Bureau International des Poids et Mesures

Consultative Committee for Units (CCU)

Report of the 22nd meeting
(15-16 June 2016)
to the International Committee for Weights and Measures

Comité international des poids et mesures

Note:

Following a decision made by the International Committee for Weights and Measures at its 92nd meeting (October 2003), reports of meetings of Consultative Committees are now published only on the BIPM website and in the form presented here.

Full bilingual printed versions in French and English are no longer published.

M. Milton,
Director BIPM

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR UNITS

as of 15 June 2016

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

Commission internationale de l'éclairage [CIE]

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

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

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]

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

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

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

The twenty-second meeting of the Consultative Committee for Units (CCU) took place at the International Bureau of Weights and Measures (BIPM), Pavillon de Breteuil, Sèvres, from 15 to 16 June 2016.

The following were present: P. Blattner (CIE), R.J.C. Brown (NPL), N. Capitaine (IAU), G. Dudle (OIML), G. Férard (IFCC), K. Fujii (NMIJ/AIST), P. Gérome (IEC), K. Hosaka (NMIJ/AIST), M. Krystek (ISO and IEC), L. Mari (IEC), R. Marquardt (IUPAC), H.G. Menzel (ICRU), M.J.T. Milton (Director of the BIPM), P. Mohr (NIST), D.B. Newell (CODATA), W. Phillips (IUPAP), E. Prieto Esteban (CEM), J. Stenger (PTB), L. Vitushkin (Rosstandart), J. Ullrich (CCU President), C.J. Williams (NIST), B. Wood (CODATA), J. Zhang (NIM).

CIPM members and Consultative Committees Presidents: B. Bowsher (CIPM), Y. Duan (CIPM/CCT President), B. Inglis (CIPM President), L. Érard (CIPM/CCTF President), T. Liew (CIPM), W. Louw (CIPM/CCRI President), W.E. May (CIPM/CCQM President), J. McLaren (CIPM Secretary), P. Richard (CIPM/CCM President), G. Rietveld (CIPM/CCEM President), T. Usuda (CIPM/CCAUV and CCPR President)

Personal members: M. Himbert (LNE-Cnam), T.J. Quinn, CBE FRS.

Honorary member: I.M. Mills, OBE FRS,

Representatives from invited NMIs: I. Yang (KRISS), B. Jeckelmann (METAS), A. Steele (NRC).

Invited guests: H. Bettin (PTB), Ch. Bordé (Académie des Sciences, Paris), R.S. Davis (BIPM), H. Margolis (NPL), L. Pitre (LNE-Cnam), S. Schlamminger (NIST).

Also present from the BIPM: E.F. Arias (CCTF Executive Secretary), E. de Mirandés (Executive Secretary of the CCU) H. Fang (CCM Executive Secretary), J.M. Los Arcos (CCRI Executive Secretary), G. Panfilo (CCAUV Executive Secretary), S. Picard (CCT Executive Secretary and KCDB Coordinator), M. Stock (CCEM Executive Secretary), J. Viallon (CCPR Executive Secretary).

Absent: sent apologies. K. Nield (CIE), S.N. Park (KRISS), A. Thompson (NIST)

1.1 Opening remarks and introduction

Prof J. Ullrich, president of the CCU, opened the meeting at 9 am, welcoming all participants. He noted that there were many attendees among them all but one CC Presidents, as well as the President and the Secretary of the CIPM and that this reflected the importance of the meeting. He also reminded members of the importance of the decisions that the CCU makes, the impact these will have on the revision of the SI and the great responsibility this placed on members to reach decisions and compromises wherever possible.

Prof Ullrich continued by welcoming Prof I. Mills as an Honorary Member of the CCU, appointed by the CIPM in recognition of his contributions to metrology and Metre Convention activities while President of the CCU.

Prof Ullrich then introduced himself to members as the new president of the CCU, and Estefanía de Mirandés as the new executive secretary of the CCU. Following this there was a round table self-introduction of all meeting participants.

1.2 Welcome from the BIPM Director

Dr M. Milton, Director of the BIPM, then welcomed to the BIPM the new president and all participants. He further stated the importance of the meeting and said that the presence of so many CIPM members at the meeting highlighted this. Dr de Mirandés then stated the intention of the BIPM to make all documents and presentations associated with the meeting freely available on the BIPM website following the meeting, with agreement from presenters (with suitable amendments made to presentations if required).

1.3 Homage to passed members and contributors to the CCU

Prof Ullrich led the CCU in remembering the significant contributions of several members and relevant scientists who had sadly died since the last CCU: Leonardo Villena (1917 - 2015), Alain Picard (1953 - 2015), Willem Kool (1953 - 2016), Bryan Kibble (1938 - 2016), Seton Benett (1945 - 2015) and Paul de Bièvre (1933 - 2016). The homage finished with Prof Ullrich leading the CCU in a short silence of remembrance.

1.4 Update from the CGPM and CIPM

Prof Ullrich proceeded to give an update from the CGPM and CIPM. This focussed in particular on the resolutions from the 25th CGPM requesting an awareness campaign about the changes to the SI and a 9th edition of the SI Brochure to accompany the revised SI. The resolutions also encouraged NMIs and the BIPM to continue all scientific work required to allow the CGPM to pass a resolution at its 26th meeting to adopt the revised SI. The current CCM-CCU roadmap includes the requirement for data to be used by the CODATA Task Group on Fundamental Constants in fixing the values of the defining constants to be accepted for publication by 1st July 2017. The CIPM agrees on these terms. Prof Ullrich also noted that the CIPM had approved the proposal made by the CCU president to start an awareness campaign relating to the new SI.

Prof Ullrich then summarised the new procedures for the election of CIPM members, the current membership of the CIPM and the CC Presidents that had been appointed. Prof Ullrich explained that a review of the membership and observership of CCs was being carried out by the CIPM. He further mentioned the decision of the CIPM to invite KRISS, METAS and NRC to the 22nd Meeting of the CCU as guests, with a request to discuss their full membership during the current CCU meeting.

Prof Ullrich concluded his update from the CGPM and CIPM by mentioning the ongoing progress with the review of the CIPM MRA and the CIPM approval of the BIPM work programme.

1.5 Approval of the agenda

The agenda was approved subject to the addition of a presentation of the remaining NPL comments on the SI Brochure by Dr R. J. C. Brown at point 5.7, followed by discussions on all remaining

comments. In addition a more detailed listing of the topics to be covered under Any Other Business, was given.

1.6 Appointment of rapporteur

Prof Ullrich proposed Dr R. J. C. Brown as the rapporteur for the meeting; Dr Brown agreed.

2. PRESIDENT'S REPORT

Prof Ullrich started his President's report by highlighting the updates to the 8th Edition of the SI Brochure that had been recently published as a short printed document as an insert for the 8th SI Brochure. The update was also available electronically. Prof Ullrich then presented the new 'info-graphics' designed for the SI that had been circulated before to all members of the CCU as well as of the CIPM and had been welcomed by the CIPM at its last meeting. It was made clear, however, that these graphics did not represent a 'logo' – this would be produced by the BIPM at a later date and presented to the CCU for comments.

Prof Ullrich went on to mention the CCU strategy, which would be updated under Any Other Business, and the joint CCM and CCU roadmap for the new SI which would be elaborated on further under the brief reports from CC Presidents. Prof Ullrich then reported on the planned timeline for production of the 9th SI Brochure. It was noted that the next CCU meeting in September 2017 should be in a position to approve the final draft of the 9th SI Brochure with the final 9th SI Brochure available by November 2018. Prof Ullrich then explained that the SI Brochure was neither a publication nor a standard. The definitions of the SI units within the SI Brochure, as decided by the CGPM and CIPM, represent the most authoritative references for the SI. It was observed that standardization bodies may specify further details for quantities and units, and rules for their application, where needed by the interested parties. However, whenever SI units are concerned, these standards must refer to the definitions by the CGPM and CIPM.

Prof Ullrich then reported on the awareness campaign for the revised SI. Prof Ullrich highlighted that the SI Promotion Task Group reported directly to the CIPM and had the task of contributing to the development of communication materials and tools prepared by the PR Expert Group. They also had the task of ensuring that materials can be used in different cultural contexts and in different languages, and optimizing the participation of NMIs from different cultural and language backgrounds and different regions. Reporting to the SI Promotion Task Group was the PR Expert Group consisting of experienced PR officers from NMIs whose task was to develop key message and plans with respect to communicating the revised SI. It was noted that the first meeting of the PR Expert Group was in November 2015 with the first official meeting of the Task Group in January 2016. After this there had been an effort to collate information and existing publicity material from all Member States on their approach to promoting the new SI by means of a questionnaire. It was explained that the objectives of the campaign were to explain that continuity of the SI system is preserved for end users and that the changes enabled realisations with ever improving accuracy and would trigger innovative new techniques of realisation. Prof Ullrich stated that the revision of the SI provided an opportunity to promote a shared understanding of the SI and promote its aims and benefits more widely.

Prof Ullrich concluded by highlighting the core products that the group was expected to produce and the principles of engagement for the group. A questionnaire among Member States had demonstrated overwhelming support for the changes to the SI. It was noted that most NMIs did not have their own PR experts and so would be likely to make use of tailored publicity material produced by the Task Group to help explain the changes to stakeholders.

3. BRIEF REPORTS ON ACTIONS TAKEN SINCE THE 21ST MEETING OF THE CCU RELEVANT TO THE ADOPTION OF THE REVISED SI

3.1 Reports from Consultative Committees

3.1.1 CCM

Dr P. Richard presented the main actions of the CCM since the last CCU meeting. In particular he highlighted that the joint CCM and CCU roadmap was being regularly updated. The main actions for the CCM in the last three years had been: periodical review of the situation with the CCM Recommendation G1 (2013), production of a CCM Recommendation to NMIs on managing the consequences of the corrections to the BIPM as-maintained mass unit (2015), re-establishing traceability to IPK (BIPM), updating of the CCM & CCU roadmap, and provisional approval of the *mise en pratique* for the kilogram. Dr Richard also stated that a Metrologia focus issue on the redefinition of the kilogram and the most important methods of realisation, is under preparation. Dr Richard concluded by outlining the next steps for the CCM. The next CCM meeting would be in May 2017 and this would produce a final review of the situation with the CCM Recommendation G1 (2013), approval of the results of the pilot study and provide final approval of the *mise en pratique*.

