Bureau International des Poids et Mesures

Consultative Committee for Units (CCU)

Report of the 23rd meeting
(5-6 September 2017)
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 5 September 2017

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

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

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]

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

National Institute of Metrology [NIM], Beijing

National Institute of Standards and Technology [NIST], Gaithersburg

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

National Physical Laboratory [NPL], Teddington

National Research Council of Canada [NRC], Ottawa

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig

Prof. M. Himbert, personal member

Dr T.J. Quinn CBE FRS, personal member

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

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

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

The twenty-third meeting of the Consultative Committee for Units (CCU) took place at the International Bureau of Weights and Measures (BIPM), Pavillon de Breteuil, Sèvres, from 5 to 6 September 2017.

The following were present: V.S. Bagnato (IUPAP), P. Blattner (CIE), R.J.C. Brown (NPL), N. Capitaine (IAU), G. Dudle (OIML), , K. Fujii (NMIJ/AIST), K. Hosaka (NMIJ/AIST), B. Jeckelmann (METAS), M. Krystek (ISO), Z. Li (NIM), R. Marquardt (IUPAC), H.G. Menzel (ICRU), M.J.T. Milton (Director of the BIPM), P. Mohr (NIST), D.B. Newell (CODATA), K. Nield (CIE), K. Pachucki (CODATA), S.N. Park (KRISS), S. Patoray (OIML), E. Prieto Esteban (CEM), J. Qu (NIM), P. Quincey (NPL), P. Sebellin (IEC), A. Steele (NRC), J. Stenger (PTB), J. Stohner (IUPAC), B. Taylor (CODATA), E. Tiesinga (NIST), J. Ullrich (CCU President), L. Vitushkin (Rosstandart), C.J. Williams (NIST), B. Wood (NRC), I. Yang (KRISS), J. Zhang (NIM).

CIPM members and Consultative Committees Presidents or representatives: L. Érard (CIPM/CCTF President), J. Fischer (CCT), B. Güttler (CCQM), M.L. Rastello (CIPM/CCPR President), P. Richard (CIPM/CCM President), G. Rietveld (CIPM/CCEM President).

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

Representatives from invited NMIs and organizations: K. Banholzer (CECIP), H. Ahmadov (UME), E. Massa (INRIM), F. Piquemal (LNE), D. Wiersma (INRIM).

Invited guests: H. Bettin (PTB), W. Bich (INRIM), C. Bordé (Académie des Sciences, Paris), N. Dimarcq (LNE-SYRTE), S. Karshenboim (LMU/Pulkovo Observatory), L. Pitre (LNE-Cnam), F. Riehle (PTB), S. Schlamminger (NIST).

Also present from the BIPM: E.F. Arias (CCTF Executive Secretary), R. Davis, E. de Mirandés (Executive Secretary of the CCU), H. Fang (CCM 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), R. Wielgosz (CCQM Executive Secretary).

1.1 Welcoming remarks and introduction

The President of the CCU, Prof J. Ullrich opened the meeting at 0900hrs. He remarked to participants that this was perhaps the most important meeting relating to the SI since 1960, when the International System of Units was first created.

Prof Ullrich then warmly welcomed the new members of the CCU: NRC, METAS and KRISS.

Prof Ullrich reminded participants of the main aims and objectives of the current meeting, namely that the CCU needed to give a recommendation to the CIPM on the redefinition of the SI, and to support this the CCU needed to provide the CIPM with a summary of the experimental data available. He went on to caution members that the main task of the CCU was to maintain the reputation of metrology – focusing on science and not politics – and provide an SI system that is stable, comparable and coherent. Prof Ullrich remarked that in making its

decision about the redefinition of the SI the CCU must bear in mind the guidelines that have been set and also take into account the advice and guidance of the other consultative committees.

1.2 Welcome from the BIPM Director

The Director of the BIPM, Dr M. J. T. Milton then welcomed participants, agreeing that this was indeed a very important meeting. He noted that the photograph from the first meeting of the CCU in 1967 contained only 13 people. The fact that the attendance at the 23rd meeting of the CCU was so much greater was, he surmised, an endorsement of the interest in, and engagement with, the process of possible revision of the SI.

Thanking the CCU Executive Secretary, Dr E. de Mirandés, for her hard work in preparing and providing access to documents in advance of the meeting, Prof Ullrich then initiated a round table self-introduction of participants.

1.3 Homage to passed members

Prof Ullrich made homage to passed members: John V. Dunworth (1917-2017) CIPM President from 1975-1985; Ernest Ambler (1923-2017) CIPM member from 1972-1989; Katharine Gebbie (1936-2016) CIPM member from 1994 to 2000; Bernard Guinot (1925-2017) CIPM member from 1978 to 1984; and André Allisy (1924-2017) who worked at the BIPM from 1961 to 1989 as Director of the Ionizing Radiation Section which he created.

The homage finished with Prof Ullrich leading the CCU in standing for a short period of silence in remembrance of these colleagues.

1.4 Approval of the agenda

The agenda was approved with addition items under Section 12 on Any Other Business: the application for CCU membership of LNE, discussion of the possible date for the next CCU meeting and, as requested by the BIPM Director, consideration of whether CCU documents can be made open access.

1.5 Appointment of rapporteur

Prof Ullrich proposed Dr R. J. C. Brown as the rapporteur for the meeting, thanking him for his report of the 22nd CCU meeting; Dr Brown agreed.

1.6 Update from the CIPM

Prof Ullrich opened his update from the CIPM by highlighting the recommendation made by the Working Group on the Implementation and Operation of the CIPM MRA and noted that the CIPM had agreed to establish an *ad hoc* Working Group to oversee the implementation of the recommendations. Prof Ullrich also noted that the CIPM had requested a short description of the 'risk-based approach to CMC review' adopted by the CCQM, CCEM and CCT.

Prof Ullrich noted that the BIPM were in the process of developing the BIPM vision, mission and objectives in time for the CGPM meeting in 2018.

Following the resignation of Dr Bowsher, Dr Brandi and Prof Inguscio form the CIPM, the CIPM voted to elect three candidates for provisional election: Dr Laiz, Dr Rastello and Dr Sené. It was also noted that the CIPM appointed Dr Castelazo as President of the CCL. Prof Ullrich also stated that a proposal to create CC vice-presidents was rejected by CC Presidents in their meeting in June 2017. Finishing his review of decisions of general interest, Prof Ullrich noted that the 26th meeting of the CGPM would be held at the Palais des Congrès de Versailles on 13-16 November 2018.

Prof Ullrich then commented on recent decisions of the CIPM relevant to the CCU. The first of these was the recommendation that the date on which a redefinition of the SI shall come into force will be 20 May 2019 (World Metrology Day). The CIPM had also noted the intention of IUPAC to propose a revised wording for the new definition of the mole and Prof Ullrich highlighted that this would be discussed later in the meeting.

Recalling proposals to the CIPM from the previous CCU meeting Prof Ullrich noted that the CIPM had agreed with the CCU proposal regarding the number of digits to be kept in numerical values of the defining constants. The CIPM had also agreed to treat the unit one in the 9th SI Brochure as in the 8th SI Brochure as the neutral element of any unit system, but to avoid calling it a derived or a base unit, and agreed to treat the radian and cycle in the 9th SI Brochure in compliance with the CGPM resolutions in force (Resolution 12 of the 11th CGPM and Resolution 8 of the 20th CGPM).

It was noted that the CCPR had been asked to update Appendix 3 ("Units for photochemical and photo-biological quantities") which will be kept as an online appendix in the 9th Edition of the SI Brochure. It was also decided that the Appendix 1 of the 8th SI Brochure shall be updated and maintained online in the 9th SI Brochure. The CIPM had decided that the definitions of the 9th SI Brochure shall not contain the term 'implicitly'.

Prof Ullrich stated that the CIPM had endorsed the latest version of the draft 9th SI Brochure as the close-to-final one. A fully edited version will be produced by the BIPM and brought to the CCU and, to the CIPM in October 2017 for final approval. It was noted that in parallel the ISO 80000-1 was being revised in the meantime and relied on some of the content of the "close-to-final" draft 9th SI Brochure available online.

The CIPM had also requested that all CCs update their *mises en pratique* before the redefinition of the SI. The *mises en pratique* will continue to be grouped in an online Appendix of the SI Brochure.

Prof Ullrich went on to inform members that the CIPM had welcomed the CCEM, CCM, CCT and CCQM as new members of the Task Group for the Promotion of the SI. It was noted that ILAC, ISO, OIML, IEC and CIE were welcomed as observers. He also mentioned the joint statement that the CCs had produced for their stakeholders, addressing the changes to be expected under the revised SI and it was noted that the statement will be considered for inclusion in the final draft of the 9th SI Brochure.

Prof Ullrich introduced the revised rules for membership decided on by the CIPM, and that the CCU was asked to adopt the same criteria for participation as the other CCs for meetings after the revision of the SI comes into force.

Prof Ullrich stated that many of these items would come up for discussion again during the remainder of the meeting. He finished his update from the CIPM by informing the CCU that the CIPM had agreed that NRC, KRISS and METAS should become members of the CCU. Prof Ullrich welcomed them again to the meeting.

2. PRESIDENT'S REPORT

Prof Ullrich started the President's report with an update on the decisions of the 22nd CCU meeting. These were now were either implemented or would be the subject of further discussion during this meeting. In particular, the proposed changes to membership had been implemented, with KRISS, METAS and NRC joining the CCU, and the draft 9th SI Brochure had been edited as previously discussed, although some issues remained and would be discussed as part of agenda item 8.2. Prof Ullrich highlighted that it was important to note that during the period until the proposed new definitions of the SI come into force the term 'revised SI' is to be preferred, but then after redefinition it should simply be called again the 'SI'. It was noted that the term 'Kibble balance' was now being extensively used within the community in place of watt balance.

Prof Ullrich informed the CCU that the joint statement of the CCs for stakeholders addressing changes to be expected under the revised SI is now complete and was available to members on the CCU website.

Next the President mentioned the CCU strategy which needed to be revised. He proposed that to do this a CCU working group on strategy should be formed with new members and that this would be discussed under agenda point 11.

Prof Ullrich then reminded the CCU of the CIPM's SI Promotion Task Group (and its expanded membership referred to above) and also the PR Expert Group, led by Mrs F. Auty (NPL) where most of the work was actually done to develop plans and key messages. Prof Ullrich gratefully acknowledged this input. As a result, there was now an 'SI download area' on the BIPM website where material associated with the revised SI was now available, including a 'brand book' giving advice on key messages and illustration guidelines and other promotional material. The use of the same logos and key messages world-wide was designed to ensure that activities by different organisations will be consistent and combine to raise the profile of the SI and metrology internationally.

Prof Ullrich then mentioned 'The Last Artefact' documentary film about the revisions to the SI that was being made and had received a major grant from NIST. It was expected that this film would be widely distributed internationally in late 2018 / early 2019.

Prof Ullrich highlighted the timeline for SI redefinition and how the activities of the CIPM's SI Promotion Task Group aligned with this, noting in particular the 'campaign period' which was expected between World Metrology Day 2018 and World Metrology Day 2019. It was noted that EURAMET was the RMO in charge of developing a poster for World Metrology Day 2018 with the topic being the revision of the SI.

Prof Ullrich concluded by saying that there was still lots of work to do on preparing material to support the publication of the revision of the SI and that the next SI Promotion Task Group meeting was scheduled for January 2018.

Following the presentation Dr Brown asked about the plans to disseminate the CC common statement document. Dr de Mirandés replied that until at least after the forthcoming CIPM meeting the document would remain on the restricted part of the CCU website.

3. REVIEW OF THE EXPERIMENTS THAT HAVE CONTRIBUTED TO THE DETERMINATION OF THE VALUES OF THE PLANCK AND AVOGADRO CONSTANTS FOR THE REDEFINITION OF THE SI

Prof Ullrich opened the agenda item by stating that he had received a letter from Dr Barry Inglis, the President of the CIPM, reconfirming that the CIPM will have to take a decision on the redefinition of the SI at its forthcoming meeting in October. Dr Inglis had noted however that given the unexpected and complex situation concerning the experimental values for the Planck and Avogadro constants that had developed after the closing date for new data, the CCU was requested to summarise the current status of the experimental values and provide a scientific review of the situation for the CIPM. Prof Ullrich emphasised that the next section of the meeting would concentrate of fulfilling this request and should conclude by providing a recommendation from the CCU to the CIPM on the revision of the SI in 2018.

