first topic of the day on the SI in the digital world.

Dr S. Eichstädt was the first to present on the topic. He began by emphasizing the importance of machine-interpretable, unambiguous digital representation of metrological information and factual data. Dr Eichstädt then noted that many of the mandatory requirements and guidance in the SI Brochure are for writing units symbols and names and for written documents, and hence do not necessarily translate to the digital world. Referring to some of the papers in the peer-reviewed literature on this topic Dr Eichstädt remarked that these often proposed fundamental changes to the SI but that these overlooked the important fact that there is no need to change the human-readable parts in order to achieve unambiguous machine-readability in digital data formats. He showed that human-readable digital content is generated by translating machine-readable information and data, and gave the examples of XML-based Microsoft Word documents and HTML-based websites. Dr Eichstädt then outlined the basic structure for digital, machine-readable units being developed under the EMPIR SmartCom project and concluded with examples where this format could be used: digital certificates (calibration, conformity assessment, etc.) based on XML format, standards based on XML format (ISO, IEC has already started on this), metadata in research data management, communication in the internet of things, and scientific publications based on XML format.

Dr RJC Brown presented on behalf of the NPL, proposing that the SI was a result of cultural, political and historical compromises and so had developed into a practical system used by humans who are able to interpret context. Dr RJC Brown said that the corollary was that the SI is not systematic, unambiguous or rigorous, and that these qualities are needed by computer science for easy parsing and interpretation. He then identified a number of areas where issues arose, classified as informatics levels for units of measurement. These were, from the most detailed to the most generic, issues of: usability (characters for units, prefixes, operators), utility (rules for unit and quantity expressions and precedence), definition (systems of quantities and operations on units and quantities) and semantics (metrology concepts). Dr RJC Brown highlighted that the ownership for these issues lay across various communities, such as the SI Brochure, VIM, IUPAC, IUPAP and ISO. However he noted that local implementation of topic-specific ontologies reached across all these areas. Dr RJC Brown proposed that the SI is currently a stable, well known and well used system and that there was a balance between stability and utility to be struck. He said that large changes to the SI to accommodate digitization would not be accepted and so these issues should be resolved by externally agreed conventions and local implementation (for instance the use of complete equations in software was mentioned again) and working with user communities to agree on a clear implementation. Dr RJC Brown concluded by recording some of the activities that the NPL were currently undertaking in this area such as the EMPIR SmartCom project, the Euramet Metrology Network on mathematics and statistics, and Euramet interdisciplinary metrology projects on digital calibration certificates and the

European open science cloud. Future work included the characterization of the uncertainty contribution arising from numerical computation, uncertainty quantification for new measurement modalities, and the reduction in confusion through replacement of *ad hoc* units and other references by machine-readable knowledge representation.

Dr Flater then presented on behalf of NIST. He began by noting that the scope of the topic was very broad from, at one end, parsing the SI to, at the other end, using artificial intelligence to draw conclusions about measurement results. He also stated that the technology industry was not willing to wait for standards bodies to come to conclusions on these topics – the field was moving too quickly and they were inventing solutions themselves. Dr Flater said that many different unit ontologies already existed and that these dealt with issues such as the radian problem in different ways. Mistakes involving unit one can be noticed and corrected by humans, but with artificial intelligence this is much more of a challenge. He proposed that the opportunity for the CCU is to provide upstream guidance on these topics for an audience comprising well trained humans and poorly trained robots. Dr Flater felt that there was risk in leaving known problems to be resolved downstream: a machine-interpretable, would-be standard that was claimed to fix all problems could overshadow the SI Brochure. Dr Flater concluded by warning the CCU not to try and ‘pick a winner’ among representation formats and languages, as the rate of obsolescence ensures that conversion will be inevitable. Prof. Ullrich said that nonetheless this was something that the Metre Convention needed to contribute to as the community was already behind in its thinking about this. He also noted that the topic would be discussed at the CIPM next week.