3.1.2 CCEM

Dr G. Rietveld reported on progress in the CCEM and in particular recognised the contributions of Dr Bryan Kibble to the development of the watt balance. It was noted that electricity was the only area where the new SI would cause a step change, and because of this public education was required. Some progress towards this goal has already been made with a number of publications on the topic. In 2015 the Task Group on the SI and the Working Group on the SI within CCEM had been merged and would liaise closely with the CIPM SI Promotion Task Group. Dr Rietveld closed by posing the question about when the revised SI in the electrical area should start following the CGPM decision. He noted that the CIPM in 2015 October meeting expressed preference for the SI changing “at day of CGPM decision” but would make final decision in October 2016. Present debate in CCEM suggested that several CCEM members showed a preference for having implementation for electricity after short transition period to handle step change, similarly to the 1990 introduction of R_K and K_J. Dr Quinn stated that once the CGPM accepted the new SI then it would be implemented, but in the case of electricity the conventional vales could continue to be used until a later date before switching. Dr Rietveld agreed that this was a possibility.

3.1.3 CCT

Dr Y. Duan reported on activities within the CCT. One of the main activities had been the review and reform of all CCT working groups and task groups in 2014. In addition the first draft of the *mise en pratique* for the kelvin had been produced and was available for comment. A Metrologia focus issue on the Boltzmann constant and the revised definition of the kelvin had been published and it was also highlighted that WG and TG meetings in all areas would take place at the forthcoming TEMPMEKO meeting at the end of June 2016, followed by the next CCT meeting in May 2017. Dr Milton asked how the CCT foresees to provide information to the users of ITS-90 on how the revised definition of the kelvin was going to affect them in practical terms. Dr Yuan replied that this would be covered under agenda item 7 on *mises en pratique*. Dr Milton reiterated the importance of understanding the relationship between ITS-90 and primary realisation.

3.1.4 CCTF

Mr L. Erard reported on progress in the CCTF, and in particular highlighted the open issue of possible future redefinition of the second. This had been brought into sharp focus because of the ability of optical frequency standards to exhibit uncertainties two orders of magnitude lower than primary caesium clocks. A roadmap towards redefinition of the second was highlighted, specifying the levels of accuracy and nature of comparisons required to enable a decision to redefine the second. A tentative date of 2026 was proposed as the earliest for a redefinition. Mr Erard stated that the issue of timescales remained very important. He reported and that there would be a strong future cooperation between ITU-R and BIPM, CIPM, CGPM, as well as other relevant organizations, to consider the various aspects of current and potential future reference time scales, and to provide advice on the content and structure of time signals to be disseminated by radiocommunication systems. Furthermore a task group of the CCTF Working Group on TAI will a) make a review of the present status of timescales, b) elaborate definitions of TAI and UTC, c) propose appropriate recommendations for consideration by the CCTF in June 2017, afterwards by the CIPM, and finally by the CGPM in 2018, and d) propose the definition of the time scale to be adopted as a reference for metrological applications after WRC-23. Prof Ullrich stated that the proposed roadmap for redefinition of the second was a very useful framework to work towards.

3.1.5 CCQM

Dr W. May highlighted the recent work of the CCQM. The CCQM is the most active and heavily attended CC, meeting once every year and with some of its 10 permanent working groups meeting twice a year. It also deals with many of the complex metrology issues, especially in the biological area. Dr May highlighted the roles and responsibilities of the CCQM and in particular highlighted the CCQM *ad hoc* Working Group on the mole whose mission was to draft a *mise en pratique* for the realization of the mole and to create awareness with respect to a possible redefinition of the mole. Dr May stated that the *mise en pratique* had now been drafted and was available on the BIPM website for comment. Dr May reflected that the chemical community had some concerns around the redefinition of the mole, particularly around why the change is required and what effects it will have. In attempting to engage better with the user communities Dr May mentioned a special session on the mole and its redefinition at the ACS (American Chemical Society) meeting in Boston in August 2015. Dr May reported that there had been good discussions at the meeting. He also stated that in recent

months there had been less discussion within the chemical community concerning the redefinition as some of the misunderstandings seem to have been clarified.

3.1.6 CCAUV and CCCPR

Dr T. Usuda reported briefly on progress in both CCs. In CCAUV the agreements and recommendations at the last meeting were noted, namely:

- the bel and neper be kept as non-SI units
- the reference value of the quantity should always be stated in SI units whenever the decibel is used, and
- to encourage the use of the SI in preference to the decibel (while noting that it would be extremely difficult to change long-standing habits relating to the use of the dB).

In the CCPR it had been noted that a change from candela to lumen (as the base unit) has no real practical benefit, in contrary, the geometrical aspects of photometry becomes hidden. In the absence of compelling reasons to change from the candela to the lumen as the base SI unit, it was highly recommended to maintain the status quo. In 2015 the CCPR had finalised the *mise en pratique* for the candela and associate derived units for photometric and radiometric quantities and the document was now on the BIPM website for comment. A joint WG of CCPR and CIE is preparing a more extensive publication "Principles Governing Photometry". In conclusion Dr Usuda stated that there were no special requests or opinions to include description of physiological quantities in the next version of SI Brochure from either CCs. He also noted that new units on non-visual effects of light (relating to the specified human photo-pigment) have been included in a draft CEN standard. This will be monitored and discussed at CCPR. Prof Ullrich remarked that physiological quantities will be of importance in future and the CCU should begin to address these soon.

3.1.7 CCRI

Dr W. Louw reported that the CCRI currently has three sections I, II and III (dealing with x- and γ-rays, radionuclides, and neutron measurements, respectively) which operate in a CC-like way but which in future will operate as Working Groups. Dr Louw also mentioned the large number of CMCs that are attributable to the CCRI. He further remarked that the main units used by the CCRI rely on the kilogram and the second, but that the uncertainties of measured quantities are so large that changes to the SI and the current uncertainties achievable on realisation of the s and kg have very little effect on the work of CCRI. In particular, no changes to the becquerel or sievert were envisaged. Dr Louw stated that an active area of investigation within CCRI was in the field of nano-dosimetry and biologically related quantities. Dr Louw added that the CCRI had no changes to propose to the units used in ionising radiation within the revised SI Brochure.

3.1.8 CCL

Dr E. Prieto reported on behalf of the CCL President who was unable to attend. Since the last CCU meeting the CCL had met in September 2015. It was highlighted that the CCL had expressed to the CCU that they were not entirely happy with the wording of the new definition of the metre because they felt it made the definition harder to understand, but that they understood the reasons behind the proposed wording and would not take the matter any further. Dr Prieto reported that the CCL's

working group on nanometrology has drafted a document 'Realisation of the SI metre using silicon lattice and TEM for dimensional nanometrology'. In future x-ray interferometry may be required to extend the SI metre realisation to pm scales. Dr Prieto also reported on the updates to recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second that are provided by the CCL, which had subsequently been accepted. Dr Prieto concluded by summarising discussions within the CCL (in particular the CCL working group on the MRA and the CCL discussion group on angle metrology) on the proposal to include the radian as an eighth base unit of the SI. The consensus was that the 'problem' of inconsistency within the current SI text is acknowledged but there is no support expressed so far from within CCL members (except for the official paper from NIST) for the proposal to make the radian a base unit of the SI. Solutions which do not require such a serious change in the SI were preferred by the CCL.

3.2 Report from the OIML

Dr G. Dudle provided the report on the OIML, in particular highlighting the technical committee TC 2 Units of Measurement. A brief history of OIML's activities concerning the new SI was given and the 2012 CIML resolution supporting the CGPM's intention to revise the SI was mentioned. Dr Dudle highlighted OIML's concern that 'the new SI remains understandable to all those who need it' and that OIML, as a user of units, was concerned with sound, understandable definitions. Dr Dudle stated that OIML had no specific statement to make about base units or on their number. Concerning the outlook for OIML it was stated that a revision of OIML document D2 on Legal Units of Measurements would be required following redefinition and it was hoped that the CCU could help with this.

3.3 Report from the other organisations and institutions, CIE, IAU, ICRU, IEC, IFCC, ISO, IUPAC, IUPAP, Académie des Sciences de Paris

3.3.1 CIE

Dr P. Blattner reported on behalf of the CIE and started by stating that the CIE supported the proposal to redefine the SI, commenting that it was an elegant approach. He continued to report that a joint CIE-CCPR committee was currently revising the document on 'Principles governing photometry' to be released following the redefinition of the SI. Dr Blattner highlighted the need in this area to have better descriptions of quantities, especially since many of the units used are the same for different quantities. One of the main additions to this document was the definition of the relationships between photometric and photobiological quantities. It was noted that the photobiological area was a relatively new community who in some cases (DRAFT prEN 16791 was highlighted) are creating new units for photobiological effects. It was the CIE's opinion that whilst non-visual effects are recognised it disapproves of the creation of new units and sought advice from the CCU. Dr Milton stated that it was important to have a discussion of these new photobiological units since it was not desirable to have a proliferation of new non-SI units. Prof Ullrich suggested that this discussion be taken later when comments on the SI Brochure and outstanding unit issues were covered.

3.3.2 IAU

Dr N. Capitaine reported on behalf of the IAU. Dr Capitaine began by highlighting the mission of the IAU to promote and safeguard the science of astronomy in all its aspects through international cooperation. The structure of the IAU – nine scientific divisions and a number of working groups – was also described. A few recent IAU resolutions were highlighted – in particular the resolution on the redefinition of the astronomical unit of length was important since it unified all IAU units so that they are all expressed in SI units.

3.3.3 ICRU

Dr H-G. Menzel reported on the activities of the ICRU. The ICRU periodically updates its guidance on fundamental quantities and units and the last of these updates was in 2011. It is also concerned with practical measurements and examples concerning radon measurement and the recommended data for ionizing-radiation dosimetry were presented. An important function of the ICRU was also to review operation quantities such as dose equivalent for area and individual monitoring for radiation protection of external radiation. The ICRU proposed to use conversion coefficients derived from the radiation protection quantity effective dose and apply these to fluence or air kerma. The potential consequences and impact on radiation protection metrology and operational radiation protection are being investigated. Prof Ullrich expressed his surprise at the range of proton energies listed as he thought this was well known. Dr Menzel replied that there were some discrepancies between measurements that needed resolution, but that the situation was generally under control.

3.3.4 IEC/TC 25 and ISO/TC 12

Dr M. Krystek reported on the work of IEC/TC 25 and ISO/TC 12. In particular that the revision of the ISO 80000 series on quantities and units must be finalised next year – this was as tight timetable and it may be that more time will be requested. Dr Krystek stated that it was ISO 80000-1 that was most relevant to the CCU. It was also mentioned that the ISO 80003 series on physiological quantities and their units may have to be cancelled because there has been very little activity in this area and it is possible that a new task force be appointed to deal with quantities and units to be used in e-health. Dr Milton asked whether, with respect to ISO 80003 and the previous presentation by the CIE, there was an appropriate liaison with IEC and CIE. Dr Krystek stated that there was a liaison but perhaps this link need to be strengthened in future.