3.1 Kibble balances and the measurement of h

Dr B. Wood summarised the status of Kibble balances globally. He noted that there were at least a dozen balances at various levels of development around the world, four that had operated and published data in 2017 (China, France, United States and Canada), another four that were now operating (Turkey, Korea, BIPM and Switzerland) and four in development (South Africa, UK, Germany and New Zealand). Dr Wood also noted the innovations that were taking place in the subject area for the balances under development: the NMISA system contained 3D printed parts, the NPL system involved a novel table-top design with one model targeting small masses and one targeting larger masses, the PTB Planck-balance system was a self-calibrating precision balance for industrial applications, and the MSL balance consisted of two pressure balances. Of the systems operating, but not yet having published data, the UME balance planned to contribute data to a consensus value by the end of 2019, the KRISS balance expected relative uncertainties less than 5×10^{-8} by the end of 2019, the BIPM balance expected uncertainties around $2\text{-}3 \times 10^{-8}$ by the end of 2019 and the METAS balance expected relative uncertainties of 2×10^{-8} by the end of 2017.

Dr Wood then concentrated on the four Kibble balances that had published results. The NIM joule balance had a relative uncertainty of 2.4×10^{-7} in May 2017 but is not currently part of the CODATA adjustment. NIM expect relative uncertainties of 5×10^{-8} in the next 2 to 3 years. The LNE balance currently has a relative uncertainty of 57 ppb in air with the aim of reducing this to less than 3×10^{-8} by 2020 when operation will be in vacuum. The Kibble balance at NIST current has published data with a relative uncertainty of 13.5 ppb operating in vacuum with mass transfers also in vacuum. Dr Wood reminded the CCU that the Kibble balance experiment should produce values of the Planck constant that are independent of both the velocity of the coil (during the first stage of the experiment) and the mass being compared (during the second stage of the experiment) and that NIST has clearly demonstrated this independence. The NRC balance has the lowest published relative uncertainty to date of 9 ppb with good demonstrations of mass and velocity independence. NRC had also produced many results, and there is no evidence of drift over time.

Opening the questioning on the presentation Dr Brown expressed his admiration for the experiments described but, having seen similar presentation over the years, asked Dr Wood whether the timescales for predictions about future improvements to uncertainties were realistic.

Dr Wood replied that when NRC had set themselves time-limited uncertainty targets they had generally met these, but he accepted in general that it can often take longer than expected to meet these targets. Dr Taylor asked Dr Wood about the likelihood of the other experiments that he had mentioned earlier yielding competitive results in the near future. Dr Wood replied that any laboratory no yet operating in vacuum probably had at least one year of resolving technical problems ahead of them once a vacuum system had been installed before starting to produce competitive results. Mr Massa then invited Dr Wood to speculate about the lowest uncertainty achievable for Kibble balance experiments. Dr Wood replied that he doubted the current NRC set-up could get much below 7 ppb, unless it was completely re-built.

3.2 X-ray crystal density project to determine N_A

Dr Fujii introduced the XRCD experiments, explaining initially the theory of how these measurements are done and how this allows measurement of the Avogadro constant, essentially by counting the number of atoms in a silicon sphere. He then proceeded to review the results of the International Avogadro Coordination (IAC) and demonstrated how many different NMIs and institutions had been involved in all the experiments to produce the final results.

The first result published in 2011 (IAC-2011) was affected by surface layer contamination by metal atoms. For IAC-15 the silicon spheres were re-polished and there were also improved lattice spacing and molar mass measurements. At this stage, the largest uncertainties remained in the volume measurement and the evaluation of the surface chemistry. For the NMIJ-17 result a new ellipsometer and new XPS apparatus was introduced. For the IAC-17 result PTB developed a new set of silicon spheres and used a new XRF/XPS apparatus. A differential lattice parameter measurement was performed using a self-referenced lattice comparator. This was described in some detail since direct lattice parameter measurements were not made and it was the first time these differential measurements had been employed. Further some additional corrections for remaining impurities were required.

The difference in the value of the Avogadro constant produced between NMIJ-17 and IAC-17 cannot be explained by their lattice parameter measurements since this was checked using the self-referenced lattice comparator and as yet the reason for this discrepancy is unclear.

Following an explanation of the corrections required to these results for re-evaluations of lattice parameters and molar masses Dr Fujii presented the final data from the different evaluations and the correlations between them. He also showed the weighted mean for the XRCD data and elaborated that this differed from the proposed CODATA-17 value by 29 ppb.

After the presentation Dr Milton asked whether the same impurity data was used to correct for the mass deficit as is used for the lattice parameter. Dr Fujii said that this data was different but that in any case it was not expected to be a large contributing factor – perhaps only a few parts in 10^{-9}. Dr Milton then asked whether the uncertainty arising from point defects uses the same measurement set as is used to correct the lattice parameters for impurities. Dr Fujii confirmed that this data was the same but that in future different techniques were going to be used to evaluate these parameters. Dr G. Rietveld asked to what extent the corrections described by Dr Fujii would affect the CODATA adjustment. Dr D. Newell confirmed that it would not as the corrected data has already been included in the CODATA adjustment. Dr T. Quinn stated his opinion that notwithstanding the remaining discrepancy the agreement between the XRCD measurement and the Kibble balance values is a remarkable achievement for such different experiments using such different physical and chemical principles.

3.3 Analysis of the consistency of the experimental data

Dr W. Bich, Chair of the JCGM Working Group on the Expression of Uncertainty in Measurement, presented his opinions on the consistency and stability of the available results from the Kibble balance and XRCD experiments.

Dr Bich introduced this study of consistency as a very important consideration given the CCM Recommendation G1 (2017) on a new definition of the kilogram which required 'at least three independent experiments' to 'yield [consistent] results'. Dr Bich stated that the word 'consistent' had disappeared from the 2017 recommendation but was still implicitly there as a function of the other requirements. Dr Bich then went on to provide definitions of independence (where guidance is given in the GUM – 'if information about one quantity is completely irrelevant for the other quantity') and 'consistency' for which no guidance is given in the GUM. A general consideration of consistency is when data scattering is comparable to individual declared uncertainties, and more rigorously when it satisfies a consistency criterion. In this respect consistency could never be considered in absolute terms and would always be dependent on one's choice of consistency test. Dr Bich stated that the most common consistency test was the chi squared distribution. He then cautioned over the use of weighted means that these only provide reliable results if the data scattering is purely random. Dr Bich went on to say that even once a consistency criterion has been chosen there was then the matter of choosing the level of confidence at which one wished to test one's hypothesis and this was also an arbitrary choice. He also stated that a better choice of consistency is related to the Birge ratio (as used in the CODATA adjustments) taking into account the available degrees of freedom together with the chi squared parameter.

Dr Bich then turned his attention to the data sent to CODATA. All the data, as received, was not consistent according to the criterion Dr Bich had set and had a Birge Ratio of 1.92, well above the critical level of 1.22. When the three data points with the lowest uncertainty were considered (NIST-17, NRC-17, IAC-17) there was still inconsistency. However when the analysis performed on the data as considered by CODATA with uncertainties increased using an expansion factor, there was now total consistency, with a Birge Ratio of 1.12 below the critical level of 1.24.

Dr Bich then discussed the time evolution of CODATA values of h about which there had been a lot of discussion prior to the meeting and in the meeting documents. He found that the six values produced since 1998 did not show consistency but that the last three values since 2010 showed much better consistency, passing at the 95% confidence level and almost passing the Birge criterion as well. (Birge ratio of 1.47 compared to a critical level of 1.41).

Dr Bich concluded by noting that the 'mass equivalent' change in the value of h had been decreasing since 2006. Looking into the future he surmised that these consistency estimate might well remain more or less as they are today for an unpredictably long time, independent of the decisions the CCU will take.

Dr H. Bettin opened the questioning by stating that Dr Bich's graph of the time evolution of h did not take into account the lengths of time between different CODATA re-evaluations. Dr Bich replied that time did not make a good abscissa in this case, the axis is instead a kind of ordinal quantity relating to the 'number' of the experiment in the event domain. Dr P. Mohr and Dr M. Krystek also agreed that time was not related to the evolution of the data presented. Returning to the consistency of the results presented Dr Brown added that these were still much better than is seen for many comparisons primary standards. Dr Newell then asked whether the

conclusion about the consistency estimate not changing for a long time related to new data of the average of the data set, and whether this would depend on whether uncertainties were reduced or not. Dr Bich did not think the conclusions would change if the uncertainties decreased and still expected the weighted mean to fluctuate around the current mean. Dr Bich went on to address a point that relating to his previous experience as a mass metrologist and put any current lack of consistency in perspective. When weighing in air and correcting for air buoyancy the corrections are based on the reference density of air and of the masses pieces used. Dr Bich observed that many years ago when the reference weight pieces changed from brass to stainless steel there was an immediate offset of 7 ppm in the density correction and mass measurement was able to cope with this.

Dr A. Steele ended the discussion by noting that he had performed a similar analysis of the time evolution of *h* with covariances included, and the data was consistent. He added that once the data is consistent there is no longer any reason to consider extrapolation over time or in the event domain. Dr Steele concluded by stating the corollary to this was that the community would not have been wrong had they fixed the value of *h* years ago but that the uncertainties would have been unacceptably large, but now they are not.

3.4 Summary of new experimental results expected in the short term, and long-term plans of primary realization

Dr de Mirandés reported on the results of the questions asked to CCU members about plans for new experimental results in the short term and about longer term plans for primary realizations. All NMIs who replied plan sustainable, long term operations of realizations of the kilogram after the redefinition, and at least over the next 10 years.

A number of efforts to resolve current inconsistencies in the determination of the Planck constant where planned, in particular PTB planned additional measurements of the Si spheres and in the next three years more silicon sphere were to be produced. However, it was clear that relatively little activity was planned up until the end of 2017 that would be significant on the timescale of the proposed revision of the SI, the main contributions were expected to be: a competitive Kibble balance result from METAS, a Kibble balance uncertainty of below 5×10^{-7} from KRISS, and that PTB expected better agreement of the XRCD experiment for the two Si crystals at least in the range of one standard uncertainty. Much more activity was expected over the next three years and Dr de Mirandés showed expected improvements in the uncertainty of the determination of *h* from 2017 to 2020. In the further future, the situation was extremely positive with at least 11 NMIs and the BIPM planning to operate primary realizations of mass at least over the next ten years.

Dr Brown started discussion of the presentation by again questioning whether the predicted uncertainties would really be reached by 2020 since, if these were taken on face value, this would provide an over-positive picture of the benefits of delaying redefinition. At this point Dr Taylor related a quote from Nobel laureate Steven Chu, “The reason I can see so far is because I am so far away.” Prof Ullrich argued that redefinition would trigger many other experiments but shouldn’t rely on them. Dr C. Williams agreed, stating that most NMIs were already working on national realizations and so there would be the same collective effort whether we re-defined now or in a few years. Dr Steele remarked upon how hard it was to make a difficult experiment better and added that all these laboratories are starting this now in order to realize the kg and that this was easier to justify funding for than for research into measuring *h*. He concluded by saying that there was just as much science to do regardless of whether the experiments were aimed at

redefinition or realization. Prof Ullrich reminded the CCU that the discussion should be focused on scientific rather than funding or political considerations. Dr Mohr felt that it didn't look as though there would be much more improvement in measurements in the short to medium term. Dr Wood reminded the CCU that realization would open up improvements and possibilities across the whole mass scale using other scientific routes. Dr Newell added that for atomic masses recoil experiments could be used. Prof Ullrich stated that he had heard from practitioners that there was unlikely to be much improvement in uncertainty at low masses. Dr Williams stated that between 1 mg and 10 µg NIST had been able to achieve improved uncertainty, but below that artefactual considerations begin to dominate the uncertainty. Mr K. Banholzer added that he agreed some uncertainties would decrease. However, he was more worried about the measurements of ng and pg masses that were required for new medicines, especially designer medicine. He expressed the need for stable values that are comparable and that these must be available to all users, and that for critical applications the community cannot afford to see difference from region to region. Returning to the comment on medicine, Dr R. Davis replied that one shouldn't mix up relative and absolute uncertainties and that even for very small doses in medicine these can be achieved with an uncertainty of 0.1 %, which is easily fit-for-purpose.