Prof. Pendrill finished the set of presentations by summarizing the approach of standardization to this topic, especially in the health area. ISO/TC 12 and ISO/TC 215 on health informatics had agreed to exchange documents, including new work item proposals and working drafts. The benefits expected from the use of this agreement on liaison include: increasing transparency of work on-going in ISO/TC 215 to ISO/TC12 members, and their possibility to influence the content of ISO/TC 215 standards; avoidance of duplication of work and structures, thus allowing expertise to be focused and used in an efficient way to the benefit of international standardization; and increasing the speed of elaboration, availability and maintenance of standards through a need to establish consensus only once. It was also noted that this work involved the Unified Code for Units of Measure (UCUM) units of measurement ontology as one of the main ontologies used in this area. A joint task force (ISO/TC 215/TF 1) quantities & units in health informatics had been set up to study existing standards on quantities and units used in e-health, identify potential market needs, perform a gap analysis and, depending on the findings, identify any need for further standards development work. This was to include identification and gap analysis on ‘normative’, ‘normative equivalent’ and ‘informative’ unit and quantity representations. Prof. Pendrill highlighted that this demonstrated the importance of balancing representations of units of measurement for print and representations for semantic interoperability. The need to set up safeguards to minimize the duplication of notation in standards on quantities and units was noted. Prof. Pendrill concluded by explaining that one of the issues with units of measurement ontologies was the requirement for their ongoing maintenance, and he wondered whether this was a task the CCU could take on.

Initiating the forthcoming discussion, Prof. Ullrich asked the question whether this was a topic the CCU should care about; if it was, should the CCU provide authoritative documents; and if so, how should this be handled. Dr Karshenboim replied that it was important for the CCU to take part, but not take responsibility. He stated that the SI was a compromise but that application to real life was a greater compromise. He gave the example that formally the units ‘gray’ and ‘gigayear’, both with unit symbol ‘Gy’ would need distinguishing, but that in practice these terms are never confused because they never appear together in a similar context. Dr Shirley felt that openness and transparency was needed when considering the SI in the digital world, so that the decisions were made collectively. He added that we should not underestimate the importance of unbroken chains of

traceability including in the digital world. Dr Steele agreed that openness and transparency is key and reviewing what had already been done in these areas was also important. He added that chain of custody and traceability was also very important and the CCU community must continue to highlight this. Dr Milton observed that in UCUM a large number of units are considered – did the CCU community wish to engage with such a large set? Dr Eichstädt thought that the focus should be on the SI since there was already an authoritative document, the SI Brochure, to work from. This would be open to further extension for other communities if appropriate. Dr Prieto Esteban was concerned that the SI should always be correctly represented in the outputs of such representations. Dr Steele mentioned that the presentation by Prof. Pendrill had shown the work already being done internationally and that CODATA had hosted large conferences on the subject of data and its interoperability. He proposed the CCU should find out more about what these groups are doing and how the CCU could contribute. Dr Fujii agreed, stating that CODATA already had a committee for the coding of units and handling big data and it seemed sensible to interact with that group. Dr Eichstädt again mentioned Section 5 of the SI Brochure and whether there should be an equivalent section for the digital world. He went on to say that ISO and IEC were a good resource of measurement units and ontologies. Mr Sebellin mentioned the IEC Electropedia, which had its own online interface for downloading units and definitions on a machine to machine basis. He also mentioned that IEC planned to deliver machine readable digitized standards in the future. Dr Blattner remarked that it was important to identify the strengths and expertise of our community since this will guide how we can contribute and where we can add value. Dr Steele agreed and added that the SI brand was very strong and defined our value proposition in this area. Dr Milton mentioned a recent session at the International Metrology Congress (CIM, Paris) at which work being carried out by the NCSLI on digital scopes of accreditation were discussed. He proposed that this could be a future model for a KCDB 3.0. Dr F. Arias added that over the last 20 years the BIPM Time Department has produced machine readable files with traceable data for users. Prof. Ullrich concluded the discussion by stating that he would take the summary of these discussions to the forthcoming CIPM meeting and would ask the CIPM to help shape and decide the core tasks of the metrology community in this area in future.