3.3.5 IFCC

Mr G. Férard reported briefly on the work of the IFCC. In particular, recent activity had comprised work within the committee to ensure that documents and nomenclature were consistent with the SI and with the VIM. Mr Férard also explained the IFCC's databank that contains more than 17 000 entries describing properties examined in the clinical laboratories, according to a structured format comprising three elements: system, component, and kind-of-property. Mr Férard also gave an update on the status of the revision of the IUPAC Silver Book on the "Compendium of Terminology and Nomenclature of Properties in Clinical Laboratory Sciences".

3.3.6 IUPAC

Prof R. Marquardt reported on IUPAC activities and in particular on the mole project where the objective was to provide a Technical Report containing a critical review of the definitions for the quantity amount of substance and its unit, mole, as well as the related unit of the quantity mass. Prof Marquardt reported that the report was almost finished and he highlighted some of the major points, namely:

- the proposed definition of the mole would reflect that the best measurements are those which involve counting;
- a common thread throughout the literature was the confusion between the definition of a unit and the realization of a unit;
- the challenge remains to rephrase definitions intended to serve measurement science such that they become comprehensible for the "man-in-the-street";
- the current definition of the mole and the quantity amount of substance lacks understanding in educational communities (teachers and students).

Prof Ullrich stated that it was good to hear that there had been extensive discussion on this topic. Dr Milton asked whether the final IUPAC proposals concerning the definition of the mole could be previewed for the CCU. Prof Marquardt replied that he preferred to wait until the report had been internally reviewed before doing this, although he stated that the minutes of the project group meeting were freely available on the IUPAC website. Dr Brown commented that when the draft recommendations had been presented to the CCQM *ad hoc* Working Group on the mole in April there had been little support for them.

3.3.7 IUPAP

Prof W. Phillips gave the update on behalf of IUPAP. In particular the activities of Commission C2: Commission on Symbols, Units, Nomenclature, Atomic Masses, and Fundamental Constants (SUNAMCO) were reported – where Prof Phillips is the vice-chair. It was stated that C2 and its chair, Vanderlei Bagnato, were committed to an energetic and robust effort to promote and explain the new SI to the international scientific community through a multi-lingual web presence. Furthermore, in the light of the upcoming SI, a reform of the Red Book (a publication of commission C2 of IUPAP on Symbols, Units, Nomenclature, and Fundamental Constants in Physics) is being undertaken. It was stated that the chair and the vice-chair of C2 strongly support the recommendation that the radian become a base unit, with an associated dimension, angle. It was stated that this recommendation was being drafted as a resolution that will be circulated to the membership of C2 for discussion, refinement, and eventual presentation to the next General Meeting of IUPAP. Currently the recommendation was of the form: "To remove the ambiguity, it is hereby recommended that the SI recognize angle (plane and phase angle) as an independent dimension and that their units cannot be expressed in terms of other SI units. This would have the consequence that frequencies expressed in terms of angle/time or phase/time do not in general reduce to 1/time, thereby removing that ambiguity in the present version of the SI. The appropriate unit for plane angle and phase angle is the radian, since this is the widely recognized conventional unit for the arguments of the trigonometric and exponential functions." Following the presentation Dr Krystek stated that, although he was a member of the C2 Commission, he knew nothing of this recommendation, had not seen it before and had not been asked his opinion on it. Prof Phillips replied that in fact this recommendation was drafted by the chair and the vice-chair only and would be circulated amongst C2 members soon.

3.3.8 Académie des Science de Paris

Prof C. Bordé gave a presentation entitled "Theoretical foundations of metrology and of the system of base units: geometry and numbers". This proposed a new framework for metrology based on geometry and numbers. It was hypothesised that future fundamental metrology will deal essentially with phase measurements i.e. invariant numbers, and all measured quantities enter these phases through geometrical properties of a 5D space-time which combines 4D space-time and the internal space of objects. In particular, mass and proper time are entangled concepts which correspond to conjugate variables in classical mechanics and to non-commuting observables in quantum mechanics: their respective units thus require a joint definition in which the unit of mass is defined from the mass difference of the two levels involved in the definition of the unit of time. A compatible *mise en pratique* requires the association of a quantum clock with a mass through a phase measurement either by atom interferometry and atom counting or in the watt balance. This theory was then generalised in the presence of electromagnetic interactions, and subsequently the link between 5D optics and the natural units of Planck were elaborated. Prof Bordé concluded that this perspective incorporates naturally all relevant fundamental constants in a logical scheme with obvious constraints of economy, aesthetics and rigor. The final aim was, of course, to adopt a system of units free of arbitrary and artificial features, in harmony with contemporary physics.

4. REVIEW OF THE STATUS OF EXPERIMENTS RELEVANT TO THE DETERMINATION OF VALUES OF THE FUNDAMENTAL CONSTANTS REQUIRED FOR THE REVISED SI

4.1 Watt balances and the measurement of *h*

Dr S. Schlamminger presented on the status of watt balances and the measurement of *h*. He started by explaining the basics of watt balance operation – a principle first conceived by Dr Kibble – and how it enables electrical and mechanical power to be equated. The status of the Watt balances around the world was then reviewed – 13 separate Watt balances were mentioned. In particular it was noted that a number of new miniaturised watt balance were being developed and whilst they were unlikely to deliver data in time for redefinition, they were likely to be important in the future realisation of mass. Dr Schlamminger highlighted the NIST Watt balance, which had gone from design to first result in five years, with a projected relative uncertainty of less 2×10^{-8} by June 2017. Dr Schlamminger concluded by stating that of the 13 watt balance mentioned 7, or possibly 8, were likely to produce a useful result (with $1.5 \times 10^{-8} \leq \sigma_h/h \leq 1 \times 10^{-7}$) by the deadline for accepted data on 1st July 2017. The best result currently was from NRC with $\sigma_h/h = 1.9 \times 10^{-8}$. Prof Marquardt asked about the accuracy of the NIST Watt balance made from Lego as an education aid. Dr Schlamminger stated that this was currently about 1% but could easily be pushed down to 0.1% with a little extra work.

4.2 X-ray crystal density project to determine N_A

Dr H. Bettin reported on the status of x-ray crystal density method to determine the Avogadro and Planck constants by giving a background to redefinition and the current definition of the mole. The large number of experimental steps undertaken at different NMIs around the world was highlighted.

Dr Bettin mentioned the recent improvements in the measurement of the molar mass determination of the silicon in the silicon sphere and how the uncertainty of this had decreased by an order of magnitude in the last five years. Following these improvements it was highlighted that the limiting uncertainties in the experiments now related to surface characterisation and the determination of sphere volume. It was noted that there were two NMIs, PTB and NMIJ, who were able to perform the volume measurement and this would help give extra confidence to the values produced. The challenges of comparing mass determinations in air and in vacuum because of surface adsorption were also described and the method for solving this via an ensemble of artefacts with similar masses but different surface areas was elucidated. Dr Bettin highlighted current agreement of the values produced by the XRCD experiment and the data from the watt balance. He then concluded by describing the improvements expected by June 2017 which would yield a new value with a relative uncertainty below 1.5×10^{-8}. These improvements were: new XPS/XRF apparatus for spheres at PTB, new XPS apparatus for spheres at NMIJ, spheres with better roundness (smaller wavefront aberration), new lattice parameter measurement at PTB and the Avogadro constant determined using Si-28 with higher enrichment.

Dr Rietveld expressed some concern about the human factors in these measurements when the 'correct' result was already known. Dr Bettin acknowledged the concern but made it clear that the experiments were done independently at different locations and only he, as head of the Avogadro project, had access to all the component data from which he produced a calculation of the Avogadro constant. Dr Schlamminger confirmed that the same approach was taken with watt balances where the measures were done blind (either by measuring an unknown mass or by operating with an unknown offset).

4.3 Determination of the Boltzmann constant k

Dr L. Pitre reviewed the status of determination of the Boltzmann constant. In particular he reminded the CCU that prior to 2009 CODATA only used two experimental values, from 1979 and 1988, to calculate the Boltzmann constant, but from 2009 onwards there had been a large number of determinations. The principles of acoustic gas thermometry were explained and the largest elements of the uncertainty budgets in the three most recent determinations from LNE, INRIM and NPL were highlighted. The lowest uncertainty determination, from NPL, needed to have a correction applied to the isotopic ratio of argon which contributed to a change in the value and an increase in the uncertainty. Experiments were ongoing to resolve the isotopic ratio problem and it was expected that this would result in a reduction of the uncertainty to its previous level. A number of other methods for the determination of k were then outlined, but currently these all had uncertainties in excess of those found for acoustic gas thermometers. Dr Pitre concluded with a review of the expected uncertainties that would be achieved for all experiments by July 2017.

Dr Brown opened the discussion by stating that he thought the results of the NPL experiments to resolve the argon isotope problem would be available very soon. Dr Milton asked why, apart from the NPL experiment, there was no uncertainty component included in any of the determinations for the realisation of temperature at the triple point of water – he asked what the state-of-the-art in this area was. Dr Pitre replied that because the NPL result had a very low overall uncertainty the uncertainty of realisation becomes a limiting factor for them, whereas the other experiments have a sufficiently high uncertainty that the uncertainty of realisation is not a limiting factor. Dr Pitre went on to express the opinion that the limit for the uncertainty in the determination of k would be about 2 parts in 10^7 because of uncertainties in the local realisation of the triple point of water. Prof Milton expressed

concern that this meant that only one experiment could currently make use of the new definition at the triple point of water. Dr Pitre conceded that whilst this was true this was only at one temperature and this problem generally did not exist away from the triple point of water. Dr Quinn clarified that the problem with temperature measurement was not the calibration of a thermometer *per se* but instead the temperature measurement of a macroscopic artefact. Dr Pitre agreed and added that changes in the type of thermometer used can cause noticeable effects. Dr D. Newell suggested that comparisons of water triple point cell could give some idea of the spread in this area. Dr R. Davis added that if we compare artefact then these problems will always arise – in particular, the triple point only exists right at the top of the cell and this is rarely measured exactly. Prof Marquardt asked whether experiments with very cold gases will give new ways of measurement. Dr Pitre thought that these techniques would help with realisation in future but not with practical real world measurement.