3.5 Report from the CCM of the fulfillment of their requested conditions and on the plans for mass dissemination after the redefinition

Dr P. Richard began his presentation by reminding the CCU that the international prototype of the kilogram is the only unique artefactual standard still in use. He then displayed and reviewed the joint CCM/CCU roadmap of the revision of the SI and reiterated the CCM conditions on consistency, uncertainty, traceability and validation. He noted that he believed these conditions had been fulfilled, although whilst observing that uncertainty expansion (of about 30 %) on the data supplied were required to force consistency, but that even with this the other conditions were still met. This conclusion of the CCM was then formulated into CCM Recommendation G1 (2017) to the CIPM which recommends to that the CIPM undertakes the necessary steps to proceed with the planned redefinition of the SI at the next meeting of the CGPM, acknowledging the measures to be taken by the CCM to ensure uniformity and continuity in the dissemination of the kilogram. In commenting on this recommendation Dr Richard stated that the recommendation was the result of a compromise obtained after long discussions during the CCM meeting. The objective of this compromise had not been to slow down the redefinition process. It had been proposed to initially use a consensus value for dissemination and this was summarized in the *mise-en-pratique* (CCU/17-07.1_04) and the forthcoming paper on the 'dissemination of the kilogram' (CCU/17-03.5_01) which were made available to the CCU prior to the meeting. Dr Richard then explained the proposed traceability and dissemination routes prior to, and after redefinition. He noted that whilst the uncertainty of an end user reference standard might have increased from 15 µg to 25 µg, this now came with an assurance of the stability of this value over time.

Dr Richard concluded by explaining the temporary use of a consensus value. This would mean that realization experiments would disseminate a consensus value instead of their own value by applying a correction to their locally realized value, until the dispersion of results was compatible with individual realizations. The consensus value would be obtained from a comparison of all realization experiments. It would be broadly equivalent to a key comparison reference value. Dr Richard stated that he was sure this approach would ensure the CCM was ready for the redefinition of the kilogram in 2018 although that the CCM was nevertheless

expecting new results for the determination of *h* to be taken into account at least until the end of 2017. Dr Richard expressed his pleasure that a large number of primary realizations were also in preparation, including using simpler, lower cost methods.

Opening the questioning of the presentation, Prof Ullrich asked with what uncertainty a laboratory having a primary realization would disseminate this after it was corrected from the difference to the consensus value and how this would relate to the uncertainty of the set of mass artefacts at the BIPM. Dr Steele answered the question by stating that the individual uncertainty would be consumed by the uncertainty of the consensus value and by using this process there is more information that one laboratory would have had on its own. Dr Steele added that the CCM decision was made now so that there was plenty of time to work on the precise details and the start of this was already detailed in document CCU/17-03.5_01.

Prof Ullrich then asked when the Key Comparison would next be repeated. Dr Richard suggested that the ongoing Key Comparison would start after the CCM meeting in 2019. Prof Ullrich pointed out that this would mean the first new realization may be not before 2020 and by this point there may be additional data and experiments to consider. At this point Dr Steele reminded the CCU that the community already has the IPK and that the traceability chains surrounding this within the existing system will not change on the day of redefinition, but will be augmented by the extra science we have done. He emphasized that dissemination will be continuous across the transition. Dr Williams added that the community will continually update the consensus value as new data comes along and the CCM will decide exactly how this is done. Dr Quinn stated that at the moment of redefinition the uncertainty in *h* moves to the IPK, but its mass remains linked to the ensemble of masses at BIPM and the uncertainty of the ensemble is well known and linked to the uncertainty in *h* at the time of redefinition. He stated that this ensures a seamless transition, and in future one could consider the consensus value process in the same way to how TAI operates, where a consensus value is produced that is steering gradually over time. Dr Steele agreed that the BIPM set of masses are linked to the IPK with a very small uncertainty and all the apparatus for mass dissemination remains in place. Dr M. Stock added that one of the objectives of the CCM pilot study was to test consistency with the IPK, the BIPM working standards and other copies and that this was achieved within 1 µg. At this point Dr J. Stenger asked what the concerns of the weighing industry might be. Mr Banholzer noted the increase in disseminated uncertainty from 15 to 25 µg and that for calibration laboratories dealing with E1 masses this should be acceptable but the community must ensure that all biases are eliminated. Prof Ullrich confirmed that the use of a consensus value should ensure this is not a concern. On this topic Dr S. Schlamminger reminded the CCU that there was a statement in 2010 from the CIML president at PTB stating that a realization within 30 µg would be acceptable for the legal metrology community.

Dr Stenger reflected that the CCU had listened to the presentations and some of the problems and now suggested that it was important to hear whether the proposals met the requirements of the stakeholders. Dr G. Dudle stated from an OIML point of view an E1 mass must have reference standards with uncertainties of 30 to 40 µg and the new proposals would fulfil this. He reminded the CCU that OIML still supports the CGPM's intention to revise the SI, and whilst this will be discussed again in 2017 any change in this point of view is unlikely. Dr Quinn interjected at this point stating that amongst stakeholders there is still some misunderstanding. He stated that one aspect to consider is the experiments to determine a consensus value of *h* and the other aspect is related to the dissemination of mass. He continued that at the moment of redefinition the uncertainty in *h* is applied to the IPK and to the BIPM mass set, which was shown to agree within 1 µg, and to this we add the uncertainty in *h* which will be very small, and

concluded that the answer for end users is that they will not see a difference. Dr Steele added that managing air buoyancy was very important, and that making comparisons in vacuum allows the uncertainty of realization to be traded off against the uncertainty in buoyancy correction. He stated that the CCM were the experts in mass determination and yet he felt their assurances were not being taken with sufficient weight and he implored the CCU to trust the CCM in this respect.

At this stage Dr Milton summarized the situation. He stated that what he had heard had been very encouraging and that thinking had moved along substantially since the CCM meeting. He cautioned against reference to the CIPM MRA when describing the consensus value process since the two processes were different. Under the CIPM MRA, when a laboratory is discrepant this can result in larger uncertainties, however what is being discussed as part of the consensus process is the dissemination of values. Dr Milton reminded the CCU that, as an example, when masses traveled to BIPM they will travel back with different values assigned, and this was not quite how the CIPM MRA worked. In order to ensure than these subtleties were understood Dr Milton encouraged the CCM document explaining how the consensus values is reached and disseminated to be completed as soon as possible.

Dr Krystek reminded the CCU that revision of the SI has benefits for all units, and that all the units are unchanged and it is only the uncertainties that move about. He also stated that the IEC was also pleased that the conventional electrical values fixed in the 1990s will come back within the SI. Dr Banholzer agreed that the SI was about more than just mass, but that mass was a special case when redefinition was being considered. Dr de Mirandés stated her conviction that nothing would change after redefinition but expressed more concern about how this consensus value would change over time and how discrepant realizations would be dealt with. Dr Steele replied that he understood the concerns that were being voiced about giving up a realization with zero uncertainty. He reminded the CCM that dispersions in realizations would be the job of the CCM to manage and that in future there will be no significant difference between realizations. Dr Williams stated that he felt that handling outlying values might shift the consensus value by up to 5 µg but this would still be all within the uncertainty of dissemination. Prof Ullrich countered that jumps between 10 and 20 µg could not be ruled out over the next few years. Dr Williams disagreed, explaining that whilst individual realizations may change the consensus value will not change dramatically. He added that as more and more values are added into consideration the harder it will be for individual values to cause a change in the consensus. Referring to the shift in the 'as maintained' BIPM mass unit of a few years ago, Dr Williams stated that a change of 35 µg was experienced in a very short time and the mass community was able to manage that. Dr M. Himbert remarked that even if there were slight changes in the future, these were most probably minor in comparison to changes in the mass of the IPK in the past. The difference would be that future value would be based on a stable reference. Dr Krystek reminded the CCU that once the value of *h* was fixed it would be possible to determine whether the mass of the IPK was changing. Prof Ullrich concluded the discussion by offering the suggestion that a logical point to redefine would be where measurements of *h* were of sufficiently low uncertainty that changes in the mass of the IPK could be easily detected. He proposed that the community was not yet at that point.

3.6 First discussion on the recommendation from the CCU to the CIPM on the redefinition of the SI in 2018

Prof Ullrich invited statements from other CCs and member organizations on the recommendation from the CCU to the CIPM on the redefinition of the SI in 2018.

3.6.1 CCEM

Dr Rietveld remarked that the revised SI has a major advantage for the CCEM community in bringing electrical measurements back within the SI. Dr Rietveld noted that the present practical realizations based on quantum standards will become direct SI realizations. He went on to state that it was also a major change for the community explaining that, in the context of previous discussions, it represented a mass equivalent change of 1 mg. This step change would be handled according to the guidelines being produced by the CCEM and in fact would only be noticeable outside NMIs to a few very high-level calibration laboratories. Dr Rietveld noted that the CCEM community need a fixed value of *h*, but (within reason) the actual value was not important. Dr Rietveld concluded by stating that the CCEM prefers an implementation of the revised SI as soon as possible given the advantages to the CCEM community and the extensive stakeholder community so far and that whilst a delay was not impossible it would be far from ideal. Dr Rietveld also observed that any advances in quantum standards in future would impact directly on SI realizations.

Dr Milton opened discussion of the topic by mentioning that the current definition of the ampere tells the user in which form Maxwell's equations should be written in the SI. Although this will not change in the revised SI, the definitions no longer give any information about the preferred form for Maxwell's equations. Dr Milton asked the CCEM and the CCU to ensure that the new *mise en pratique* stated which ways of writing Maxwell's equations should apply. Dr Brown agreed with this suggestion noting that the recent paper in Metrologia by Dr P. Quincey and Dr Brown on units systems had made exactly this suggestion, giving examples of how this issue could be resolved. Dr Bich commented, referring back to previous discussions, that the time evolution of the CODATA value for *e* was very similar to that for *h* and that if one had concerns about the time evolution of *h* and its consequences then one should also be concerned about the time evolution of *e*. Dr Karshenboim replied that this discussion referred to the time evolution of our ability to measure these quantities, not of the quantities themselves, and Dr Newell added that the real test of time evolution of measurements come from observation of the fine structure constant over cosmological timescales.

3.6.2 CCT

Dr J. Fischer presented the views of the CCT starting with a presentation of the final state of Boltzmann constant determinations. The history of CODATA adjustments of *k* also showed good consistency over the years and the latest three values have all involved three different measurement methods. Dr Fischer stated that the adjusted value of *k* has a relative uncertainty of 0.37 ppm, well below the CCT requirement, and that there were three methods with uncertainties below 3 ppm (one more than was required). All the data agreed well and there was no reason not to go ahead with redefinition. Dr Fischer also noted that there was no correlation to other constants being considered. He further went onto to consider that all the current methods had reached their technical limits and many of these experiments had now terminated. As such, it was suggested that NMIs now needed to concentrate on implementation at high and low temperatures where the new definition will have most advantages. Indeed, Dr Fischer observed that many NMIs already realized the kelvin with thermodynamic methods. Dr Fischer concluded by stating that the CCT has recommended to the CIPM that a fixed numerical value of the Boltzmann constant with 8 digits should be adopted for the definition of the kelvin, and more generally it was the CCT's preference that all four units were defined as scheduled.

Following the presentation Dr Newell agreed that because of cross-relationships between constants it was far preferably to redefine everything at once. Dr Rietveld observed that because the eighth digit of the current CODATA adjustment is a zero there would be an option to only use seven digits since the final zero is likely to be dropped in future usage. Dr Davis concluded discussions on the presentation by clarifying from the time series of CODATA adjustments for *k* that a few experiments had just missed CODATA deadline as so it had been several years until they were included in the overall evaluation. Dr Davis observed that this was another good reason not to consider the evolution of measurement of constant in the time domain.