10. FURTHER DISCUSSION ON THE DEFINITION OF THE TERM ‘UNIT’

Returning to the unit topic Prof. Ullrich presented his considered proposal for a way forward. The proposed name of the group would be the CCU WG on units. Prof. Ullrich presented the draft terms of reference and proposed that the definitions should take into account the requirement to reach consensus at the CCU, the need for translation into other languages and also the desire for machine readability as previously discussed. In particular Prof. Ullrich asked for a proposal for the terms “unit”, “quantity” and “value of quantity” to be addressed. Prof. Ullrich stated that the group should report on the terms “unit”, “quantity” and “value of quantity” by September 2020 in order to give time for participants to discuss the proposals within their organizations and bring back an official position to the next CCU meeting. Dr Steele wondered whether the terms of reference should be expanded to include achieving more general consensus at the JCGM-WG2 on the VIM. Prof. Ullrich replied that this may be covered by CIPM discussions next week on core metrology terms more generally, but this would not be known until after the CIPM meeting. Prof. Ullrich specified that perhaps this could include an expansion of the terms of reference to include terms which specifically enter into national legislation, including the requirement to achieve consensus with the OIML, and then to ensure proper representation of these findings at JCGM-WG2 (VIM). This extended working group would then be called the CCU Working Group on Core Metrological Terms (CCU-WG-CMT).

The draft terms of reference for this group would be to³:

- Identify core metrological terms that enter into CGPM Resolutions and national legislation and which are therefore in the interest of Member States;
- Establish definitions for these core metrological terms in close collaboration with OIML and other non-governmental organizational stakeholders;
- Ensure proper representation in the JCGM WG2 (VIM).

Dr Stenger thought that including other important terms such as ‘magnitude’ and ‘reference’ in this discussion was important. Dr Flater was of the opinion that when the work was started the terms that needed clarification would identify themselves. Dr Milton commented that an important requirement for information transfer from the CIPM to JCGM-WG2 (VIM) had been identified but that this communication should be two-way.

As Prof. P. Neyezhnikov was the CIPM member in liaison with the JCGM he was suggested as the chair of the CCU-WG-CMT, with membership coming from NSC IM (chair), NRC, NMIJ, NPL, NIST, INRIM, PTB, CEM, METAS, LNE, Rosstandart and M. Himbert (as a personal member). Dr Milton added that the scope of JCGM-WG2 (VIM) goes well beyond core metrological terms and asked whether the CCU-WG-CMT should also engage with the wider agenda – for instance nominal properties. Prof. Ullrich replied that a widening of the scope to mirror all activities of the JCGM WG2 (VIM) should be discussed at the CIPM. Responding to comments from Dr RJC Brown and Dr Karshenboim on the difference between the definition and explanations of terms, Prof. Ullrich felt that this was also an important area for the CCU-WG-CMT to cover. Prof. Ullrich also stated his request that the CCU-WG-CMT should improve the liaison between the BIPM, ISO TC 12, IEC TC 25 and IUPAP C2 in order to enable more coherent revision of standards in future.

11. DISCUSSION ON THE POSSIBLE EXTENSION OF THE AVAILABLE RANGE OF SI PREFIXES

Dr RJC Brown gave a presentation on the possible extension to the range of available SI prefixes. He began by highlighting the current range of SI prefixes and explaining their utility as a mechanism to express results using ‘human scale’ numbers, allowing clear communication across scientific disciplines and discouraging the use of local units. Dr RJC Brown highlighted the drivers for expanding the range of SI prefixes. Alongside the ever-present desire to provide prefixes for communities not served by the current range (for example astronomy, particle physics) are the requirement to respond to advances in science and technology in covering measurements over an increased range of orders of magnitude, and also the related desire to prevent unofficial terms becoming *de facto* adopted. Dr RJC Brown stated that finally two drivers are currently found in the information technology area, and in particular for the expression of data storage using (the non-SI units) bits, bytes and octets. With the size of the global datasphere increasing exponentially and the advent of quantum computing, this community will need to cover orders of magnitude in excess of yottabytes in the near future. Dr RJC Brown also noted that this community far preferred the use of decimal prefixes to the IEC binary prefixes originally intended for this use. A number of terms in the popular literature which were gaining support and momentum were noted: brontobyte, geopbyte and hellabyte in particular.

³ At the CIPM meeting the following week the creation of the WG CMT was approved with the scope and membership as proposed during the CCU meeting (decision CIPM/108-25).