4.4 CODATA TGFC report on the analysis of the currently available data from these experiments

Dr Newell began by giving the background to the CODATA TGFC, highlighting that in general the process undertaken by the group was on a four year cycle, although the period around redefinition would be slightly different, as explained later. He then elaborated on the recent 2014 CODATA adjustment of the fundamental constants and reviewed the new values that had been produced, in particular detailing the process for the Planck, Avogadro, Boltzmann and fine-structure constants. Residuals remained small for the Planck, Avogadro and Boltzmann constants and expansion factors were not considered. For the fine-structure constant the internal consistency had decreased and this had resulted in a shift in the recommended value by about one standard deviation of the old value. Dr Newell then explained the critical closing dates for data. The 1st July 2017 is the closing date for data for special CODATA constants adjustment to determine exact values of h, e, k, and N_A for the revised SI. By this date data must be published or available in a preprint accepted for publication. The 1st July 2018 is the closing date for data for CODATA constants adjustment to determine new set of CODATA recommended values consistent with the revised SI (this replaces the 31st December 2018 normal closing date). By this date data should be published or available in a preprint for publication.

Prof Marquardt opened the questioning by asking which equations will undergo the most strain when the defining constants are fixed. Dr Newell replied that CODATA used physical laws which it believed to be exact and so this should not be a problem. He remarked that some constants, of course, will become non-exact in the new SI. Dr P. Mohr added that the constants are independent of each other and so there is no strain on the system. Dr Brown added that he thought Prof Marquardt was referring the problems encountered in an over-constrained system, but that this was not the case in the new SI. Dr Rietveld asked about the timescales for the forthcoming process. Dr Newell replied that the new results will be presented to the CCU in September 2017 and Dr B. Wood added that the 2018 CODATA adjustment would be the first where the four fundamental constants are already fixed.

5. CCU RECCOMENDATIONS TO THE CIPM ON THE FUTURE REVISION OF THE SI

5.1 Discussion of the draft resolution to the CGPM

Prof Ullrich presented the current draft resolution to the CGPM which included the latest comments from the BIPM and the CIPM. He highlighted the changes that included reference to 'seven defining constants' from which the 'seven base units are deduced'. Prof Ullrich expanded on this point stating that whilst in principle no distinction between base and derived units is necessary the SI will continue to encompass the present set of 7 base units. However Prof Ullrich continued that there was a clear hierarchy with the defining constants at the very top and the base units being derived from combinations of these defining constants. Prof Ullrich highlighted the concern from Dr Milton that in some of the base unit definitions the first reference is to a derived unit rather than to the unit being defined. It was stated that this would need further debate although the way the definitions were currently written probably aided understanding.

Dr J. Stenger stated that he did not see the problem with the current formulation since these seven units are then explained in terms immediately after in the text. He was also of the opinion that it was better to introduce first the units that are usually used, and not put the more formal description in powers of the base units first, which may be off-putting to some readers. Dr Milton expanded on his point, saying that for the definition of the ampere the first unit that is reached is the coulomb and there is a danger of this looking like the definition of the coulomb instead. Dr Krystek added that ISO would support mentioning the units that are commonly used first. Dr A. Steele mentioned another aspect of the ordering of units, in reference to the candela he felt that is was not appropriate for the definition to begin with units of negative exponent rather than a positive exponent. Prof Ullrich replied that in this respect there is no strict ordering for units, and this can be changed – it is much better principle to have the ordering in a way that is most understandable. Dr Quinn added that in most cases the ordering respected as much as possible the physical equations on which the expressions were based.

Prof Bordé added that in the definition of the second 'splitting frequency' was meaningless and should be replaced with 'transition frequency'. There was general agreement on this point. Prof Marquardt asked whether it was also important to add between what energy levels the transition occurs. Dr B. Jeckelmann stated that these definitions were not designed to define everything in detail, and Prof Ullrich added that the explanation could not be too long. Dr B. Jeckelmann also mentioned that in the case of the kilogram there was no clear understandable link or physical model between the defining constants and the base unit. Dr C. Williams interjected that the ampere remains a base unit but was never actually realised, only ever as a derived unit. In this respect charge is more fundamental and we could use this in the definition. Analogously he stated that action could be used instead of mass. Prof Phillips pondered how best to relate h to mass for a school student. He postulated that h is actually used as a conversion factor between frequency and energy and is better expressed in this way rather than as a quantum of action. Prof Phillips concluded by going further and stating that the distinction between base and derived units had now become blurred so why not do away with the distinction entirely.

Prof Phillips's intervention triggered a lengthy and involved debate about the status of base units within the revised SI. Dr Steele felt that many of the concepts the CCU was struggling with were enshrined in the principles of how the SI currently operates. He suggested that the defining constants

help make contact with the future of the SI whereas the base units maintain the link to the past. Prof Mills stated that he liked the distinction between base units and derived units. Dr Brown added that this distinction was necessary if dimensional analysis was to be retained and remarked that the proposal to include radian as a base unit, with angle as a new dimension, seemed contrary to the proposal to do away with the distinction between base and derived units. Dr Milton said that the vast majority of users of the SI understand base units as the subset from which the derived units come – this is what schools teach and the 'man in the street' understands. He emphasised that the SI has a set of derived units that are calculable from the base units and that this is a deep-seated principle. Dr Quinn agreed and stated that whether or not we call them base units all derived units come from these. Dr Williams disagreed, arguing that teaching the coulomb is much easier than teaching the ampere and that whilst one should respect history one should also look to the future. Dr Williams proposed an Appendix to the SI brochure which dealt with some of these simpler unit relations. Dr Stenger expressed the opinion that in the past a unit and an artefact had been the same thing, but now the definition is disconnected from realisation and now the laws of physics, not artefacts, are required for realisation and in this way the revised SI becomes more real and more understandable.

Dr Blattner stated that the CIE would be content with a situation where there was no distinction between base and derived units. He proposed that base units could be described in a historical note. Dr Krystek disagreed stating that base units are not necessary but since there are currently used and help people to understand the system it is best to keep them. Dr Prieto further questioned the language in the draft resolution and whether the base units are 'obtained', 'defined' or 'derived' from the defining constants. Dr Stenger reminded the CCU that any system of units must be designed for practical use and to move forward there needs to be agreement on something, and perhaps this needs to be the concept of base units that is currently used.

Following some debate about whether or not the base units could be referred to as the 'traditional' base units (generally this was thought to be a bad idea as it made it sounds as though they were archaic or no longer relevant) Prof Ullrich asked for some new proposals around the discussion points of the draft CGPM resolution to be drafted and discussed further on the second day of the meeting.

5.2 Report on the status concerning the number of digits to be chosen for the defining constants

Dr Newell gave an update on the choice of the number of digits for the numerical values of the revised SI defining constants. In doing this he considered the status of the present SI 'defining constants' that will be experimentally determined in the re-defined SI (the mass of the IPK, permeability of vacuum, the TPW and the molar mass of ^{12}C) and the requirement for these to retain their previous values within the uncertainty subsequently placed upon them by redefinition. This introduced the idea of consistency factors whose values vary slightly depending on the number of digits chosen for the new defining constants in the SI. The options ranged from consistency factors being exactly one (Case 1: most digits fixed) to consistency factors being one within the new uncertainty (Case 3: least digits). Dr Newell advised that is was best to be flexible in choosing the number of digits since the final value of the defining constants were not yet known. He also mentioned additional options that could be considered, namely uncertainties being expanded to $k = 2$, or the use of single digit uncertainties. Dr Newell stated that the final values and uncertainties will come from the special 2017 adjustment of the fundamental constants. He concluded by

recommending that the minimum number of digits be chosen as allowed by appendix 3 for simplicity (Case 3).

Opening the discussion Dr Stenger agreed with Case 3, stating that Case 1 used precision that is not currently available and that specifying extra digits risks more mistakes being made. He stated that the smallest number of digits consistent within the stated uncertainties should be chosen. Prof Phillips agreed that the main criterion is that everything still agreed within the stated uncertainties. Prof Ullrich was not so sure and believed that Resolution 1 of the 24th CGPM implied the old 'defining constants' must remain exactly equal to their value prior to redefinition and this implied Case 1 was preferred. Dr Quinn stated that the next CGPM could adopt a different resolution and there was no requirement to be held to the previous resolution. Dr Milton felt it was best to have consistency factors as close as possible to one so it can be stated didactically that there was no change at the point of redefinition. Prof Phillips disagreed stating that other constants would change and we are willing to accept that so why these additional digits should be endured for the rest of time.

Dr I. Yang said that the triple point of water would still be used after redefinition and a smaller number of digits for *k* could cause significant differences in temperature measurement, adding that the changes to temperature measurements were accepted in general because there were benefits to other parts of the temperature scale. Dr Rietveld stated that the 1990 conventional electrical values have a defined number of digits and that measurements have already advanced beyond this accuracy and this may well happened again in future. As a result he postulated that we should and would use the number of digits required for the experiment. Dr Quinn expounded on the nuances of temperature measurement stating that there was no free choice about the triple point of water, it must continue to be 273.16 K, and that it was required for practical use of ITS-90.

Dr Newell calculated that in order for the TPW to retain its well-known numerical value, *k* would need 8 digits, and not the 7 in Case 3. It was therefore decided to choose Case 3 with the exception that *k* should have 8 digits and Dr Newell would revise Appendix 3 of the draft CGPM resolution accordingly.

5.3 Report on the WG on "Dimensionless Quantities"

Dr Stenger reported that the WG on Dimensionless Quantities had been formed following the 21st CCU meeting in 2013 and the group had met in person once in February 2015. Dr Stenger highlighted the terms of reference of the WG, namely to: review the treatment of "dimensionless" quantities in the SI Brochure, identify potential issues, and propose changes to the SI Brochure. In particular, there were two keys issues:

1) Communities such as that working in biotechnology request that measurement results expressed in counts be recognised as being "traceable to the SI", for which the quantity counts would need a unit, and

2) The use of Hz = 1/s and rad/s = 1/s which leads to errors of 2π in some calculations. The WG had subsequently fed proposals back into the Drafting Committee for the 9th SI Brochure.

Dr Stenger then set out the position that there are formally no "dimensionless quantities" but instead there are quantities with the dimension "number" – mathematically this is the neutral element in any set of dimensions. It is the dimension of all quantities being pure numbers and the coherent unit associated with the dimension number is one, 1. The unit 1 is the neutral element of any kind of set of units. It does not require explicit definition (there is no choice), however it is usually omitted for practical reasons, acknowledging common practice. Dr Stenger elaborated that the present draft of the

9th brochure avoids the formal introduction of the dimension number, but associates the unit 1 to all quantities being numbers, making counts traceable to the SI.