3.6.3 CCQM

Dr B. Güttler presented the CCQM position with regard to the CCU recommendation. He began by stating that, whilst a full discussion within CCQM had not taken place up to this point, the CCQM clearly does not have the same requirements for accuracy as the CCM. Mass determinations are of central importance in quantitative chemistry and the continuity conditions imposed on redefinitions of SI base units have ensured that the molar mass constant M_u is still 1 g/mol with finite, very small relative standard uncertainty ($< 1 \times 10^{-9}$). This is thirty times smaller than the relative uncertainty achievable in the most accurate realization of the mole and several orders of magnitude smaller than the uncertainties in examples of more common realizations of the mole. Dr Güttler stated that the implications of this was that the redefinition has no effect on the work of chemistry in practice – although he further noted that chemistry made decisive contribution to the requirement of the other CCs, in particular for the molar mass determination of silicon. Dr Brown added at this stage that molar mass determination was also crucial in the acoustic gas thermometry experiments to determine *k*.

Dr Güttler concluded that the CCQM had demonstrated its commitment to redefinition and had contributed to the work related to the redefinition at the highest level of accuracy, but that neither fixing the Avogadro constant now, nor a delay until later, is critical for CCQM. He elaborated that the CCQM expects that the data provided should also not be wasted by long delays in the redefinition process and that therefore a clear route and timescale for the process should be fixed.

Dr Brown opened comments on the presentation by stating that he felt the new definition of the mole would allow for more accurate realization of chemical amount at very tiny amounts where molecular counting was feasible. Dr Brown also pointed out that the redefinition meant that the molar mass scale and the atomic mass scale would have the same relative uncertainty which provided a pleasing symmetry for chemists. There followed some discussion, led by Dr Krystek about to what extent the molar mass constant would change as a result of this redefinition. Dr Newell replied that when the molar Planck constant is fixed the exactness of the molar mass constant has to be sacrificed to avoid an over-constrained system, adding that there were long discussions about what constants could have their numerical values fixed very early on in the current process. Dr Davis added that the uncertainty in the atomic mass unit is reduced by over an order of magnitude. Dr Taylor pointed out that retaining the definition of the atomic mass unit as 1/12 of the mass of a ^{12}C atom ensured that all relative atomic masses would remain unaffected.

3.6.4 Other institutes and organizations

At this stage Prof Ullrich invited other institutes and organizations who had submitted comments to the CCU prior to the meeting to present their views with respect to the CCU recommendation.

Dr Brown began by presenting NPL's position. NPL were in total agreement with the recommendation of the CCM to proceed with the current schedule for the revision of the SI and specifically with the redefinition of the kilogram. It was NPL's view that the "discrepancy" in the reported values for the Planck constant is not an atypical situation in the history of these, and indeed all, measurements. NPL's felt that the published values contributing to the CODATA value for *h* represent a suitably and sufficiently consistent set of data to allow redefinition. NPL believed that the fixing of the value of the Planck constant using this data set will not lead to any significant change in the mass scale in future. Hence it was, in NPL's opinion, sensible to proceed as outlined in the CCU/CCM roadmap. Dr Brown went on to state that the use of a consensus value for the kilogram under the control of the CCM, arrived at through a comparison of primary realizations, was a sensible and pragmatic solution to the apparent discrepancy in the realization experiments and will ensure the ongoing uniformity of the world-wide mass scale.

For the CIE, Dr P. Blattner reminded the CCU of the lessons learnt form the decision to redefine the candela in 1979. He stated that despite the discrepancies that existed the CGPM decided to go ahead with redefinition, and quoted the former BIPM Director Dr J. Terrien at the time, "the new definition broadens the range of methods available for its realization and paves the way for progress". Dr Blattner concluded by stating that the CIE supported this fundamental conceptual change in the SI.

On behalf of OIML Dr Dudle referred to his earlier statements expressing support for redefinition and also demonstrated again that the increased uncertainty in the disseminated mass scale would not be significant for legal metrology although he cautioned careful adherence to the CCM recommendation to ensure continuity and avoid negative impacts. He concluded that OIML supported the CGPM's intention to revise the SI.

Dr B. Jeckelmann presented the METAS view. He summarized that there were no 'show stoppers' to the decision to go ahead with redefinition in 2018, although he proposed that the time period available up to the proposed date for redefinition should be used to collect and consider more experimental data, should this become available.

This suggestion then prompted a debate on whether the cut-off for accepting new data should be extended. Whilst Dr Krystek felt this was a positive decision, Dr Brown felt this was not fair since, had people who submitted data known the deadline was to be extended, they would have done things differently; Dr Mohr agreed. Prof Ullrich wasn't sure that any more significant data would be expected in the near future anyway, but wondered if there was an extension what the final date for the data might be. Dr Stenger stated that since the current data shows systematic biases it would be useful to accept as much extra data as possible. Dr Steele countered that the only real reason for extending the data deadline would be to allow data from the Avogadro experiments to be considered together as a single value within the CODATA least squares adjustment. Dr Williams expressed concerns that, whilst the resolution sent to the CGPM did not necessarily need to contain the final values, extending the deadline for data would potentially allow discrepant data to come back into the data set putting extra pressure on the final CGPM decision. Dr Milton reminded the CCU of the fixed timescales leading up to the CGPM, such that documents needed to be sent out nine months prior to the meeting. He added that it would send a strong sign of confidence to the CGPM if the final figures were available by that date, which would mean that there could be very little extra time, if any, to consider new data. Dr Quinn summarized the situation by stating the question about data comparability would not have

arisen were it not for the latest IAC-17 values and so it was only worth waiting for new data if the discrepancy relevant to this value was going to be resolved on this timescale. Dr Bettin replied that PTB were working hard on this topic currently, and a new Si sphere was expected in six months. Dr Quinn cautioned against any rush to do this. He stated that whilst the situation need to be resolved it was better, given the plans for an ongoing consensus value, to carry on with redefinition and then sort out this issues in less of a rush afterwards. Dr Mohr felt that there is always the promise of more data just around the corner and so at some point a hard deadline needs to be drawn. He added that the planned timescale allowed opportunity to disseminate the values and information about the change to stakeholders which would be lost if the timescale for accepted data was extended. Dr Richard countered that the CCM would be open to accept more data if this was possible and Mr Banholzer agreed that more experiments would be preferable. Dr Newell disagreed, stating that the criteria were already met. Dr Fujii added that even if the deadline was extended there was unlikely to be a dramatic change in the CODATA values produced. Prof Ullrich concluded what had become a lengthy debate by stating that there was consensus that if the CCU proposes to go ahead with redefinition then it was also sensible to continue with the present roadmap.

Presenting on behalf of NRC, Dr Steele stated that NRC supported redefinition in 2018, arguing that all technical requirements had been met and that there was endorsement from the relevant CCs. NRC emphasized that CCU oversight is important to ensure that there is no inconsistency in the system, which would be an impediment to redefinition. Dr Steele proposed that the CCM dissemination of consensus kg remains appropriate while individual realizations are introduced and improved around the world, and he concluded by encouraging CIPM to extend data deadline to enable publication of IAC consensus value for use in the CODATA analysis. Dr Mohr replied stating that CODATA had considered the possibility of using an IAC consensus value but when this was done the Kibble balance data didn't look as consistent.

Dr Bettin presented the PTB view. It was felt that the consistency requirement from the CCM Recommendation G1 (2013) was not met and this would result is a loss of prestige of the SI in industry and science and the aim of the new SI to achieve great stability would not be met. Dr Bettin highlighted the remaining 70 µg discrepancy between NIST and PTB as evidence of this. He then presented a slide which showed that drift in the copies of the IPK since 1889 may have amounted to 50 µg and stated that this was a concern, but that a bigger concern was the change in the CODATA evaluation of *h*, which Dr Bettin represented as a line representing a change of 192 µg over the last 16 years. In summary PTB recommended gaining more measurement results from current and future mass realizations experiments prior to realization. He proposed that a delay by one CGPM would be too much but a postponement by two years or so would allow for better data and results. This provoked a heated debate on the presentation of the data and the conclusion that had been drawn. Dr Mohr stated that he didn't think that any past change in the measurement values of *h* was a good predictor of what might happen in the future. Dr Newell added that Dr Bettin's diagram did not include all national copies on the IPK some of which showed more dramatic shifts than the ones Dr Bettin displayed. Dr Himbert added that the graph presented did not compare things that were the same, stating that a comparison of mass pieces displays relative accuracy whereas the other plot examines improvements in measurements of a fundamental constant over time. Dr Wood argued that as plotted the variation in *h* was just displayed as a linear trend and was misleading but in reality, it was tending of a consensus value with an increasingly small uncertainty. He also added that Kibble balance experiments go back for a longer time than the CODATA evaluations of *h*. He concluded that mass metrology had improved only incrementally over a long period of time, whereas Kibble balance and Avogadro experiments had improved by many orders of magnitude over the same time period. Returning

to the trend in the CODATA evaluations of *h* that Dr Bettin displayed, Dr Steele argued that this plot did not show the uncertainties in these evaluations and when this is done it is seen that the values are consistent within their uncertainties over time. Dr Williams added that a NIST evaluation of current data showed that choices of different subsets of data produced a value that only moved around by a few ppb, and this was likely to be even smaller in future. He reminded the CCU that the CCM has a plan to deal with differences in sovereign realizations if these arise. At this stage Dr Quinn hypothesized that in arguments about whether evaluations of *h* showed a significant trend over time were colored by the fact that the slope of the data observed was an artefact of the fitting procedure and was in no way related to drift. Furthermore, the uncertainty in this slope was very large. He further added that these CODATA evaluations are not repeats of same experiments, they are evaluations of the best data available at the time, and as such it is not appropriate to fit trend lines through them. Prof R. Marquardt added that he thought that this progress in data showed our ability to improve experiments over time. Adding to the debate on data fitting, Dr Krystek stated that the data represented a heteroscedastic data set and so was not amenable to performing the normal linear regression procedures. He went on to state that referring to drift in this contest was not appropriate since these data should not be plotted in the time domain. Concluding the discussions Dr Taylor added his personal opinion that the most recent IAC-17 value had underestimated their measurement uncertainty as a result of determining the lattice parameter as an extrapolation and not as a separate experiment.

Dr Schlamminger presented the NIST position on redefinition, initially returning to the subject of time series plots, but now showing evolution of the uncertainty and consistency in individual evaluations of *h* and how this had improved over time. He also went on to mention the changes in the CODATA values and that new CODATA values supersede previous values and so it made no sense to consider trends, especially since if and when errors are spotted in historical data these are not corrected retrospectively. He concluded by stating NIST's belief that redefinition should go ahead as planned.

Dr F. Piquemal stated that LNE were in favour of redefining the kilogram in 2018 relying on the vales of *h* accepted before 1st July 2017, expressing the conviction that the four CCM conditions were strictly fulfilled.

Prof Ullrich then invited institutes and organizations who had not so far spoken on this topic to express their opinions. Dr E. Prieto Esteban stated on behalf of CEM that redefinition should go ahead on the planned timescale. Dr L. Vitushkin stated on behalf of Rosstandart that redefinition should go ahead as planned. Dr N. Capitaine stated on behalf of the IAU that they were in favour of redefinition as proposed but had no opinion on the optimum time for this to occur. Dr H-G. Menzel on behalf of the ICRU expressed a neutral opinion, since the redefinition had no effect on the radiation community. On behalf of IEC Mr P. Sebellin abstained stating that redefinition would have a low impact on the work of the IEC and trusted the CCU to take the right decision. Dr Krystek stated that ISO abstained on this matter but that his personal opinion was to go ahead with redefinition. Prof Marquardt said that IUPAC were in favour of redefinition on the timescales agreed and Prof V. Bagnato confirmed that this was also the position of IUPAP. Dr I. Yang said on behalf of KRISS that whilst there was no reason to delay redefinition but that if there were a delay in the final deadline for data to be accepted it may be that KRISS would contribute relevant values. Dr J. Zhang stated that NIM took a neutral stance on redefinition of the kilogram but were otherwise if favour of going ahead with redefinition. The view of INRIM, said Prof D. Wiersma, was that very good work had been done and they supported going ahead with redefinition. Prof Ahmadov stated that UME supported a delay in the deadline for data to be accepted. Moving onto the personal members of the CCU, Dr Quinn remarked that there was

a reputational risk to metrology if the community did not go ahead with redefinition and that he was very much in favour of proceeding on the planned timescale. Dr Himbert stated that he was in favour of going ahead with redefinition, adding that if there was something hidden in the physics of the realization experiments that was not currently apparent we might uncover this in the future but that the community would deal with this as they had many times before.