Having surveyed the letters and symbols currently in use Dr RJC Brown had concluded that the only letters remaining for use were 'r', 'q' and possibly 'b'. Taking into account previous conventions for producing prefix names (based on Latin and Greek numbers representing the power to which 1000 was raised) Dr RJC Brown proposed ronna (R) and quecca (Q) for 10^{27} and 10^{30} , respectively, and, because it would be unbalanced not to also extend the range in the sub-multiple direction, ronto (r) and quecto (q) for 10^{-27} and 10^{-30} , respectively. (If b was thought to be available for use then bundecca (B) and bundecto (b) for 10^{33} and 10^{-33} , respectively, could also be proposed). Dr RJC Brown went onto to suggest that if a much larger extension to the range of SI prefixes was required then this would need the reintroduction of double, or compound, prefixes and proposals for how these would work were also made. This involved combining yotta and yocto with the existing range of SI multiple and sub-multiple prefixes, respectively, i.e. kiloyotta, megayotta, and milliyocto, microyocto, etc.

Dr RJC Brown concluded by highlighting that introducing new prefixes to the SI represented an addition to the SI whose use was optional and as such was a very low risk action with respect to implementation. He contrasted this with the proposal to introduce angle as a base quantity, which had been discussed earlier in the meeting. This, he proposed, was a change to the SI whose use would be compulsory and therefore was a much higher risk action with respect to implementation.

Dr Karshenboim opened the discussion by questioning whether SI prefixes were actually used widely outside the metrology community, as opposed to the use of scientific notation, raising the area of cosmology where prefixes were not used. Dr RJC Brown replied that in all areas he was aware of SI prefixes were widely used in place of scientific notation. He went on to explain that the reason cosmology did not use SI prefixes is because the current range did not extend to cover the orders of magnitude dealt with by cosmology, and indeed this would be a further benefit of his proposal. Dr Blattner was very supportive of the proposals stating that if the CCU did not act then unofficial proposals will likely be adopted. He also added that he preferred an initial small extension to the range followed at a later date by the use of double prefixes if that were to become needed. Dr Steele also supported the need to take action on this issue now stating that some unofficial names were already being used. He was of the opinion that an initial small change subsequently followed by an introduction of double prefixes would be hard to implement. Dr Steele proposed minimizing the number of changes required to the system and therefore the use of double prefixes should be investigated. Dr RJC Brown replied that one of the reasons double prefixes were banned when the SI was formalized was because there were no rules for their usage. The present proposal has simple and clear rules to govern usage.

Dr Stenger was not in favour of an expansion to the range of SI prefixes. He was of the opinion that many users were not fully aware of, nor did fully use, the current range and increasing the range risked errors being made. Dr Stenger wanted instead users to use scientific nomenclature for higher orders of magnitude. Dr Sebellin felt that this was not possible for 'bytes' as these could not be easily expressed with scientific notation. Prof. Ullrich noted that sometimes the SI prefixes are used to label new subject areas and promote new fields, for example nanotechnology, femtosecond lasers, etc. Dr Krystek felt that the current number system allowed for easier communication of large numbers using scientific notation and whilst an expansion to the system of prefixes did no harm, as Dr RJC Brown had suggested, it also did not help. Dr RJC Brown disagreed with this stating that communities did not use scientific nomenclature when prefixes were unavailable, they instead invented their own local, non-SI units – citing again the example of cosmology. Dr RJC Brown went on to argue that a preference for scientific notation was not a valid argument against the introduction of revised SI prefixes, adding that the whole benefit of the proposal was that it was a neutral, optional addition to the SI. He continued that if, as Dr Stenger and Dr Krystek suggested, people would prefer to use scientific notation then that option remained available to them, as it always had and always would. For those that needed the new prefixes they would be useful and become well known, and

would guard against the adoption of unofficial names. For those that did not need or use them no harm would be done. Referring to other written comments to the CCU, Dr Steele recalled that whilst the coherence gained by using the SI units (without prefixes) was good, the use of SI prefixes was more beneficial in many cases. He noted that this was the reason that the SI prefixes were introduced in the first place. Dr Tiesinga stated that he preferred the use of new prefixes, which also sounded better when spoken, than the use of scientific nomenclature, adding that it also helped non-experts to understand new areas.