Addressing the matter of angles and frequency, Dr Stenger explained that there are many more quantities than units (fortunately) and that it was important to use the correct unit for the quantity, but one should not infer the quantity from the unit. Dr Stenger gave the examples of 'kerma and dose equivalent' and of 'frequency, angular velocity and decay rate', which are different quantities with the same dimension. Dr Stenger reported that the WG could not come to a compromise on this issue: two positions remained. The first expounds that Hz = cycle/s = 2π rad/s, therefore if Hz = 1/s, then $1 = 2\pi$, which is wrong, and therefore Hz and 1/s are not coherent. The second position suggests that the problem does not exist because 'cycle' is not a unit, and therefore Hz and 1/s are coherent. The WG decided to bring the issue to the drafting team and CCU. The drafting team did not reach a consensus either and decided to prepare two draft versions of the Brochure. Draft 1 was presented to the CIPM and underwent a consultation of NMI directors and CCs. It describes "dimensionless" quantities in chapter 2.2.3 "Dimensions of quantities" more generally and specifically where needed. It avoids radical changes, acknowledging common practice when using these quantities, while fixing inconsistencies. Draft 2 is consistent with this position with the exception of the treatment of angles and frequencies. This was to be discussed further by Dr Mohr and Prof Phillips in their presentation on the topic.

Prof Ullrich proposed to delay item 5.4 on review of the draft of the 9th SI Brochure until after the remaining comments from METAS, NIST and NPL had been presented.

5.4 Presentation of the METAS comments

Dr Jeckelmann presented the METAS comments on the 9th SI Brochure. These comments concentrated on what the status of the SI Brochure itself was and whether the SI Brochure and the definitions it contained were currently in a form that it was accessible to all user communities (such as school and academic institutions, research and development in science and engineering, standards organisations, and legislators). It was the belief of METAS that the SI Brochure should meet the quality standards defined for scientific publications, namely: declared authorship, scientific rigour in the presentation of the concepts, citation of proper references and clarity of presentation. Dr Jeckelmann stated that *mise en pratique* documents are needed in addition which describe how the units (according to the present state of the art) are realized in practice. He further stated that the current base unit definitions are only clear and unambiguous if the base unit to be defined is of the same dimension and kind as the underlying defining constant: s, mol. For other base units, the presentation is not understandable without additional knowledge of the underlying physics. In particular the kg was highlighted by Dr Jeckelmann as an example of where the physical model linking the definition with reality was missing and indeed that compared to the list of defining constants the base unit definitions gave no additional insight.

5.5 Presentation of the NIST comments

Dr Mohr and Prof Phillips presented the NIST comments. These were based on the proposal that plane angle and phase angle are physical quantities with units that are independent of other SI units, so an eighth defining constant for the unit radian should be added. Furthermore it was proposed that frequency and quantum mechanical phase are general physical quantities that appear in different

forms, such as classical rotations or electromagnetic radiation, all of which may be described by the coherent SI unit radian/second. Finally it was stated that the base units of the present SI are not the fundamental defining units in the new SI, so they should be termed "traditional base units" in the new SI.

Dr Mohr then highlighted the changes to the SI Brochure that would be caused by the introduction of radian as a base unit. Dr Mohr explained some consequences of these proposed changes, in particular: the unit for Hz, i.e. cycles/second, explicitly includes the non-SI unit cycle and is therefore not a coherent SI unit and instead, rad/s is the coherent SI unit for frequency, and Hz should be considered a unit "permitted for use with the SI."; The unit for angular momentum is J s rad^{-1} is no longer degenerate with the unit for action J s; The unit for torque J rad^{-1} is no longer degenerate with the unit for energy J.

Prof Phillips stated that the SI base units no longer have a special status based on their having been chosen to be the ones defining the SI. That special status belongs to the defining constants, which will now have zero uncertainty. However he conceded that it remains convenient to have a "core set" of units for the purpose, for example, of "checking units" or doing "dimensional analysis". Hence NIST recommended that 'base units' be referred to as 'traditional base units' within the revised SI.

Prof Phillips also recommended changing the name of ε_0 and μ_0 within the SI Brochure to the 'vacuum electric permittivity' and the 'vacuum magnetic permeability', respectively, since this is what is commonly understood by their usage. Prof Phillips concluded by supporting Dr Mohr's statements on the radian, citing in particular examples relating to mistakes made in cavity quantum electrodynamics.

5.6 Presentation of the NPL comments

Dr Brown presented NPL's comments of the draft 9th SI Brochure. Dr Brown stated that this reflected the position outlined in recent publications in Metrologia on angle and counting by Dr Brown and his colleagues Dr P. Quincey and Dr P. Brewer. Initially Dr Brown outlined the options for the treatment of angle within the SI and then the implications of treating it as a base quantity. Dr Brown stated that giving angle a dimension in the SI would mean modifying many fundamental formulas and units and although it would be entirely possible to include plane angle within the SI as an eighth base quantity this would be at the expense of a major upheaval in terms of basic mathematical and physical equations. NPL considered that it would be far harder to achieve global acceptance for this change that for the current proposed changes to the SI. In the area of angle, therefore, NPL proposed that the CCU should not accept angle as a base quantity (and associated base unit, or additional units) within the SI at the current time. The CCU should seek to clarify the subtleties of angle within the 9th SI brochure. To this end some new text was been proposed by NPL which currently appeared in "2.2.3 Dimensions of quantities" as a compromise. Dr Brown continued that any problems with quantity calculating software could be solved by specialist software that uses the 'underlying' equations elaborated in NPL's papers on angle, while the SI conventions stay as they are. In this way the SI would not use different equations to all maths and physics textbooks. The 'underlying' equations could be explained in a short Annex to the SI Brochure if necessary.

Dr Brown then turned his attention to counting and other quantities of the 'dimension number'. He stated that there was no need to create additional units for counting quantities – by analogy he showed how in other contexts it would be deprecated to add qualifying information to units, but that the issue with counting was that the unit '1' was rarely explicitly shown and as a result this left a gap

that was sometimes filled by non-SI units. He expounded on a number of reasons why additional counting units (including cycle) should not be adopted within the SI, not least because this did not abrogate the requirement for a full description of the quantity being expressed. Dr Brown was of the opinion that now was the time to embrace counting with the SI since it was only going to become more important in future. This was in part because in chemistry and biology the numbers being counted are small and a more user-friendly presentation of the results prefers number and in part because the items being counted are not a homogenous set (e.g. cells, or non-identical particles in air) compatible with using the mole. Dr Brown continued that just because specialist communities use non-SI units such as 'mcl', always have done and always will do, this doesn't mean that the SI should change to accommodate them – it should be the other way around. He stated that the SI should outline the most general and simple application; specialist areas may invoke their own implementation if self-consistent within their community, although this is not encouraged. He made it clear that this was not a matter of pedantry but was important to maintain clarity of understanding at the highest level. Dr Brown also proposed that the SI should also recognise explicitly the difference between pure number counting and ratios of quantities of the same kind (for example mol/mol). The latter allows the use of SI prefixes, provides more information, and prevents the use of other, deprecated 'units'. Dr Brown then presented NPL's recommendations, namely:

- the SI should not adopt any new units for counting or other quantities with the dimension 'number';
- a full description of the quantity being expressed is even more important in these cases;
- the SI should recognise 1 as the unit for expressing counting within the SI and explicitly use 1 in units for intensive counting quantities, where possible, to demonstrate counting (for example, $1/m^3$ is preferable to m^{-3} (although these are equivalent));
- for ratios of quantities of the same kind, always express the units explicitly to aid understanding, elucidate the difference between these units and pure counting, and allow the use of SI prefixes.

Dr Brown concluded that as a general principle one should always seek to solve ambiguity by providing extra information in the description of the quantity, not in the unit. The unit never in and of itself provides a description of the quantity. In this way, he proposed, the SI is kept as simple, universal and applicable as possible. NPL proposed an addition to the SI Brochure to make clear the importance of a proper and adequate description of the quantity being expressed, and also some additional text to distinguish counting from ratios of quantities of the same kind.

Following the presentation from Dr Brown, Prof Ullrich showed the proposed text provided by NPL, edited slightly by Prof Ullrich, that was proposed for inclusion in the draft SI Brochure. There was general agreement among the CCU that these were useful additions.

5.7 On expressing the value of the Planck constant

Following these presentations there was a brief statement from Prof Mills on expressing the value of the Planck constant. Prof Mills began by expressing agreement with most of the presentation of Dr Brown, the exception being on topics concerning angle where he agreed with the NIST position. Prof Mills went on to state that it had become customary to express the value of the Planck constant in two forms h and $\hbar$, with that latter having a numerical value that was smaller by a factor of 2π. It is then said that $\hbar = h/2\pi$.

In fact, Prof Mills proposed, these are actually different ways of expressing the same quantity by using different units (J s/cycle and J s/radian, respectively). He highlighted that the problems arise from failing to distinguish clearly between the value of a constant, and the numerical value when expressed in particular units. Prof Mills recommended that the CCU should retain the units cycle and radian when expressing the Planck constant, noting that cycle and radian cannot both be equal to 1 because in fact 1 cycle = 2π radian. In this way the rule that the symbol for the Planck constant represents the value of the constant, rather than its numerical value in particular units, is followed. Prof Mills stated his belief that the best way to do this is to regard the quantity angle as a base quantity with its own dimension, rather than describing angle as a dimensionless derived quantity as in the current SI.

5.8 Discussion of previous presentations

After acknowledging that many of the topics raised in items 5.3 to 5.7 had already been covered during discussions earlier in the meeting Prof Ullrich opened the debate on the presentations.

Dr Stenger reminded that most of the changes have been accepted, but the discussions on base units and angles remain unresolved. The new proposed text to deal with base units may have resolved the former problem. However he postulated that the changes on angle proposed were so fundamental that if they were taken forward at this stage it would put the whole redefinition of the SI at risk. Dr Stenger suggested that the angle issue should be "put on hold" and considered again for the 10th edition of the SI Brochure. Dr Krystek explained that the fundamental philosophical disagreement on angle arose from whether frequency and angular velocity could be considered as the same physical quantity or not. Dr Krystek was of the firm belief that they were different physical quantities and could not be equated: frequency comes from the inverse of period whereas angular velocity is a change of angle with time. He continued that angle has a mathematical definition that is a pure number and that the zero vector in vector space was equivalent to 1 within the SI and one could not have two units for the same thing. Dr Mohr replied that radian could be replaced with 1 and indeed this was what was currently done in the SI, but that radian and cycle were not the same thing and so both could not be 1.

At this stage Dr Bowsher intervened recognising the 9th SI Brochure as a great improvement and a good basis for progress and that a lot of good work had been done. He considered that perhaps the draft 9th SI Brochure did not help the 'man in the street' any more than the 8th SI Brochure, but that perhaps it was not the right "vehicle" to do that. On angle, Dr Bowsher was clear that there was not the level of agreement required to make such a fundamental change and so he proposed not to ruin the current version of the draft SI Brochure by making such a large change right at the end of the process. Prof Mills agreed that this was not the right time to make a change with regard to angle but he did want it to be discussed in the CCU. Dr Williams also agreed that the angle debate should not derail the redefinition and suggested that much of the current confusion could be removed by including an Appendix about suggested usages of these units. Dr Brown suggested that most confusion could be avoided by a better description of the quantities being expressed. Dr Steele commented that the suggested edits to the SI Brochure are good and the difference between the proposals is the clarity of expression of what is being measured. However Dr Steele also mentioned that he did not agree with the METAS presentation: the SI Brochure must speak to scientists, although it would be a useful exercise to ensure that these principles are set out as simply as possible in the current draft. Dr Stenger was in favour of keeping the SI Brochure as universal and compact as

possible and not making it too abstract or lengthy. He felt that any additional examples required could be put into an Appendix.