Following this round table expression of views, Dr Newell stated that CODATA officially remain neutral with respect to redefinition but that the personal views of all the committee's members were to go ahead with redefinition. Dr Rietveld added a personal opinion that the CODATA value was robust and would not change substantially with additional data and so redefinition should proceed. Dr M. Rastello added that the community should learn the lessons of the bravery of the CCPR 40 years ago and go ahead with redefinition, although she stated her support for taking advantage of the time remaining to collect more data.

3.7 Discussion on the redacted text of the CCU recommendation to the CIPM

Prof Ullrich introduced the proposed options for the text of the CCU recommendation to the CIPM. Given the almost unanimous support for going ahead with redefinition it was clear at this stage that the CCU recommendation should be edited to provide a positive recommendation to the CIPM. Prof Ullrich noted that work was also recommended on the CCM document describing the dissemination of mass traceability following redefinition, although this was a matter for the CCM.

There followed some discussion of the exact text of the recommendation. Dr Stenger reflected that CCM Recommendation G1 (2017) was important in this context and should be referred to in the CCU recommendation. Dr Steele thought that perhaps the text could be taken as implying that the CCU was already considered to have accepted the CCM Recommendation G1. He added that the section on realization currently made little sense and the CCU should come up with language that acknowledged the support and input of the CCEM, CCQM, CCT and CODATA as well as the CCM. This was followed by some discussion about how the current discrepancy in the data was handled in the recommendation. Prof Ullrich stated that whilst the uncertainty in the consensus value may decrease but the discrepancy in the data may well remain the same. Dr Wood argued that the discrepancy between the Kibble balance and Avogadro experiment would not be a permanent feature unless errors in the underpinning equations were uncovered, which was thought to be unlikely as this would represent completely new physics. Dr Steele argued that the recommendation should contain text to state that the SI system will be the same following redefinition but will be stronger and more amenable to accommodating future scientific improvements. Prof Ullrich curtailed discussion, suggesting that the detailed editing would need to be performed by a drafting committee and brought to the CCU for its approval during the second day. Prof Ullrich proposed Dr Milton, Dr Williams, Mr Massa, Dr Fujii, Dr Steele, Dr Stenger and Dr Richard to constitute the drafting committee.

Bringing the first day to a close Prof Ullrich asked PTB as the only CCU member strongly against revision of the SI on the proposed timescales whether they would be able to tolerate the majority decision of the CCU. Replying to this question Dr Stenger said that, yes, PTB had presented its arguments but if they were not supported more widely then it was important to accept the majority opinion and proceed. This magnanimous reply triggered a round of applause from the meeting participants and clearly signaled that the CCU would recommend to the CIPM to proceed with revision of the SI on the previous agreed timescales. This brought an end to the first day of the meeting at 1730hrs.

4. REVIEW OF THE EXPERIMENTS THAT HAVE CONTRIBUTED TO THE DETERMINATION OF THE BOLTZMANN CONSTANT *K*

The second day of the meeting opened at 0900hrs with Dr Fischer presenting the data from experiments that had contributed to the determination of the Boltzmann constant. Dr Fischer highlighted the timeline of efforts of the last 15 years in the area. He mentioned the four independent methods that were available for determination of *k*, and then reviewed the results from acoustic gas thermometry (AGT) experiments at LNE and NPL that had contributed to two results with the lowest relative uncertainty determination of *k* at 0.6 and 0.7 ppm, respectively. The NPL result had initially highlighted some discrepancies in the experimental method that had been resolved by the execution of very precise molar mass measurements of the argon gas used. The AGT experiments at CEM, INRIM and the NIM-NIST experiment, which used a cylindrical resonator, were also presented. The challenge for the PTB dielectric-constant gas thermometer had been the measurement of pressure to a relative uncertainty of 1 ppm, to allow an overall relative uncertainty of the determination of *k* of 1.9 ppm. The refractive index gas thermometer at NIST, and the Johnson noise thermometer experiments at NIST, NIST/NIM and NMIJ/AIST were also reviewed. It was noted that Doppler broadening thermometer experiments had also been performed but the uncertainties of these were not competitive. Dr Fischer then reviewed the data considered by CODATA, which formed a consistent set and a much clearer picture than for the previous discussions of *h*. Dr Fischer concluded by stating that the data had met all the conditions of the CCT and as a result the CCT had earlier in the year agreed CCT Recommendation T1 "that the CIPM finalizes the unit redefinitions through agreeing to fix the values of the fundamental physical constants, from which a fixed numerical value of the Boltzmann constant with 8 digits will be adopted for the redefinition of the kelvin".

5. CODATA TGFC REPORT ON THE ANALYSIS OF THE FINAL EXPEDRIMENTAL DATA

Dr Newell introduced the topic by stating that Resolution 1 of the 24th CGPM in 2011 had invited CODATA to continue to provide adjusted values of the fundamental physical constants based on all relevant information available. Dr Newell stated that it would be these CODATA values and uncertainties that will be those used for the revised SI. He proceeded to review the methods by which the fundamental constants had been determined prior to CODATA. This task had been taken over by the newly established CODATA TGFC in 1969. Dr Newell then explained the observational equations that were used to relate the constants being considered, and highlighted the least squares adjustment methodology used to provide the values of these constants. Dr Newell stated that as per Decision CIPM/104-09 of the 104th CIPM meeting in 2015 the cut off for new data to be accepted for publication was the 1st July 2017. Dr Newell reviewed the data that had been available to CODATA after this date. As had been discussed previously Dr Newell showed that the data for *k* formed a consistent set, but the data for *h* required an expansion factor to be applied to the quoted uncertainties to ensure a consistent data set. Dr Newell then reviewed the CODATA 2017 values of *h*, *e*, *k*, and N_A and the number of

digits to which these would need to be fixed at the point of redefinition to ensure $m(K)$, μ_0, and $M(^{12}C)$ remain consistent within their relative standard uncertainties, and that T_{TPW} remains consistent at the level it can be presently realized. The CIPM had chosen, on the recommendation of the CCU, to fix the minimum number of digits to meet these requirements. Dr Newell highlighted that it was the uncertainty in the fine structure constant that determined the number of digits of *h*, *e*, and N_A. This would imply the use of 8 digits for *k*, but since the final significant digit is a zero it is likely that this final digit would be dropped. Dr Newell concluded by listing the other constants that would experience improved uncertainties following redefinition, stating in particular that all energy conversions would have no uncertainty.

Dr Brown opened discussion by stating that he was aware that a new result *k* from VNIIFTRI, originally published in Russian in a Russian journal, and asked Dr Newell whether this result would be included and if it was what effect it would have. Dr Newell replied that he had been notified about this result in late August and he was currently determining whether the work met the administrative and technical requirements for acceptance. Dr Newell noted that if the result was accepted the final digits of *k* would change from '03' to '08' and hence round to 8 digits would result in the final digit being a '1' and not a '0'. Dr Brown suggested that from a purely aesthetical point of view this was satisfying since it meant the full precision with which *k* was fixed would not be lost in the future. Dr Fischer suggested that accepting the result would cause a 10 μK shift in the triple point of water following redefinition but that this would still be acceptable. Dr Newell clarified that initially CODATA would decide whether the data meets requirements for inclusion and will do this in collaboration with CCT. Prof Ullrich clarified that in this case the CCU recommendation to the CIPM would need modification to state that the final value of *k* needed to await this decision.

The situation with respect this new data was evolving in real time during the meeting and by the middle of the second day it seemed apparent that this new data would not be included in the final evaluation of *k*.

6. FINAL RECCOMENDATION FROM THE CCU TO THE CIPM ON THE REDEFINITION OF THE SI IN 2018

The CCU turned its attention to reviewing the updated resolution that had been produced by the drafting committee overnight. Dr Milton reviewed the changes that had been made and each section was discussed in some detail.

There followed relatively lengthy discussions about several aspects of the detailed wording of the preamble to the recommendation that were largely inconsequential to the final conclusion and recommendation, reflecting the nature of editing by committee. Dr Williams felt that progress since 2014 should be specially acknowledged, because of the timeframe set by the CGPM in 2014, whereas Dr Stenger thought this should remain unchanged since progress in these topics was also made earlier than 2014. Dr Bettin felt that an explicit statement should be included about the extraordinary mass comparison that had taken place, whereas Dr Steele felt it was enough that this was already refereed to implicitly in the acknowledgement about significant advances being made in these topics. Dr R. Wielgosz and Dr Rietveld intervened at this point to state that neither the CCQM nor the CCEM, respectively, had produced resolutions supporting

redefinition that could be quoted within the CCU recommendation. Dr Steele felt the recommendation still needed to reflect the support of the CCEM and CCQM for redefinition. It was felt that a better form of words could be found to reflect this although Dr Quinn thought that the final solution was not too important since the CCQM and CCEM presidents would be in the meeting when the decision was made by the CIPM and would be able to properly represent the views of their CCs. Where the recommendation referred to 'defining constants' Dr Taylor pointed out that the current SI used defining constants so this phrase should be made more specific. Dr Brown suggested that a change to 'new defining constants' would solve the problem. Since detailed matters were being discussed, Dr Brown continued, stating that the preparation of the SI Brochure was referred to as being 'well advanced' whereas in fact this under-recognized its current status which Dr Brown proposed should be nearer to 'close to completion'. Prof Marquardt was also keen to recognize that the dispersion in value referred to related to the Avogadro constant as well as the Planck constant and the text should be changed accordingly.

At this stage Dr Taylor expressed concern that the CIPM would be confused about the plans to disseminate the unit of mass after redefinition and hence a short document would be required for the CIPM to explain how this would work. Prof Ullrich agreed, stating that the President of the CIPM had asked for this document including the mathematics that would be used to generate the consensus values. Dr Richard responded that the CCM has prepared a first draft of such a document and this will be available in advance of the CIPM meeting. He noted that this was being prepared by the authors of document CCU/17-03.5_01 plus Dr Steele. Dr Steele added that the CCM had already put substantial work into this document. He went on to say that it was important to remember that the architecture of the measurement system in place doesn't change at the point of redefinition since the IPK will still be equivalent to exactly 1 kg at the point of change and this will lead to a seamless transition. Prof Ullrich said that he would still like more clarity in the exact process for dissemination following redefinition. Dr Wood expressed surprise at this request since this was not something that was continually asked of the mass community over the last 128 years, adding that those decisions are often made as requirements dictate but are rarely predefined. Dr Stenger replied that he thought more clarity in the whole process would help, expressing his opinion that the drift in primary mass standards currently is such that it is not thought much will be learnt about this drift from Kibble balance measurements in the near future. He encouraged the CCM to include mass artefacts when including a consensus value, until there is enough confidence in Kibble balance measurements to give information about the drift of mass artefacts. Dr Quinn replied that it was important to consider that the only thing that would change at the point of redefinition would be that the uncertainties present in the measurement of h would switch to the artefactual standards. Dr Steele reminded the CCU of the origins of the consensus values: the collective knowledge of realization determinations has a low enough uncertainty but the individual realizations do not and this why a consensus value is required. He suggested that, whilst the consensus value is not the same thing as a Key Comparison Reference Value currently, these two concepts would approach each other as the measurement technology advances.

Summarizing this final statement and concluding the discussion Dr Richard stated that he foresaw distinct phases following redefinition:

a) From 21st May 2019 until the report of the first inter-comparison, dissemination of mass traceability would be the same as currently (with an additional uncertainty component coming from the definition).

b) From the report of the first inter-comparison to the time when the data from realization experiments are consistent, dissemination of mass traceability would be via a consensus value.

c) From time when the data from realization experiments are consistent into the future, dissemination of mass traceability would be via individual realization experiments

Phase c) is equivalent to the way most NMIs disseminate other quantities currently and the comparability of this stage would be managed under the CIPM MRA.

7. BRIEF REPORTS ON ACTIONS TAKEN SINCE THE 22ND MEETING OF THE CCU RELEVANT TO THE ADOPTION OF THE REVISED SI

7.1 Reports from the Consultative Committees and review on the status of the mises en pratique of the revised SI

7.1.1 CCAUV

Dr G. Panfilo reported briefly on behalf of the CCAUV. Due to historical reasons and technical benefits, other logarithmic scales the neper and the bel had been used in a specific technical area. CCAUV welcomes the draft 9th edition of the SI Brochure which includes those non-SI units as accepted for use with the SI in Table 8. Dr Panfilo concluded that although the future revision of the SI does not make immediate impact to AUV metrology, it will ensure to underpin future requirements for increases in accuracy. It will also enable quantum measurement standards in AUV metrology. In this respect, the revision is beneficial to AUV metrology and the CCAUV supported revision on the timescales proposed.