Dr Milton also expressed concern that if the CCU did not act then unofficial prefixes would be adopted. He asked Dr RJC Brown whether he thought any of the current unofficial proposals had any merit and could be adopted. Dr RJC Brown said that they all used symbols already in use for other units or prefixes and so could not easily be accepted. The only exception was brontobyte, if the CCU thought 'b' was available for use. Dr Milton felt that given the main current driver was the expression of 'byte' then 'b' should not be considered. Dr Wood felt that however far the prefix range was expanded, at some point when the range ran out scientific notation would have to be used. Dr Krystek was of the opinion that no one would understand two letter prefixes if double prefixes were to be used. Dr Ullrich disagreed stating that if they were to be adopted then they would become well used and well known. Dr RJC Brown felt that the use of 'r' and 'q' to provide an extra six order of magnitudes would suffice for information technology purposes for more than 20 years.

Mr Massa was not in favour of any extension to the range of SI prefixes stating that the current range sufficed for modern science. Dr Blattner countered that it would be harmful if other non-official committees started inventing prefixes. He felt the CCU should provide them with a clear way forward by adopting new prefixes. Dr Milton was of the opinion, given the recent discussion on the digitization of the SI, that double prefixes could be difficult to deal with, but if these double prefixes were made from the existing SI prefixes symbols then these problems would be limited. Dr Milton gave the example that he thought 'megamega (MM)' and 'gigagiga (GG)' would be easy to accept (similar to the previous, now obsolete, usage of 'micromicro'). Dr RJC Brown replied that the problem with such an approach was that one could end up with two terms for the same multiplier, i.e. megamega = tera = 10^{12} , gigagiga = exa = 10^{18} , which would cause confusion. Dr RJC Brown stated that his proposed rules for the use of double prefixes solved this issue, were simple and would quickly become well known, i.e. take the largest or smallest current prefix and combine this with the other existing prefixes, i.e. kiloyotta, megayotta, gigayotta, and milliyocto, microyocto, nanoyocto etc. Dr Steele stated that whilst the papers produced by Dr RJC Brown on the topic had expressed the arguments very clearly he felt a way forward would be to produce a more discursive position paper from the CCU to the CIPM with some more in-depth thinking. Such a paper would highlight the benefits and drawbacks of each approach and also what the risks and opportunities were to expanding the range of SI prefixes. It was agreed that Dr RJC Brown would provide a report on this discussion to Prof. Ullrich to present at next week's CIPM meeting in order to seek CIPM endorsement for a CCU position paper to be produced, which would identify a favoured course of action.

12. CCU STRATEGY FOR THE NEXT 10 YEARS

Prof. Ullrich presented the current CCU strategy document and invited comments on its content.

Dr Dimarcq thought it was necessary to add the need to establish the link between the SI second and other units, especially to evaluate a possible impact due to any future redefinition. Dr Prieto Esteban mentioned in the phrase "that use of the unit s^{-1} to express counts", 'counts' should be replaced by

‘counting rate’. Prof. Pendrill asked whether the strategy should mention nominal properties. Prof. Ullrich replied that this should be considered by the CCU-WG-CMT.

With the proposal to find a consensus on angle and dimensionless quantities finalized earlier in the meeting, it was agreed that the CCU Working Group on Angles and Dimensionless Quantities in the SI (CCU-WGADQ) would be closed – members of the group were thanked for their efforts. Dr Steele suggested that it was now important that the President of the CCTF should be a member of the CCU WG on Strategy. Prof. Ullrich mentioned that previously Dr Arias had been the CCTF representative on the group. Dr Milton thought that a good option would be to include Dr P. Tavella, the CCTF Executive Secretary on the CCU WG on Strategy and there was general agreement that this was a good way forward.

Following this discussion, the CCU Strategy Document was approved, and the Terms of Reference of the CCU WG on Strategy were also approved.

13. ANY OTHER BUSINESS

Under any other business Prof. Ullrich brought forward the request for membership of the CCU from INRIM and the request for ongoing observer status at the CCU from NSC IM.