Prof Ullrich summarised the agreed changes and suggested that an *ad hoc* working group should work on a consensus text to be reviewed by the CCU on the second day of the meeting. He also agreed that the whole process should not be endangered by adopting proposals that were too controversial at this late stage.

5.9 Other comments to be discussed / recommended by the CCU

Prof Ullrich then introduced the remaining miscellaneous comments on the SI Brochure. There was a comment from KRISS which related to the definitions in the brochure being hard to understand for non-scientific readers, however it was generally thought that this had been dealt with following earlier discussions. A comment from the CCEM asked whether 'var', which is a commonly used unit in electrical power should be added to Table 8 (non-SI units accepted for use with the SI). In posing the question Dr Reitveld asked whether the list in Table 8 was meant to be exhaustive or not. Dr Krystek replied that it was very difficult to have a complete table and indeed this is a table for units accepted for use with the SI, not just all non-SI units in use. Dr Newell agreed saying that if the var was accepted there were other units in common use, such as 'gal', that should also be included. As a compromise Dr Krystek suggested that var could be included in ISO 80000-6 'Quantities and units -- Part 6: Electromagnetism'.

At this point, commenting on the previous discussion and more generally on the SI Brochure, Dr Milton reminded the CCU that the SI Brochure is a compilation of CIPM and CGPM decisions on the SI. As such Table 8 lists non-SI units accepted by the CIPM and CGPM for use with the SI. For cases such as the var, Dr Milton suggested that if there were strong opinions the CCEM should make a formal request to the CCU and the CIPM for a decision to be made on acceptance. Dr Milton further proposed this as the method to deal with any contentious issue with respect to the SI.

Concerning the comment from the CCEM about the timing of the implementation of the revised SI, Prof Ullrich stated that the CIPM would take a final decision on this in late 2016, and there would be further discussion at the CCU on this point later in the meeting.

On the comment "luminous efficacy doesn't sit comfortably at the very top table of measurement with the other six defining constants" it was generally agreed that this should be retained and Dr Blattner added that it was very important to keep the link to photometric response within the SI. Prof Phillips suggested that the candela would find its natural place once the base unit distinction is finally lost.

There was a comment on degree Celsius and why the capital letter is maintained when tesla, henry, etc, do not use one. Prof Ullrich explained that this was dealt with under 5.2 of the SI Brochure on unit names: "In English, the names of units start with a lower-case letter.… In keeping with this rule, the correct spelling of the name of the unit with the symbol °C is "degree Celsius" (the unit degree begins with a lower-case d and the modifier Celsius begins with an upper-case C because it is a proper name)."

On the comment requesting guidance on how to write the plural of multiplying units, such as the plural of 'pascal second' Prof Ullrich stated that it was not the role of the CCU to give guidance on matters of English grammar. However, Dr Brown proposed that 'pascal second' is a compound noun made of two nouns, and in these cases the second noun takes an -s for the plural, so 'pascal seconds'.

(He added that the first noun acts like an adjective in this example and adjectives in English are invariable.)

There was an additional comment stating that in the present SI Brochure it is not clear enough which of the cgs units are authorised to be used with the SI, which are not recommended, and which are strictly forbidden for usage with the SI. Dr Milton asked why the table including cgs units had been omitted from the draft 9th SI Brochure. Prof Ullrich replied that the SI Brochure was meant to be about SI units and so in this revision a harder line was taken on non-SI units. Dr Stenger added that the intention was to write a brochure that was concise and easy to use. He didn't see a reason to include things that are not part of the SI and added that the ISO 80000 series of standards is very helpful in covering some of these additional issues. However Dr Milton retorted that it was important to keep the SI Brochure useful and these units were still in use alongside the SI. Dr Blattner interjected that other photometric units should be considered if this was the case. Dr Krystek replied that it was the role of standards committees to deal with these non-SI units. Prof Ullrich agreed and stated his intention to keep the SI Brochure as concise as possible.

5.10 Approval of a consensus version of the draft of the 9th Brochure and the draft of the CGPM resolution for recommendation to the CIPM

In moving towards consensus drafts for the CGPM resolution and the 9th SI Brochure, Prof Ullrich canvassed the opinion of members on the timings laid out in the CGPM resolution. There was very little support for the revised SI coming into effect from the moment that the CGPM accepts the resolution. Dr Williams suggested that this would be very difficult to accommodate from a legal traceability standpoint and that if the SI were to be revised at the moment the CGPM made the resolution the CGPM would also need to provide a path to full implementation. Prof Phillips preferred implementation on 1st January 2019. Dr Steele favoured the CGPM decision being made on the day but implementation being deferred to a specific date. By analogy he suggested that the CGPM would also be voting on other matters (for example the BIPM dotation) which would not come into effect on the day itself. Dr Steele suggested World Metrology Day 2019 as a suitable implementation day. Dr Quinn countered that previously changes to base units had always been implemented at the time of the CGPM decision. Dr Brown felt that changes would be better deferred to 1st January 2019 as this gave sufficient time to properly publicise the change without extending the period of uncertainty for too long. Dr Brown also felt that to have everything in place to accommodate a change occurring on the day of the CGPM itself could be seen to pre-judge the decision of the CGPM. Dr May agreed, stating that it was better to delay implementation and communicate the changes and impact properly. Dr Rietveld felt that the major issues were in the electrical area where the changes had a significant effect. He stated that everything could be prepared in advance but expressed concern about what would happen if then something changed at the last moment. Dr Louw saw no issues from a CCRI perspective with any timescale but cautioned that legal changes would be required in most countries. Dr Bowsher agreed that a short delay was appropriate not least because this would help Member States work more closely with their governments to ensure cooperation over the changes. Dr Dudle mentioned that regulators in different countries would have their own say about when the legal requirements of the change are implemented. Dr Stenger said that he thought it important to keep the period of uncertainty surrounding any change as short as possible.

Prof Ullrich summed up the discussions concluding that the consensus of the CCU was to have a delay in implementation either to 1st January 2019 or World Metrology Day 2019. Prof Ullrich then closed the first day of the meeting.

6. REVIEW OF THE REWORDING OF THE APPENDICES OF THE CGPM DRAFT RESOLUTION PROPOSED BY THE *AD HOC* DRAFTING TEAM

At the beginning of the second day of the meeting a text produced overnight by the *ad hoc* drafting team was presented by Dr Newell. This was generally welcomed by the CCU as a good improvement. Prof Himbert suggested that the conventional values (for electricity) could not be abrogated, and this should therefore be worded instead as the decision to implement the conventional values (for electricity) was abrogated. Dr Rietveld cautioned that if the electrical community doesn't immediately adopt the conventional values following the change in the SI then they cannot be abrogated at the time of the CGPM – and this would need to be accounted for in the final text. Dr Newell presented some more of the proposed changes and a further discussion about the use of the terms 'defined' and 'fixed' in the text of the base unit definition ensued. On this point Dr Stenger cautioned the CCU not to go backwards and proposed to make only the small changes suggested to the existing text. There was general agreement on this point. Dr Steele added the request to move 'cd sr' to the front of the base unit definition for the candela. Finally Prof Phillips raised the remaining issue of angle, asking what Hz really meant in the definition and proposed an addition of 'where Hz = 2π rad/s'. Prof Ullrich asked for the CCU's opinion on this by a "show of hands" amongst members. There was a large majority against the proposal with most members voting (with only NIST and the IUPAP vice-chair in favour). Prof Ullrich stated that this opinion would be transmitted to the CIPM.

At this point Prof Marquardt showed the proposal made by the IUPAC Task Group on the new definition of the mole which included the concept of the Avogadro number as well as the term 'chemical amount'. He stressed that this proposal was not an official IUPAC proposal, and that it emerged naturally from the work of the Task Group, which was still to be submitted for internal IUPAC review. Dr Brown reiterated that when this proposal had been discussed at the CCQM *ad hoc* WG on the mole there had been little support for it, not least because it seemed to confuse amount of substance with counting and also because it would lead to the less helpful expression 'chemical amount of X' rather than 'amount of X' which is how amount of substance is usually applied in practice. Dr Davis mentioned that the IUPAC Green Book already lists 'chemical amount' as an alternative to amount of substance. Prof Ullrich requested that the CCQM examine the IUPAC proposal and give an opinion on it to the CCU.

7. REVIEW OF THE NUMBER OF DIGITS TO BE CHOSEN FOR THE DEFINING CONSTANTS AFTER CONSIDERING THE NEEDS OF THE TEMPERATURE COMMUNITY

Dr Newell presented the revised proposal which adopts Case 3 as the preferred option but using 8 digits for the Boltzmann constant in order to satisfy continuity in the triple point of water being 273.16 K. There was general agreement on this point. Prof Ullrich concluded that when the final values were available this would be discussed again at the next CCU.

8. CCM / CCU ROADMAP FOR THE ADOPTION OF THE REVISION OF THE SI

Dr Richard reported on the CCM / CCU roadmap for the adoption of the revised SI. He highlighted the conditions that needed to be met prior to redefinition (R1: three independent experiments (XRCD & WB) with consistent results with relative uncertainties $< 5 \times 10^{-8}$; R2: at least one result with a relative uncertainty $< 2 \times 10^{-8}$; R3: extraordinary calibration with IPK at BIPM; and R4: validation of the *mise en pratique* according to the CIPM MRA). He reported that R3 has already been met and a Metrologia special issue was being prepared that worked towards R4. R1 and R2 were making good progress and were expected to be met by the time of the 1st July 2017 deadline for data. Dr Richard concluded by stating that no significant deviation from the timeline on the joint roadmap was expected.

Dr Newell pointed out that the CODATA least squares adjustment referred to should be the first under the revised SI and not the final one under the "old" SI. Dr Quinn asked what would happen to the IPK following redefinition? He suggested that the CGPM resolution should contain reference to the requirement for it to be preserved, similar to the resolution concerning the old metre artefact which had required it to be preserved. Dr Steele agreed stating that the CCM had assumed that this would be the case.