7.1.2 CCEM

Dr Rietveld reported that the CCEM had met in March 2017 with a half day devoted entirely to the revised SI. It was noted that the CCEM had completed its *mise en pratique* for the ampere and other electrical units and there were no major changes to the version that have already been presented to the 22nd CCU meeting. Dr Rietveld reminded the CCU that CCEM also needed guidelines for the implementation of the revised SI because of the step change for electrical metrology. This guidance for the electrical community was that if their expanded uncertainties were more than 2.5 times the step change there was no need for actions, whereas if their uncertainties were less than 2.5 times the step change the advice would be to numerically correct or recalibrate. There would be a requirement for the whole community to update their reference value of R_K and K_J. Dr Rietveld stated that there had been agreement to use 16 digits (generally the maximum allowed by most software) for R_K and K_J in calculations.

Dr Dudle mentioned that he had observed that the *mises en pratique* across the CCs currently do not use consistent nomenclature, an example being the term ‘base unit’ which is present in some and not others. Prof Ullrich agreed that it would be a good idea to have a common language for these documents that should be as close as possible to usage in the SI Brochure.

7.1.3 CCL

Dr Prieto Esteban reported on behalf of the CCL. He opened by describing the proposed use of the SI lattice parameter measurement (mentioned previously in the context of the Avogadro experiment) as a possibility for length realisation in nanometrology. There has also been discussion with the CCQM on this subject. Three documents were being edited for consideration by the CCL as new entries into the *mise en pratique*. Dr Prieto Esteban went on to raise concern regarding the future availability of stable gas lasers. In industry, the majority of lasers used in dimensional metrology are He-Ne gas lasers – their traceability comes via iodine stabilised He-Ne lasers, typically at 633 nm. Discussion within CCL Discussion Group 11 (lasers) and at a recent CCL meeting highlighted increasing lack of availability of specialized He-Ne tubes (for iodine laser preparation) and of new iodine cells. This was to be discussed further at the next CCL meeting. Dr Prieto Esteban concluded by presenting the updates to the recommended values of standard frequencies for applications including the practical realization of the metre and secondary realisation of the second, and then finally a proposal for a new entry on the BIPM website about the practical realisation of the metre.

7.1.4. CCPR

Dr Rastello gave a short update on behalf of the CCPR. She reported that in 2015 the CCPR finalized the *mise en pratique* for the definition of the candela and associated derived units for photometric and radiometric quantities in the SI and that a joint WG of CCPR and CIE is preparing a more extensive publication "Principles Governing Photometry". Dr Rastello also mentioned the revised text and on-line appendix on photochemical and photo-biological units that had been provided for the draft 9th SI Brochure, and would be discussed later. Dr Rastello concluded by stating that the CCPR supports the revised SI in order for it to become a fully consistent system adding that the candela continues to be linked to the watt and, therefore, the definition of the kilogram. Traceability to the candela can still be established via radiometric methods using absolutely calibrated detectors. However, the best uncertainties in the field of photometry and radiometry are several orders of magnitude larger compared with the expected changes influenced by the redefinition of the kilogram, so there will be no practical change to the field.

7.1.5 CCQM

With the CCM having already given its opinions and the CCRI not represented at the CCU (ionising radiation metrology is not affected significantly by the revision of the SI), Dr Güttler presented the CCQM's position. Dr Güttler highlighted that the CCQM had established an *ad hoc* WG on the mole to deal with many of the issues associated with redefinition. The tasks of the committee included preparation a CCQM draft for a *mise-en-pratique* of the mole, proving a response to the CCU draft of the 9th SI Brochure and a response and input to IUPAC activities, who were a major and very active stakeholder in the process. In particular, Dr Güttler highlighted that the last meeting of the *ad hoc* WG had finalised wording of the draft of the *mise en pratique* of the mole (available at BIPM website), finalised their wording for the Joint CC statement on the revision of the SI, considered and discussed the recommendation of the IUPAC for the redefinition of the mole and, as a result, recommended a revised wording of the definition of the mole to the CIPM. Dr Güttler also mentioned the CCQM pilot study P160 on a

comparison for molar mass of ^{28}Si via the virtual element approach, which has proved crucial for the results of the Avogadro experiment.

7.1.6 CCT

Dr Fischer reported that the CCT had met in June 2017 and the issue of the redefinition of the kelvin represented a large part of the meeting. Notably, information on the techniques that have been employed for the determination of the Boltzmann constant were given and a report on available data was presented. Dr Fischer highlighted once more CCT Recommendation T1 (2017) made to the CIPM recommending going ahead with redefinition of the kelvin. Many of the CCT WGs associated with the work of redefinition had now been closed as their work was finished. Dr Fischer concluded his talk be reviewing the *mises en pratique* available for kelvin realisation via primary thermometers. At least four different methods were currently in operation. Dr Fischer explained that the temperature community would have in parallel primary realisations and a defined temperature scale (via ITS-90). He also highlighted the known relationship between thermodynamic temperature and ITS-90 and how this led to easy conversion between the two quantities. Dr Fischer also explained the relative uncertainties in temperature realisation for thermodynamic temperature and ITS-90. This clearly showed the uncertainty benefits of redefinition at very low and very high temperatures, although in the mid-range ITS-90 still exhibited a lower uncertainty, not least because the fixed points in ITS-90 are assigned zero uncertainty. Dr Fischer stated that for the foreseeable future most temperature measurement in the core temperature range will be calibrated to ITS-90, which will remain intact, with defined values for all of the fixed points including the triple point of water. The uncertainties in ITS-90 will not change and remain dominated by uncertainties in the fixed-point realisations. Dr Fischer went on to say that at the point of redefinition the uncertainty of k is transferred to the value of the triple point of water. He concluded by stating that in the short term thermodynamic measurements and ITS-90 measurement will co-exist but in the long term with the improvement of primary thermometry thermodynamic measurements may replace ITS-90.

Dr Stenger opened the questioning of the presentation by stating his concern that ITS-90 was still a secondary scale of conventional values, not fully traceable to the SI, and thermodynamic temperature must be considered above this in the measurement hierarchy. Dr Williams, referring to the relationship between thermodynamic temperature and ITS-90 asked why the uncertainty in this relationship increased at above 500 K. Dr Fischer replied that this related to the use of different primary thermometers at different temperatures. He added that there was a special arrangement in thermometry whereby the values of the fixed points are assigned zero uncertainty. Dr Steele concluded the discussion by stating that there was a practical temperature scale, ITS-90, and a realisation of thermodynamic temperature, but currently is it easier to realise ITS-90, and that was why no immediate change to temperature dissemination was expected.

7.1.7 CCTF

Concluding the representation from the CCs Mr L. Erard presented on behalf of the CCTF. He stated that no actions had recently been taken relating to revision of the SI as there was no direct impact on the CCTF. He noted that all units, expect for the mole, will in future be related to frequency and the definition of the second. Mr Erard also stated that the last CCTF meeting in June 2017 had considered all new frequency data and had updated their strategy document, including on a possible redefinition on the second.

7.2 Reports from other organisations and institutions

7.2.1 CIE

Dr Blattner began by reminding the CCU of the agreement between the CIE and the CIPM and how this related to the responsibilities of the two organisations with respect to photometric units. He went on to state that the CIE had been involved in the review and update of the *mise en pratique* for photometric and radiometric quantities and the generation of an updated appendix 3 for the draft 9th SI Brochure. Importantly Dr Blattner described the work of CIE JTC 9 on the CIE system for Metrology of intrinsically photosensitive retinal ganglion cells (ipRGC) influenced light response, in ensuring that definitions of new quantities for emerging photometric units were brought back within the SI. He concluded by mentioning the recent memorandum of understanding signed with EURAMET and the ongoing work of the CIE to produce technical publications and documentary standards.

7.2.2 IAU

Dr Capitaine described recent progress within Commission C.A3 on Fundamental Standards within the IAU the outputs recently produced of nomenclature for fundamental astronomy and nominal units for stellar and planetary astronomy. She concluded by reviewing current IAU recommended values for the astronomical constants. Following the presentation Dr Milton speculated that the recent measurements of gravitational waves by the astronomical community claimed a precision of parts in 10^{23} which, if correct, might be the most precise measurement ever made.

7.2.3 ICRU

Dr Menzel highlighted the new reports recently published by the ICRU, in particular on key data for ionisation radiation dosimetry and recommended values that will have impact on primary realization of dosimetry standards at the level of their stated uncertainties. He also mentioned that the ICRU has written (jointly with ICRP) a draft report proposing the revision of the definition of operational quantities for area and individual monitoring for radiation protection of external radiation. The proposal is to use conversion coefficients derived from the radiation protection quantity effective dose and to apply these to fluence or air kerma for the definition of operational quantities, and comments to this document were encouraged. Dr Menzel concluded by asking whether there had been any consequences of the workshop on physiological quantities and SI unit, held in November 2009. Dr Milton stated that, whilst he was not BIPM Director at the time, he was aware that a report had been produced and this covered quantities going beyond just radiation science. He added that if the ICRU had specific concerns or interests in the matter then they should contact the CCRI and that the CIPM continued to be very keen to identify cross-cutting metrology issues when these occurred.

7.2.4 IEC

Mr Sebellin presented some facts and figures about the IEC, not least their 1444 active projects being worked on by approximately 20 000 experts. He reiterated to IEC's requirement to use SI units in their documents and that their approach to uncertainty in measurement was now widely

based on the GUM. Whilst Mr Sebellin stated that the new SI approach will have a low impact on IEC they agreed with the decision to go ahead with revision and were keen that the best value possible for the Planck constant was agreed upon.

7.2.5 ISO

In the absence of representation from the IFCC, next Dr Krystek made a short statement, on behalf of ISO. He reminded the CCU that revision of the ISO 80 000 series of standards was almost complete and that only Part 6 was still under revision currently, but all parts were expected to be published next year.

7.2.6 IUPAC

Prof Marquardt reported that after the 22nd meeting of the CCU, one major IUPAC activity has been IUPAC project 2013-048-1-100 ("Mole Project"). The outcome of this project was a Technical Report, published in Pure and Applied Chemistry giving arguments in favour and against the new definition of the mole and the kilogram, two key units in the work of chemists. Prof Marquardt added that it was based on thorough literature research and a broad consultation among chemists, physicists, National Adhering Organisations and member bodies of IUPAC. In summary, the report strongly favours the currently proposed redefinition of the mole and the kilogram, while suggesting a slightly modified wording of the definition of the mole, which Prof Marquardt said would be discussed later in the meeting.

7.2.7 IUPAP

Prof Bagnato told the CCU that the IUPAP General Assembly would be held in Sao Paolo in October and would include a workshop on new frontiers and challenges in physics, including consideration of SI units and fundamental constants. He went on to describe how IUPAP Commission C2 were putting together publicity material to promote the SI, primary standards and research into fundamental constants, which was expected to be available in October. Prof Bagnato also explained that IUPAP were having a deep discussion about the place of the radian in the SI. This was taking longer than expected. However, when published, he hoped these thoughts would help feed into the debate about dealing with angle in future editions of the SI Brochure. He concluded by stating that a new edition of the IUPAP red book on units and constants was being produced currently.

7.2.8 OIML

Dr Dudle briefly reported on behalf of OIML that work would start later this year to revise all relevant documents to prepare for the proposed revision of the SI.

7.2.9 Académie des Sciences de Paris

This item actually appeared between agenda points 8 and 9, but it has been summarized here together with the reports from other organizations. Prof C. Bordé gave a presentation entitled "On the theoretical foundations of the system of base units". This proposed a new framework for metrology based on natural Planck units which was presented as an introduction. Since the

gravitational constant *G* cannot be presently measured with sufficient accuracy, Planck's mass should be replaced by an atomic mass difference in order to shift from Planck's time to an atomic time. To be consistent, Planck's charge should be replaced by the electron charge. This is the basis of 5-D matter-wave optics. Prof Bordé concluded that this perspective incorporates a natural theoretical framework for the redefinition of the SI which is completely described by the connection between 5D geometry, metric tensor and metrology. He went on to claim that this incorporates naturally all relevant fundamental constants in a logical scheme. He proposed that action and entropy are the two cornerstones of the future SI and they should be explicitly introduced in its formulation, adding that the definitions for time and mass units would be coupled.