Mr Massa presented the request from INRIM (Italy), highlighting INRIM’s activities within the Metre Convention and the CIPM MRA. He also reviewed the scientific work undertaken at the organization, emphasizing activities relating to the recent revision of the SI, and concluding with INRIM’s recent peer-reviewed publication record. The case was unanimously approved by participants and Prof. Ullrich stated that he would make the recommendation for membership to the CIPM.

Prof. Neyezhnikov presented the request from NSC IM (Ukraine) highlighting the history of the institute, its current organizational structure and areas of scientific work, its participation in the CIPM MRA, and concluding with a review of key publications produced by NSC IM. The case was unanimously approved by participants and Prof. Ullrich stated that he would make the recommendation for ongoing observer status to the CIPM.

Prof. Ullrich then asked, with reference to the earlier presentation of Prof. Holden, whether it would be beneficial for the International Mathematical Union to be a liaison organization to the CCU. Drs Krystek, Shirley and Prieto Esteban supported the proposal, with Dr Shirley asking whether this would be a two-directional liaison. Dr Milton said that this was the preferred mode of liaison and gave the recent example of the liaison being worked up with IUPAC which was two-directional. Dr Milton cautioned that the IUPAC collaboration was already very well established, and it would be necessary to determine what IMU committees it would be relevant for BIPM to contribute to, and also to inform the IMU of the requirements for liaison status. Prof. Ullrich stated that he would report these discussions to the CIPM, but in any event would like to invite the IMU back to contribute to the next CCU meeting.

Dr Stock stated that he would write to all participants and check whether it would be possible to make their working documents and presentation files open access.

14. DATE OF THE NEXT CCU MEETING

Prof. Ullrich proposed that the next CCU meeting would be in September 2021, with the next meeting of the CCU WG on Strategy in February 2021.

Prof. Ullrich thanked participants for their input to the meeting and hoped they would be staying after lunch for the special half-day devoted to the second, but in any event wished them safe travel home. Prof. Ullrich also thanked the staff of BIPM for their organizational and logistical assistance prior to and during the meeting.

In the absence of further business Prof. Ullrich closed the meeting at 12.55 pm.

Dr R. J. C. Brown
Rapporteur, 14 October 2019

15. ACTIONS AND DECISIONS FROM THE 24TH MEETING OF THE CCU 2019

4.1 *Actions*

- A1. Improve liaison between ISO TC 12, IEC TC 25, IUPAP C2 and the CIPM and its CCs for future revision of relevant standards for units. (CCU WG on units, to make a proposal)
- A2. Add a question on implementation of revised SI within national legal metrological framework to the questionnaire for stakeholders. (M. Stock)
- A3. Discuss questionnaire for stakeholders at the CIPM meeting (about coordination with OIML about question on legal implementation, and part C for academic organizations) and at NMI Directors meeting next week (send to which NMIs) (J. Ullrich, M. Milton)
- A4. CCU WG on units to make a proposal to CCU on the definition of “unit”, “quantity”, “value of quantity” by end September 2020, possible extension of scope to be discussed by CIPM next week (15-16 October 2020).
- A5. NMI members and liaison organizations to bring official opinion on definition of “unit” and units for angles and dimensionless quantities to next CCU meeting (2021).
- A6. RJC Brown to prepare summary on prefix discussion for J. Ullrich, who will present topic to CIPM next week (15-16 October 2020).
- A7. Proposal of INRIM as new CCU member to CIPM. (J. Ullrich)
- A8. Proposal of NSC IM as new CCU ongoing observer to CIPM. (J. Ullrich)
- A9. Proposal of liaison with IMU. (J. Ullrich)
- A10. Invite IMU for next CCU meeting. (J. Ullrich)
- A11. Check with all attendees on open publication of working documents and presentation files (M. Stock)

4.2 *Decisions*

- D1. CCU Strategy Document approved with some minor changes
- D2. ToR of WG-S approved
- D3. WG on “unit” formed: NSC IM (chair), NRC, NMIJ, NPL, NIST, INRIM, PTB, CEM, METAS, LNE, Rosstandart, M. Himbert
- D4. WG on angles and dimensionless quantities closed
- D5. Next meeting of CCU: September 2021
- D6: Next meeting of CCU WG-S: February 2021