Dr Steele asked when the results of the pilot study would be available? Dr M. Stock replied that if everything went to plan the results would be available before the end of the year, although the reporting would follow the rules of a Key Comparison even though it is a Pilot Study. Dr Wood asked what link to the IPK should finally be used. Dr Williams added that this was important for the CCU and CCM to decide so that a proper assessment of the data could be made adding that it is important to ensure that the community can properly realise mass. Dr Steele agreed that it was important to ensure the traceability path to the IPK was clear for producing the final data prior to redefinition. Prof Ullrich agreed that this was an important point.

9. REVIEW OF THE STATUS OF THE MISES EN PRATIQUE OF THE NEW DEFINTIONS

9.1 Kilogram

Dr Richard explained that the current *mise en pratique* for the kilogram is very short. The new *mise en pratique* for the kilogram is a much longer document, including many appendices and Dr Richard gave a brief summary of the proposed table of contents. He then went into more detail on Section 3 of the document, on dissemination of the mass unit and concluded by reviewing the history of the draft, the first version of which had been produced in June 2010. Dr Newell asked about the status of the pilot study results prior to redefinition. Dr Steele replied that the pilot study result as published would not inform the CODATA least square adjustment. Dr Richard added that the ongoing Key Comparison would then begin after that.

9.2 Ampere

Dr Rietveld reminded the CCU that the revised SI has a major impact on electrical units such that the present quantum electrical standards become direct realisations of the SI units of voltage, resistance and current. Dr Rietveld highlighted the methods for realising the ampere (single electron transport devices, using Ohm's law based on the Josephson and quantum Hall effects, and via a calculable capacitor). Similarly he explained that the volt may be realised using the Josephson effect and the value of the Josephson constant (where the $K_{J\text{-}90}$ conventional value is replaced by values based on the values of h and e). Dr Rietveld noted that in the case of the volt the step change was about 1 part in 10^7 and the consistency factor in this case was not 1. The ohm could be realised using the quantum Hall effect and the value of the Von Klitzing constant R_K (where the $R_{K\text{-}90}$ conventional value is replaced by value based on the values of h and e) or via a calculable capacitor and the value of ε_o. Dr Rietveld also noted that μ_0 would no longer have the exact value $4\pi \times 10^{-7}$ N A^{-2} and would need to be determined experimentally. Dr Rietveld concluded by reminding the CCU that the revision of the SI will have a major impact on electrical units but that the advances in quantum standards would lead to a direct improvement in the realisation of these units. Dr Rietveld stated that the electrical community was looking forward to being once again fully part of the SI.

Opening the discussion Dr Newell stated that if electrical measurements came from the calculable capacitor then there was no change from the current SI. Dr Milton asked whether the calculable capacitor route linking mechanical to electrical units is mentioned in the *mise en pratique* as he proposed that we were now moving away from this to a quantum metrology realisation. Dr Steele replied that this mechanical to electrical relationship now existed in the equations governing the Watt balance instead. Dr K. Fujii stated that whilst the new definition would bring about a step change most of industry was comfortable with this, although he was concerned that the implications of the change had not been more widely disseminated as, for instance, a number of text books and other teaching aids would need changing. Dr Rietveld replied that he wasn't sure of what work had been done so far but that Prof Ullrich would report on the CIPM awareness campaign later in the meeting.

9.3 Kelvin

Dr Yuan highlighted that the *mise en pratique* for the kelvin only included top level realisations, and should also provide a flexible path for expanding the range of thermometric methods in future. He stated that the new definition of the kelvin was independent of any material and favoured no fixed point over any other and favoured no measurement method over any other. He elaborated that the new *mise en pratique* would use thermometers based on well-understood physical systems, for which the equations of state describing the relation between T and other independent quantities can be written down explicitly without unknown constants. The document would also give brief descriptions of the types of primary thermometry that could be used for realisation and would also give criteria to be met for inclusion of a method within the revised *mise en pratique*.

9.4 Mole

In opening his presentation Dr Davis stated that whilst the effect of the change in the definition of the mole will be small it had still generated significant debate in the literature. Dr Davis briefly reviewed the methods for realisation, the most accurate of which was silicon XRCD experiment. He also highlighted the techniques that were used in common practice for realisation and dissemination:

gravimetry (which required a correction for purity), use of the ideal gas law (with correction for non-ideality as required) and electrolysis. Dr Davis also highlighted some consequences of the redefinition: R and F will have fixed values, whereas the molar mass constant and the molar mass of ^{12}C will no longer be exact. However the uncertainty on these values that are no longer fixed will be less than one part in 10^9 and in invisible to practical chemical measurement thereby allowing continuity with the previous definition. Prof Marquardt asked what level of uncertainty could be achieved currently for the most accurate chemical measurement. Dr Davis replied that electrolysis could achieve about 3 parts in 10^6 whereas the most accurate measurements of the amount fraction of gas mixtures were about 1 part in 10^4.

10. REVIEW OF THE DRAFT OF THE 9TH SI BROCHURE

Returning to the draft of the 9th SI Brochure, Prof Ullrich stated that agreement was required on the remaining issues.

It was agreed that additional proposed text in section 1.1 would clarify the status of the base units.

It was agreed that the additional text proposed by NPL at the start of section 2 about adequate description of quantities was a useful addition with minor modifications. Dr Stenger suggested that the second part of the proposed text be moved to the section on dimensions in the SI brochure and this was agreed. Prof Himbert thought it wise to change the example concerning molecules to one mentioning photons to avoid any confusion with the mole. Dr Milton more generally asked why the marginal notes, present in the 8th SI Brochure, have largely disappeared, stating that such an illustrative point could go into a marginal note and this would better balance the text. Prof Mills agreed saying that he had thought of marginal notes as examples to aid the understanding of the reader who might need help understanding the more formal text of the SI Brochure.

Regarding changes to the text in Section 2.2 on SI units it was agreed to add text to describe that the presence of base units within the SI system enables dimensional analysis. At this point Prof L. Mari added that it was not the presence of base units that enabled dimensional analysis but rather the presence of dimensions associated with these base units.

Following some further discussion of the definition of the kilogram it was decided to leave out a footnote tentatively proposed following the METAS comments since it now seemed rather out of place. Dr Steele stated that as he understood the problem it was not desirable to have the definition phrased in a way that it seemed to refer to a specific particle or entity.

Prof Mills summarised the base unit issue stating that in the current SI we are happy to say that derived units are products of powers of the base units and so in the revised SI we should be happy to say that the base units are products of powers of the defining constants since this is an analogous representation. Dr Steele thought this was a very good summary and should be included somewhere in section 2.2.

Prof Ullrich also reminded the CCU that changes to the text of the Brochure would need to be reflected in the text of the CGPM Resolution, where appropriate, and *vice versa*.

Dr Milton stated that the ampere definition needs to refer to the 1990 convention. Dr Rietveld disagreed stating that there should be reference to this but not in the definition itself.

The changes in the name of ε_0 and μ_0 within the SI Brochure to the 'vacuum electric permittivity' and the 'vacuum magnetic permeability', respectively, were also accepted.

Dr Blattner argued that '1' was required in front of each of the base unit definitions so that, for example 'A' became '1 A'. This was generally accepted and Dr Krystek agreed that the unit as stated must have a number associated with it. This led, in turn, back onto the subject of '1' as a unit and a somewhat lengthy discussion ensued. Dr Steele expressed his discontent about pure numbers having a unit associated with them. Prof Phillips added that in his opinion the decision as to whether pure number must have a unit is a matter of philosophy. Dr Williams added that he felt these issues had not been fully discussed within the CCU. Prof Ullrich stated that the biological community required a unit for counting. Dr Krystek agreed adding his opinion that if a large community that was growing in importance needed traceability to the SI we should help them. Dr Krystek added that '1' as a unit was necessarily a part of any system of units – there was no choice in this matter – the choice was whether the '1' was explicitly used as a unit. Dr Brown felt that for quantities that were ratios of the same kind of quantity it was very important to be able to express the units as a ratio for clarity and to allow the use of SI prefixes – he stated that this option was not available for counting quantities. Dr Brown also noted that there was already reference to '1' as a unit in the 8th SI Brochure.

Following this discussion Prof Ullrich asked for a "show of hands" on the issue of explicitly listing '1' as a unit for counting within the SI. The outcome was very close, but with a majority of members not expressing any opinion on the issue. Prof Ullrich stated that he would take this opinion to the CIPM. However, Prof Ullrich also suggested that the CCU WG on angle and dimensionless quantities should re-form in order to discuss this topic and reach a proposal for a way forward. Dr Stenger listed the membership of the WG at which stage there was a call for other interested parties to become involved. Dr Prieto, Dr Steele, Prof Mari and Dr Blattner expressed an interest. Prof Ullrich asked the group to report to him well before October 2016 so proposals could be considered in advance of the CIPM meeting. Dr Bowsher stated that the proposal to find a solution was a good one but the terms of reference for the re-formed WG must be clear and well defined so a solution can be found in time for the October CIPM meeting. Dr Stenger agreed that it would not be possible to have an open-ended discussion and the WG must work with the text that was already in the draft 9th SI Brochure. There was general agreement on this point.

Returning to the status of the SI Brochure Prof Ullrich stated that it was a document requested by the CGPM from the CIPM. Dr Quinn added that it was not a normative document but an explanatory one. Prof Phillips wondered whether that meant it had no authority. Dr Quinn replied that it was a very authoritative document, but did not have normative authority in the same way that an ISO standard voted on by Member States has authority. He added that it was up to local bodies to adopt the SI Brochure as a normative document if they so choose. Prof Milton intervened, reminding members that the SI Brochure is authoritative when it refers to decisions of the CIPM or the CGPM. He again postulated that if there are matters that are controversial then they should be passed as resolutions of the CIPM first, prior to appearing in the SI Brochure.

11. STATUS OF OPTICAL CLOCKS

Dr H. Margolis presented the current status of optical clocks. The improvement in the fractional uncertainty of optical clocks in recent years surpassing the uncertainties of clocks based on microwave transitions might suggest that it would soon be time to redefine the second. However Dr Margolis stated that this was not yet the case and that the presentation would explain why. Dr Margolis presented the frequency standards that can be used to realise the SI second as secondary representations, however the uncertainty (by definition) cannot be better than that of Cs primary standards. The list of transitions recommended by the CIPM as secondary representations of the second now includes one microwave standard and seven optical standards. Dr Margolis then showed the results of recent local comparisons of optical clocks showing fractional frequency differences of 1.8×10^{-17} or better. However comparisons between remote clocks are considerably more difficult and are currently a limiting factor in improving the definition. Dr Margolis highlighted several attempts to improve the comparison of remote clocks using satellite transfer (for example between PTB and NIST) and using optical fibre (PTB and SYRTE). NPL is now in the process of comparing Sr optical lattice clocks with SYRTE using an optical fibre link running under the English Channel.

