Bureau International des Poids et Mesures

Consultative Committee for Units (CCU)

Report of the 19th meeting
(26-28 May 2009)
to the International Committee for Weights and Measures

Comité international des poids et mesures

Note:

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

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

A.J. Wallard,
Director BIPM

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR UNITS

as of 26 May 2009

President

I.M. Mills, International Union of Pure and Applied Chemistry [IUPAC], Commission STU, Emeritus Professor of Chemistry, Department of Chemistry, Reading.

Executive Secretary

C. Thomas, International Bureau of Weights and Measures [BIPM], Sèvres.

Members

Centro Español de Metrología [CEM], Madrid.

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

International Astronomical Union [IAU].

International Commission on Illumination [CIE].

International Commission on Radiation Units and Measurements [ICRU].

International Electrotechnical Commission [IEC], Technical Committee 25.

International Federation of Clinical Chemistry and Laboratory Medicine [IFCC].

International Organization for Standardization [ISO], Technical Committee 12.

International Organization of Legal Metrology [OIML].

International Union of Pure and Applied Chemistry [IUPAC], Commission STU.

International Union of Pure and Applied Physics [IUPAP], Commission SUNAMCO.

National Institute of Metrology [NIM], Beijing.

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

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

National Physical Laboratory [NPL], Teddington.

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig.

State Committee of the Russian Federation for Standardization and Metrology, Rostekhregulirovaniye of Russia [VNIIM], Moscow.

M. Himbert.

T.J. Quinn.

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

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

The Consultative Committee for Units (CCU)* held its 19th meeting at the International Bureau of Weights and Measures (BIPM) headquarters, at Sèvres, from 26 to 28 May 2009.

The following were present: J. Bastie (CIE), C.A. Borghi (IEC/TC 25), N. Capitaine (Observatoire de Paris, IAU), R. Dybkaer (IFCC), J.L. Flowers (IUPAP, NPL), K. Fujii (NMIJ/AIST), A. Fylkner (ISO/TC 12), P. Gérôme (ISO/TC 12), M. Himbert (LNE-INM/Cnam), J.T. Janssen (NPL), S. Karshenboim (VNIIM), A. Leitner (BEV, OIML), Zuliang Lu (NIM), H.-G. Menzel (ICRU), I.M. Mills FRS (President of the CCU, IUPAC), P. Mohr (NIST, IUPAP), D.B. Newell (NIST, CODATA), J. Obdržálek (IEC/TC 25), E. Prieto (CEM), T.J. Quinn CBE FRS (Director Emeritus of the BIPM), J. Stenger (PTB), A. Thompson (NIST), A.J. Thor (ISO/TC 12), A.J. Wallard (Director of the BIPM), B.M. Wood (NRC-INMS, CODATA).

Invited: F. Arias (BIPM), Ch. Bordé (Académie des Sciences, Paris), R.S. Davis (BIPM), L. Érard (CIPM, LNE), J. Fischer (PTB), P. Gill (NPL), J. Kovalevsky (Honorary member of the CIPM), M. Kühne (Deputy Director of the BIPM), M.J.T. Milton (NPL), A. Picard (BIPM), Ph. Richard (METAS), F. Riehle (PTB), M. Stock (BIPM), B.N. Taylor (NIST), R.I. Wielgosz (BIPM).

Also present: E. De Mirandés, D. Le Coz, J.R. Miles, L. Mussio, and C. Thomas (Executive Secretary of the CCU) from the BIPM.

Excused: M. Gläser (PTB), and Z. Zhang (NIM).

The President opened the 19th meeting of the CCU, and extended a warm welcome to all present.

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* For a list of acronyms, click here.

The attendees joined the President in congratulating Prof. Bordé on his election as Member of the Académie des Sciences, Paris, and Prof. Himbert on his election as Member of the Académie des Technologies, Paris.

Dr J. Stenger was appointed Rapporteur.

The Agenda was approved.[1]

2 PRESIDENT'S REPORT

The President reminded the participants of the far-reaching responsibilities of the CCU for maintaining, revising and developing the International System of Units, the SI, and revising accordingly the SI Brochure. At its last meeting in June 2007 the CCU essentially took the decision by a large majority to recommend a redefinition of the kilogram, the ampere, the kelvin, and the mole to fix the values of the Planck constant h, elementary charge e, Boltzmann constant k, and the Avogadro constant N_A respectively. Since then the President presented the report of the CCU to the 23rd CGPM.