7.3 Report from the CIPM Task Group for the Promotion of the SI

Prof Ullrich stated that this item had been covered under the President's report.

7.4 Report from the BIPM Director on the preparations for the General Conference on Weights and Measures in 2018

Dr Milton reported that he was working together with the CIPM bureau to generate a program for the 26th meeting of the CGPM from 13-16 November 2018 and in particular the session relating to the decision of the revision of the SI. Dr Milton proposed that on the morning before the final session where the revision to the SI would be voted on there would be a presentation of the benefits of the revised SI, and this was intended to be an open session. He stated that there would be more information available after the NMI Directors' meeting in October, and reminded the CCU that there was already a section of the BIPM website devoted to the forthcoming CGPM.

8. CCU RECOMMENDATION TO THE CIPM ON THE FUTURE REVISION OF THE INTERNATIONAL SYSTEM OF UNITS (PART II)

8.1 CCQM new proposal on the explicit-unit wording regarding the redefinition of the mole

Dr Güttler presented on the CCQM recommendation for a revised wording of the definition of the mole. Initially he showed the proposed definition from the draft of the 9th SI Brochure and subsequently displayed the input that been received from IUPAC after extensive consultation, engagement and debate with their members. He had noted that the IUPAC had reported that there was an overall positive appreciation of the redefinition of the mole, but that a different wording for the definition had emerged from their discussions. Dr Güttler went on to say that IUAPC had remarked that the recent advances in science and our ability to determine the value of the Avogadro constant allows a redefinition of the mole in terms of the explicit number of elementary entities. IUPAC has commented, very positively, that the proposed change realigns the definition of the mole with the way most chemists understand it. Dr Güttler concluded by proposing the CCQM recommendation for a revised wording of the definition of the mole,

which represented a slight modification of the IUPAC proposed text to bring this slightly closer to the other definitions with the draft 9th SI Brochure.

Dr Stenger opened the debate on this proposal by asking what was wrong with the current definition. Dr Güttler replied that it was important to add extra transparency for the user, the chemistry community, who understood the concept on number of entities more clearly and would prefer this to be explicitly stated. Prof Marquardt added that whilst the current definition in the draft 9th SI Brochure was clear to experts it was unlikely to be accessible to a broader community and so a more straightforward definition is preferred based on the number of entities contained in a mole. Dr Brown added that it had been an important addition of the CCQM to add reference to the relevant defining constant of the revised SI in order to ensure broad consistency with the other SI base unit definitions.

Continuing the debate Dr Himbert was cautious about a definition which included the definition of the quantity within it and stated that it needed to be checked that this didn't result in any inconsistencies. Dr Wielgosz replied that this had been checked and it didn't cause any inconsistencies. Dr Güttler added that, historically, for the mol, unlike other SI base units, the definition of the unit had been agreed prior to the definition of the quantity being fully described and this was why this explanation was needed. Dr Fischer was in favour of dropping the reference to the symbol, n, for amount of substance and also to removing the list of entities that could constitute a mole. Dr Brown replied that it was very important to have this list of entities in order to define the system that included the entities being described and also so the mole was not open to trivial usage as a counting quantity for non-identical components. Dr Bich felt that the order of the final two sentences should be swapped and Dr Krystek agreed, reminding the CCU that ISO and IEC deal with quantities (via the ISO 80 000 series of standards) and so this non-essential text relating to the quantity should be moved to the bottom.

More substantial arguments against the new definition came from Dr Karshenboim and Dr Taylor because it destroyed the symmetry currently present across the seven definitions. Dr Taylor also felt it unwise to include reference to the Avogadro number since this had not been defined properly. Dr Wielgosz intervened at this point explaining the long journey that the CCQM and IUPAC had been on since 2009, involving many workshops and a huge quantity of stakeholder engagement, in order to find compromise and come to this joint position. He added that many in the chemical community would not understand it if a committee, comprised mainly of physicists, voted against their proposal. Prof Marquardt asked the committee, semi-rhetorically, who the SI Brochure was intended for: a small group of metrologists, or the broader community. He stated that the very extensive survey performed by IUPAC had demonstrated that the new wording was not clear to chemists, especially those trying to teach the definition, and this was why IUAPC had proposed an alternative. Dr Stenger said that he appreciated the worry about teaching the definitions but there had been a long discussion on this topic some time ago and this had achieved a broad consensus on the systematic approach to follow for all units. He expressed his concern that this change was being performed in a hurry at the last moment. Dr Williams disagreed, arguing that the mole serves the chemistry community and this should be a small exception that we make in this case. Dr Milton stated his agreement with Dr Williams, adding that the history of this topic goes back to 1971 when the original definition of the mole was formulated with IUPAC and that the opinion of this community should be respected. He added that he didn't want to see the revision of the SI trigger an era where the IUPAC had a different perspective to the BIPM on this issue. Prof Wiersma added his support, stating that it was very important that these definitions were understood by the relevant user communities and he also encouraged the use of notes beneath the definitions to provide additional context. Dr Quinn supported the proposal to take into account the view of the chemical community but also

supported the earlier suggestion to reverse the order of some of the text. Prof Ullrich agreed with the proposal to accept the proposals of the chemical community and also expressed support for a change in the order of the text of the definition. Dr Steele endorsed the positive debate that had occurred and the engagement of the chemistry community adding that if there was one place where it was possible to make a compromise on the symmetry of the definitions, this was the place where it could be done. Dr Brown agreed, adding that in the revised SI the mole relies on no other units for its definition and no other units rely on the mole for their definition and so in this sense it is independent.

During the following lunch break it was agreed that Dr Brown, Dr Güttler, Dr Wielgosz, Prof Marquardt and Prof J. Stohner would finalize the wording of the definition according to the discussions that had occurred. This produced the following, final wording (with the 'Y' replaced by the final digits recommended by CODATA):

> "The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly 6.022 140 8Y × 10^{23} elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.
>
> The amount of substance, symbol n, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles."

A subsequent short discussion ensued about the merits of the Avogadro number within the definition, but this came to nothing and it was also clear the chemistry community wanted this referred to as well. Therefore, the above working was accepted by the CCU for recommendation to the CIPM for inclusion in the 9th SI Brochure.

8.2 Review of the draft of the 9th edition of the SI Brochure. Final discussion of the edited version for recommendation to the CIPM

Dr Milton informed the CCU that the BIPM drafting team had produced the most recent version of the 9th SI Brochure making only editorial changes to the English and structure of the previous version. He stated that during this process a number of issues had arisen where the drafting team had proposed changes that were now being brought to the CCU for approval.

Prof Ullrich agreed that the editing team had done an excellent job and that this edited version was an excellent starting point for discussion. The edits made thus far by the editing team were accepted.

At this point, there was a lengthy discussion about the text in 2.2.1 of the draft SI Brochure concerning the nature of the cesium frequency $\Delta\nu_{Cs}$. In particular the drafting team had highlighted that there may have been contradiction between the first and second part of the sentence. Eventually it was decided that the sentence was not contradictory. The constant was described as the "unperturbed ground-state hyperfine transition frequency" is indeed "unperturbed" and the second part of the sentence simply states that it "may be affected by the environment" but it is taken that during realization of the definition it is not subject to perturbation. The text was left unchanged. There was also some subsequent discussion, raised by Dr Stock, about why the symbol "Δ" was used as part of this defining constant as the number represented an absolute frequency and not a frequency difference. Dr Karshenboim felt that the

term was more properly described by calling it an 'absorption frequency'. At this point both Dr Steele and Dr Krystek argued that the last CCU had done a lot of editing of the SI Brochure and had agreed now only to accept editorial changes. They urged the CCU not to do editing such as this in the plenary. Dr F. Arias agreed that the wording discussed had been approved at the last CCTF meeting with no objections and Dr F. Riehle agreed that nothing must be changed that would affect CCTF usage.

Prof Marquardt stated that the text related to the definition of the mole would need some editing as a result of the new wording of the definition of the mole that was agreed earlier in the meeting and this was supported.

Prof Ullrich brought to an end this discussion of *ad hoc* comments and asked the CCU to concentrate on resolving the questions that Dr Milton had raised on behalf of the BIPM drafting team.

Returning to his previous presentation Dr Milton initially raised the issue of the graph and table within 5.4.1. He remarked that whilst the presentation of the units and labels is not incorrect it represents archaic usage and needed updating. Dr Brown remarked that since the philosophy of the 9th SI Brochure was to minimize the content not directly relevant to the SI this could be removed entirely since the section only related to proposed best practice in plotting graphs. Dr Krystek felt that it could not be left as it was and must be changed. It was agreed to change this graph and find a better example.

Dr Milton then turned his attention to a sentence in Section 4 stating that 'The CIPM has therefore decided to compile a list of the conversion factors to the SI for such units and to make this available to the BIPM website'. Dr Davis commented that the CIPM did decide this but it never appeared, although other texts are freely available that list this information (e.g. the NIST compilation of unit conversions). It was agreed to delete this sentence.

Regarding the text relating to angle on page 11, it was noted that it would be useful in this location to add reference to add the most recent CGPM resolution on angle from 1995 to provide appropriate context, and this was agreed.

In section 2.2 Dr Milton highlighted that it would be appropriate to introduce the text from resolution 1 of the CGPM (2011) to give the explicit explanation of the units being used with the defining constants, and this was agreed.

Dr Milton went on to propose that in section 2.3, when considering the equations in the base unit definitions it was better for clarity to replace the ellipsis, that are used when the reciprocal of the exact numerical values of the defining constant are expressed thereby producing non-exact decimals, with 'X'. This was agreed.

Of the six proposed corrections and improvements to the draft 9th SI Brochure suggested by Dr Milton, just one was rejected. Referring to section 2.3 Dr Milton reminded the CCU that the definitions of the candela and the kelvin do not depend on c, and so this text should be edited. Indeed, it is entirely correct to state that since the units of h are kg m^2 s^{-1} these definitions only require the defining constants h and $\Delta\nu_{Cs}$ to be used. However, the phrase "where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$" is not incorrect as written but, as described above, the text relating to c is superfluous. The CCU decided not to make a change, although Dr Brown suggested that a recasting of the final clause was required to solve the problem.

Following this review of the drafting team's comments there were then some more general discussions. Dr Bich suggested that the requirement expressed on page 3 of the draft 9th SI Brochure that both the estimated value of the measurand and the uncertainty associated with that value must be expressed in the same unit may by some be taken to mean that even the use of

decimal sub-multiples is not allowed, i.e. a result in kg must have an uncertainty in kg, and not in mg. There was little agreement with Dr Bich on this point and Dr Krystek added that sub-multiples of a given unit still represent the same unit.

Dr Zhang then suggested that in section 2.3.1 of the draft 9th SI Brochure the position of '(1/683) W/sr' should be brought forward in the sentence so it is associated more closely with the radiant intensity it qualifies. The proposal was generally accepted.

The CCU then moved on to deal with a number of special requests that had been received to reinstate definitions and units that had been removed from the 8th SI Brochure when preparing the draft 9th SI Brochure. In general, Dr Stenger thought that the agreement had been for the document to concentrate on the SI and leave practical application issues to the standards community, otherwise he concluded there could be no end to the number of requests received. He added that it was up to ISO to explain non-SI units to the relevant communities. Dr Steele added that the principle of the 9th SI Brochure draft has been to introduce the revised SI, and perhaps there could be a preamble to state this and explain its brevity as compared to the 8th edition of the SI Brochure. Dr Krystek remarked that he had submitted the ISO proposal on reinstating the nautical mile and the knot because he saw other requests for reinstatements being lodged. Dr Krystek went on to state that his opinion was that the CCU should either accept all of these proposals of none of them. Dr Blattner reminded the CCU that there had been a clear timeline to comment and, referring to proposals from the CCPR, this had been adhered to. Dr Rietveld expressed his surprise that the last CCU had invited a proposal on the var, but that if there was not really going to be open to discussion then he would not have produced the proposal. Dr Brown interjected to state that these matters had to be considered according to their classification. For instance, Dr Brown continued, the var is a special name for the volt-ampere which is an SI unit. It is the name var which is not one of the 22 special names for SI units currently listed in Table 4 of the SI Brochure. Dr Brown contrasted this with the case of the knot and nautical mile which were clearly not SI units, or special names for SI units. Dr Vitushkin added at this point that the geodesy community were not happy with losing the gal – which had the same status as the var described above.