Dr H. Margolis highlighted the prerequisites for a re-definition of the second, namely:

- improved methods for comparing optical clocks must be developed in different laboratories, especially on an intercontinental scale;
- a coordinated programme of clock comparisons, to build confidence in the optical clocks, anchor their frequencies to the current definition of the second and establish the leading contenders for a redefinition;
- evaluation of relativistic effects at an improved level of accuracy, including the gravitational redshift of the clock frequency;
- a framework and procedures for the optical clocks to be integrated into international timescales.

Work to address some of these requirements was ongoing under the ITOC (International Time Scales with Optical Clocks) clock comparison programme, which has also used transportable Sr optical lattice clocks as part of the comparison and had performed clock comparisons via broadband two-way satellite time and frequency transfer. The comparison had produced very good result so far, especially using the GPS IPPP (Precise Point Positioning with integer ambiguity resolution) technique which had been shown to be feasible at this level of accuracy for the first time.

Dr Margolis reported that in September 2015 the CCL-CCTF Frequency Standards Working Group (WGFS) had to deal with an over-determined set of clock comparison data for the first time, meaning that some frequency ratios could be determined from the results of several different measurements. As such it was no longer possible to treat each optical clock in isolation when considering the available data. Dr Margolis reported that new methods had been developed for analysing such data sets: to check the level of internal self-consistency and to derive optimal values for the ratios between the operating frequencies of the clocks. These methods were used by the CCL-CCTF WGFS to update the list of CIPM recommended frequency values in September 2015.

Dr Margolis concluded by describing an ambitious clock-based geodesy project as part of the ITOC project where clocks were used to perform a direct measurement of the earth's gravity potential with high resolution by using the gravitational redshift. Theoretical calculations had shown that

sensitivities of 1 cm in height should be achievable. The proof of principle experiment had been undertaken by operating a transportable strontium lattice clock in a tunnel underneath a mountain on the French-Italian border and comparing this with static clocks at INRiM.

11.1 Conditions and timeline for the redefinition of the second

Dr F. Arias presented the conditions to be fulfilled before the redefinition of the second. She highlighted the need to meet requirements of industry and society, or science and of timescales, when making this decision. On the pre-requisites for a redefinition Dr Arias highlighted that there must be:

- At least three different optical clocks having demonstrated validated uncertainties of about two orders of magnitude better than the Cs clock (few 10^{-18});
- At least three independent measurements of the same optical clock in different institutes are compared;
- At least five ratios between optical frequency standards, each measured at least twice by independent laboratories and agreeing;
- At least three independent measurements of optical frequency standards with respect to three independent Cs primary clocks (Cs fountain uncertainties are the limitation);
- Regular measurement reports over at least ten days submitted for TAI.

Dr Arias highlighted that in order to achieve this, the main technical challenge that needed to be overcome was ability to perform intercontinental comparisons with sufficient accuracy. Bearing this in mind and all the pre-requisites listed Dr Arias though that a decision at the 28th CGPM in 2026 to redefine the second might be possible.

Dr Stenger commented that he did not really understand the requirement for the first condition (relating to the requirement for three different optical clocks) since it would be preferable to just have one type which is completely understood. In this case, he explained, it is up to science to choose a certain transition frequency to use, and this is different to, for instance, the Boltzmann constant where we need several independent measurement of this fundamental constant.

12. ANY OTHER BUSINESS

12.1 Task Group for the Promotion of the New SI

Prof Ullrich again highlighted the work of the CCU Task Group on Promotion of the New SI and suggested that if there were any additional proposals for membership of this group then they should be made to the CIPM. Dr Prieto, Prof Mari and Dr Dudle volunteered the CCL, IEC and OIML, respectively, to sit on the group.

Prof Ullrich highlighted the objectives of the campaign and the desire to present a shared understanding of the SI. In this respect 2018 provided a unique opportunity to talk about the SI and not just at the level of the re-definition. Prof Ullrich highlighted the key message that the task group were proposing, namely:

- The SI is a world-wide endeavour and approach – it is a universal language of measurement
- Using the rules of nature to create the rules of measurement
- The changes to the SI will provide a springboard for future innovation

Prof Ullrich presented how the messages transmitted would be subtly different depending on the audience that was being engaged with, and the principles of engagement of the process and of all publicity material produced. Prof Ullrich concluded by highlighting the timeline of the task group's work leading up to the 2018 CGPM.

Referring to the name the 'Revised SI' or 'New SI' used in the current material, Dr Williams stated that he thought 'Quantum SI' was now a better description. Dr Steele thought just 'SI' was sufficient since following redefinition the SI will no longer be 'new' or 'revised'. Dr Quinn agreed stating that even the term 'quantum SI' would become old after a while. Prof Ullrich concluded the discussions by saying that he would put forward to the Task Group the opinion of the CCU that following redefinition the 'SI' is the best description, but that in literature prior to redefinition it may be appropriate to talk about the future 'revised SI' where appropriate.

12.2 CCU strategy

Prof Ullrich highlighted the updates to the CCU strategy, not least because of the outcomes of the current CCU meeting. It was noted in the strategy that the CCU had approved a close to final version of the 9th SI Brochure based on the drafting team version and taking into account the new developments at the meeting. Prof Ullrich stated that at the next CCU meeting in 2017 there would be a discussion on whether a meeting was required in 2018 and further, what the future work programme and meeting schedule for the CCU should be. Prof Phillips commented that this strategy should include the 'SI' and 'revised SI' nomenclature discussed previously. The updates to the strategy were approved.

12.3 CCU membership

Prof Ullrich proposed that the CCU ask the CIPM to make KRISS, METAS and NRC full members of the CCU following their attendance at the current meeting as guests. This was approved by the CCU.

12.4 Kibble Watt balance

Dr Quinn played a recording of a segment of a talk given by Dr Kibble at NPL on 17th March 2016 during a meeting entitled 'A History of Units from 1791 to 2018' organised by the Institute of Physics' History of Physics Group where Dr Kibble described how he had originally conceived the idea of the watt balance. Following the recording, in recognition of Dr Kibble's contribution to the area, Dr Quinn invited the CCU to henceforth refer to the watt Balance as the 'Kibble-watt balance' or the 'Kibble balance'. Prof Phillips stated that when he first worked at NIST it had been on the Watt balance and so he thought this was an excellent idea. Dr Williams expressed a preference for the Kibble balance. Prof Himbert added that the Kibble balance translated better into French than the Kibble Watt balance. Dr Wood added that he preferred the Kibble balance, not least because the watt balance had always been somewhat of a misnomer since it is actually a joule, or var, balance.

Dr Wood added that perhaps the CCU should also start referring to the equation defining the operation of the watt balance as the 'Kibble equation'. There was general agreement from the CCU to start referring to the 'Kibble balance' in all official documents.

12.5 Concluding remarks

Prof Ullrich concluded the meeting by highlighting the open issues for solution by the CCU WG on Angles and Dimensionless Quantities, namely: the units for dimensionless quantities in section 2.2.3, and the treatment of radian with the 9th Brochure. Prof Ullrich made it clear that the terms of reference for the work of the WG was to edit, amend and correct the current text of the draft 9th SI Brochure and not to introduce fundamentally new concepts. The WG were to send their proposals to Prof Ullrich for CCU consultation by September 2016.

Prof Ullrich mentioned that Prof Mills had stepped down from the SI Brochure drafting team and that Dr Davis had been proposed in his place. Prof Milton was also to be added to the SI Brochure drafting team. Both points were agreed by the CCU.

Prof Ullrich reviewed the decisions of the 22nd CCU taken during the meeting and these were approved by the CCU.

13. DATE OF NEXT CCU MEETING

The next meeting of the CCU was proposed for 5-7th September 2017.

14. CLOSURE

In the absence of any other business, the President of the CCU, Prof Ullrich, closed the meeting at 2.30 pm and thanked participants for their contributions, reports and participation in the discussions. Prof Ullrich thanked the staff of the BIPM for their support in hosting the meeting and wished all attendees a safe journey home.

Dr R. J. C. Brown
Rapporteur, 23 June 2016

DECISIONS OF THE 22ND CCU

1. That KRISS, METAS and NRC be proposed as new members of the CCU to the CIPM.

2. That the Draft Resolution be corrected as follows:

- Exchange Appendices 1 and 3.
- The definitions of the base units stay as they are but with the addition of "implicitly" before "defined" in the definition of the base units in Appendix 3.
- Change "hyperfine splitting" by "hyperfine transition frequency" in the definition of the second.
- Change the order of units in the definition of the candela to be cd sr kg^{-1} m^{-2} $s^{3.}$
- Acknowledge in the draft Resolution the special status of the IPK after the redefinition.
- Regarding the mole, the CCU invites an official request from IUPAC to the CCQM to discuss a reformulation of the definition of the mole. The eventual CCQM proposal to the CCU should be discussed in the 2017 meeting of the CCU.
- Reformulate the abrogation of the Josephson constant to explicit that the abrogation refers to a decision and not to a value.
- Change to "vacuum magnetic permeability".
- Acknowledge that the values of the defining constants come from a special CODATA adjustment in 2017.

3. That the 9th edition of the SI Brochure be corrected as follows:

- Prefer "vacuum magnetic permeability" and "vacuum electric permittivity".
- Keep "base" units (do not add "traditional").
- Explicit the status of the Brochure in the introduction: the Brochure is a CIPM document requested by the CGPM.
- Issues regarding the treatment of the radian and of the "unit 1" to be discussed again by the working group on angles and dimensionless quantities (WGADQ).
- Add in the chapter devoted to dimensions the paragraph proposed by the NPL that encourages users to describe the quantities they report and in particular those quantities that participate in ratios of quantities of equal dimension.
- In answer to METAS comments, add the text shown by Prof Ullrich stating that the base units are not strictly necessary anymore but kept for historical reasons.

4. That "var" will not to be added in the draft Brochure tables as a unit allowed to be used with the SI, but that the CCEM may submit an official request to the CCU and the CIPM.

5. That the number of digits to be chosen for the defining constants should be according to case 3 (provided that this brings the TPW temperature to 273.16 K).

6. That the working group WGADQ established at the last meeting be extended by the addition of Emilio Prieto, Alan Steele, Luca Mari and Peter Blattner. The group should report to the CCU president well before October 2016.

7. That the drafting team of the 9th edition of the SI Brochure be extended by the addition of Richard Davis.

8. That the term “Kibble balance” is to be preferred from now on in all CCU documents.

9. That the updated CCU strategy has been approved.

10. That during the transition period until the new definitions of the SI come into force, the term “revised SI” is to be preferred. After the redefinition, it should simply be called again “the SI”.

11. That the implementation date for the new definitions should be World Metrology Day in 2019.