The CCU decided to include side notes concerning the var and the gal in the draft 9th SI Brochure.

The debate turned to discussion of re-inclusion of the bar and mmHg which had been requested by the CCM working group on pressure and vacuum. The specific difficulty here was that the bar was referred to in Resolution 7 of the 9th CGPM (1948) and it was not clear whether this decision had since been abrogated or not. However, on further inspection the resolution appeared to relate to the writing and printing of unit symbols and numbers and not specifically to their acceptance as units. Dr Milton explained that the criteria for inclusion in the SI Brochure related to whether a unit was addressed in a CGPM resolution or CIPM decision. Whether the unit was still in common use should also be taken into account. Dr Krystek observed that the knot and nautical mile were still in common usage and were very relevant to international organizations who were not represented at the CCU. He therefore felt he needed to speak up on their behalf. Dr Krystek stated that if the bar and mmHg were re-instated then he would request that the knot and nautical mile were also re-instated. The CCU decide not to re-instate the bar, mmHg, knot or nautical mile into the draft 9th SI Brochure.

There followed a discussion on the proposals by the CCPR for amendments to the text of the brochure and also on an on-line Appendix 3 on photochemical and photo-biological quantities. Dr Rastello proposed that the last sentence in 2.1.1 relating to the nature of K_{cd} was vague and

made a proposal to include more detail. There was also a proposal to move the position of K_{cd} within the description of the defining constant so it was clearer what this referred to which was agreed by CCU. Dr Stenger cautioned against too much extra detail since this section was designed just to introduce the defining constants. Dr Blattner supported the proposal for the extra text since it made the link between the watt and the lumen at one wavelength. The CCU decided to accept the modifications to the draft 9th SI Brochure that were agreed with the CCPR at the meeting.

8.3 Review of the draft resolution for the CGPM. Final discussion of the edited version for recommendation to the CIPM

Prof Ullrich stated that he saw no reason to change anything in this draft resolution apart from adding the defining constants and the updated wording of the definition of the mole. The CCU agreed to this proposal.

9. COMMEMORATION OF THE 50TH ANNIVERSARY OF THE ADOPTION OF THE ATOMIC SECOND

Dr N. Dimarcq presented on the 50th anniversary of the atomic definition of the second. He began by explaining how some earth rotation fluctuations were predictable and some were not and explained how the definition of the second had evolved from the fraction of a mean solar day (until 1956) to a fraction of the tropical year 1900 (from 1956 to 1967). Hence there had been a clear requirement for a definition not depended on the earth's rotation. This had happened in 1967 when the current atomic second definition had been adopted. Dr Dimarcq went on to review the progress in Cs clock accuracy and examine a typical uncertainty budget for a cold Cs atom clock. He concluded by showing the progress that had been made with optical clocks such that they had now surpassed the accuracy of atomic clocks and hypothesized that this would in due course result in a new definition of the second. Dr Dimarcq reminded the CCU of the assumptions made about the constancy over time and space of atomic resonant frequencies and if variance in these was ever detected then this would have a large bearing on a future redefinition, although he stated that much more comparison data was needed from different clocks over different times to assess this.

10. UPDATE ON THE ROADMAP OF THE REDEFITNION OF THE SECOND

Dr Riehle introduced this topic by reviewing the current status of single ion optical clocks and how these differed from neutral atoms lattice clocks. Generally, the single ion optical clocks had the drawback of low signal to noise ratio. Neutral atoms lattice clocks required a strong laser but resulted in high stability and a high signal to noise ratio, especially when operated at the magic wavelength where the frequency dependent light shift is the same for both states.

Dr Riehle stated that one of the current technical issues being grappled with was the length of time that it takes to average the frequency noise of a clock. He went on to state that the use of

optical free-space links and their very high stability would allow this to be tested and compared between different clocks in future. Dr Riehle then reviewed the CIPM recommendation for the CCL-CCTF working group on frequency standards that recommend secondary representations of the second be evaluated as candidates for a new definition. He then described the progress that had been made with this to date. He explained that absolute measurements were limited by the current definition of the second but if frequency ratios are used much lower stabilities can be demonstrated.

Dr Riehle concluded by summarizing the benefits and drawbacks of a new definition and speculating that the time for definition may be right when the progress with optical standards begins to slow down. He also reminded the CCU that the gravitational redshift will ultimately limit timescales on Earth to parts in 10^{-18}. Finally, the roadmap was highlighted which suggested that the earliest CGPM meeting which might decide on a redefinition would be in 2030.

Dr Stenger opened questioning of the presentation asking why three separate approaches were required prior to redefinition – stating that ultimately only one will be chosen and effort on the others would have been wasted. Dr Riehle compared the case with the previous discussions of *h* in that it was better to have as much independence from contributing experiments as possible. He added that these other clocks would still be able to be used in the laboratories that developed them. Dr Milton asked whether the redefinition requirements could be summarized in a single phrase, for instance a given accuracy over a given averaging time. Dr Riehle answered that a one day average would be a reasonable time to relate the required accuracies to. Dr Milton was keen that this caveat should be added to the roadmap requirements in future. Dr Dudle asked whether the accuracies achieved by comparison over short distance would be able to be replicated between continents. Dr Riehle suggested that this would be considerably more challenging. Dr Arias commented, returning to the agreed set of milestone necessary prior to a new definition, that the requirement to contribute regularly to TAI was very important and required these clocks to operate successfully over long time periods.

11. PERSPECTIVES FOR THE CCU AFTER REDEFINTION OF THE SI

11.1 Reappointment of the CCU working group on strategy with new members

Prof Ullrich stated his intention to reform the CCU working group on strategy with new members. He also proposed some terms of reference for the working group, which he stated may need some discussion by the working group, and would be brought to the next CCU meeting for a decision. He commented that it was important that the working group comprised those with different backgrounds from both inside and outside the metrology community.

Prof Ullrich proposed that the working membership would be:

Dr Arias, Dr Brown, Dr de Mirandés, Dr Karshenboim, Prof W. Phillips, Dr Prieto Esteban, Dr Richard, Dr Rietveld and Prof Ullrich (chairman).

Prof Ullrich proposed an initial term of four years for members with a maximum of two terms.

The proposal was approved by the CCU.

11.2 Presentation of the new rules for membership of CCs

Prof Ullrich presented the new rules for membership decided by the CIPM. Prof Ullrich commented that the CIPM had decided that the CCU should also follow these rules, with the caveat that, unlike for other CCs, they would not be applied until after revision of the SI. Prof Ullrich highlighted that the intention was to increase the intensity of cooperation with external institutes by having formal relationship documented and put in place. This would define properly the status of liaisons, guest and individual experts. Prof Ullrich stated that there had been objections to this and so it warranted some discussion.

Prof Bagnato started the discussion by suggesting that the CIPM should apply special rules for the CCU adding that there had been no consultation and discussion about this before it happened and that a wider discussion was required before a decision was made. Prof Stohner expressed his support for this position and Dr Capitaine read out the letter from the IAU objecting to this change. Dr Milton replied to these objections, firstly apologizing that the change was not communicated well but reiterating that it was the intention of the CIPM to do a better and stronger job of collaborating with liaison organizations. He stated that there were approximately 20 liaison organizations within six out of nine of the CCs and a further 20 organizations that liaised directly with the BIPM – he compared this with 58 Member States of the BIPM. Dr Milton added that some liaison organizations operated under official memorandums of understanding and some through joint committees but that there were still a number where the link is historical and based on contact persons – he postulated that this was where a formal exchange of letters was required to formalize the link. Prof Ullrich added that he didn't envisage difference is the way the CCU worked or came to decisions as a result of the changes.

Dr Blattner highlighted that the agreement between the CIPM and the CIE is a positive example of how this relationship can work well. Dr Dudle stated that OIML respected the position of the CIPM and that the decision belongs to member states of the Metre Convention. Mr Sebellin reminded CCU that these changes reflected the way in which most international organizations worked, having members who financially contribute and liaisons who provide appropriate additional technical contributions. Dr Quinn stated that he regretted the decision of the CIPM in this respect, adding that it did not take into account the particular reason for the CCU membership of the international scientific unions. This was because, he went on, decisions made by the CCU affect the whole of science and hence it was important to make sure all member international scientific unions were in agreement with these decisions when they were made. Dr Quinn added that whilst the CIPM said that nothing has changed, something important will have changed in that the liaison organizations will not be allowed to vote in future. Dr Quinn proposed that the CIPM should be asked to reconsider their position on membership with respect to the CCU. Dr Wielgosz replied that a lack of formal agreement has led to many problems in the past, in particular different letters with different views being received from different people in the same organization. Dr Steele felt that that the CCU should retain a special status with respect to membership and proposed that the CCU make a recommendation to the CIPM to this effect.

Prof Ullrich agreed to raise the issues discussed with the CIPM on the CCU's behalf.

12. ANY OTHER BUSINESS

Prof Ullrich advised the CCU that an application for membership of the CCU had been received from LNE. The CCU approved this membership request unanimously. Mr Massa commented

that there may be other NMIs who wish to apply for membership. Prof Ullrich suggested that the new membership rules will make this process much clearer.

Prof Stohner took the opportunity to thank the CCQM and the CCU for taking a decision with respect to the wording of the definition of the mole that was extremely positive for the chemistry community.

Dr Milton advised the CCU that most other CCs were now making their documents freely available after meetings unless the authors said otherwise and this should also be the aim for the CCU. However, he remarked that on this occasion there was a lot of material that was in draft form and in the process of review and so it was probably wise not to make this open access for now (including preprint of papers which cannot be made publically available). Dr Milton said that this should be discussed again at the next CCU meeting.

13. DATE OF NEXT CCU MEETING

Prof Ullrich stated that no meeting was required next year but that a date in June 2019 would be suggested for the next meeting of the CCU.

In the absence of any other business, the President of the CCU, Prof Ullrich, thanked participants for their contributions, reports and participation in the discussions, and the Rapporteur and Executive Secretary for their assistance. Prof Ullrich also thanked the staff of the BIPM for their support in hosting the meeting and wished all attendees a safe journey home.

Prof Ullrich closed what he referred to as ‘an historic meeting’ at 1830hrs.

Dr R. J. C. Brown

Rapporteur, 13 September 2017

CCU DECISIONS AND RECOMMENDATIONS

The CCU:

1. Recommends to the CIPM to proceed with the revision of the SI in 2018 according to the previously proposed timescales.
2. Notes that CODATA will make a decision before the CIPM meeting on the inclusion of the Russian measurement of *k*, and the CCT will decide on the final number of digits to be assigned to the numerical value of the Boltzmann constant to be fixed.
3. Accepts the edited draft 9th SI Brochure and some of the modifications proposed by the editing team as agreed during the CCU meeting.
4. Decides to include a side note concerning the var and the gal in the draft 9th SI Brochure.
5. Decides to accept the modified wording for the definition of the mole agreed during the CCU meeting in the draft 9th SI Brochure.
6. Decides to accept the modifications to the draft 9th SI Brochure agreed with the CCPR.
7. Decides to accept Appendix 3 as proposed by the CCPR as an online appendix in the draft 9th SI Brochure.
8. Agrees to recommend to the CIPM to keep Appendix 1 of the 8th SI Brochure "Decisions of the CGPM and the CIPM" both printed in the SI Brochure and as an online appendix.
9. Accepts the Draft Resolution to the CGPM dated 10 November 2016 as the final version to be recommended to the CIPM, changed only to include the modified wording for the definition of the mole.
10. Agrees to re-form a strategy working group, with its members and proposed terms of reference as agreed in at the CCU meeting.
11. Agrees to communicate to the CIPM the views expressed by international scientific unions about the change of their memberships to liaison status.
12. Recommends to the CIPM the acceptance of LNE as a new member of the CCU.
13. Agrees to hold its next meeting in June 2019 with the exact date to be decided.