The President expressed his wish to revisit these basic decisions only if significant developments during these two years give reason. The meeting should however take decisions about the best wording for the redefinitions.

Prof. Thor wished to note that his statement as on page 7 of the Report to the 23rd CGPM from the CCU did not only express his personal view.

[1] For organizational reasons some of the contributions were presented in an order other than that given in the Agenda. However, these minutes follow the Agenda for better readability.

3 REPORTS ON DEVELOPMENTS SINCE THE 18th CCU MEETING

3.1 Report on the watt balance experiments

Dr Stock gave an update on the various watt balance experiments.

The watt balance experiment at the NPL will be shut down in July 2009. The deviation by 3 parts in 10^7 of its 2007 experimental value of Planck's constant from the CODATA value remains unexplained.

There have been no new results from the NIST's watt balance during the last two years. Tests are ongoing with test masses of 0.5 kg, 1 kg, and 1.5 kg, made of steel, gold and platinum-iridium.

The METAS balance reached a relative standard uncertainty of 4×10^{-7}, based on more than 4000 hours of measurements. A publication is planned in 2009. METAS is preparing a successor experiment with a newly designed magnet and expects to take data between 2013 and 2015.

The LNE started an experiment in 2001. It does not expect to be able to present results in time for the CODATA 2010 adjustment.

The BIPM started its watt balance in 2003 with a room-temperature set-up. However, it aims to develop a set-up based on a superconducting coil in combination with a permanent magnet, for which results may not be expected before 2011 at the earliest.

The NIM started a joule balance in 2006, in which a 200 g weight is balanced by the electrically induced force between two coils. The inductances are determined by mutual induced voltage.

The MSL started a watt balance in 2007 using a different approach based on pressure balances and employing sinusoidal motion of the coil. This work is in the feasibility study stage.

Prof. Kühne and Prof. Bordé expressed concern that very few new values of the Planck constant will be available at the time of the next CODATA adjustment.

Dr Wood confirmed that the NPL watt balance experiment will be transferred to the NRC, and that they will try to present results as early as possible.

3.2 Report on the international Avogadro experiment

Mr Picard reviewed the Avogadro (XRCD) experiment.

The re-assessment of the molar mass of natural silicon at the IRMM led to a 1.2 ppm shift of the value of the Avogadro constant compared to the value published in 2005. Thus, the result is now in agreement with the 2006 CODATA value. However, this result is preliminary, and the reason for this shift is not yet fully understood. An alternative measurement of the molar mass using ICP mass spectrometry is presently being pursued at the PTB.

The results with enriched ^{28}Si spheres – also preliminary – indicate an agreement with the CODATA value with a standard uncertainty of 0.1 ppm. The largest contribution to the uncertainty budget presently arises from the volume determinations, which are performed at the PTB and the NMIJ by spherical and non-spherical interferometry, respectively.

The Avogadro consortium targets a relative standard uncertainty of 2.1 parts in 10^8. It is not obvious, however, that this will be achieved in time for the CODATA 2010 adjustment.

Dr Wielgosz commented that Recommendation Q1 (2009) of the CCQM also invites alternative measurement of the molar mass.

The CCU discussed the measurement of the molar mass and the comparability of the watt balances, which primarily measure the value of the Planck constant, and the XRCD experiment, which primarily measures the Avogadro constant. There was agreement that the experimental information on the molar Planck constant hN_A, which is needed for this comparison, is certainly adequate for our needs, since it is linked to the uncertainty of the fine structure constant, α, which is of the order of a few parts in 10^9.

3.3 Report on the Boltzmann constant experiments

Dr Fischer reported on the status of the Boltzmann constant experiments and concentrated on a review of the uncertainties achieved by different thermometry methods. These are acoustic gas thermometry (AGT), dielectric constant gas thermometry (DCGT), refractive index gas thermometry (RIGT), Johnson noise thermometry (JNT), and Doppler broadening thermometry (DBT). In 2007 the CCT addressed a report to the CIPM, stating that a redefinition of the kelvin based on a fixed Boltzmann constant could be recommended when three different methods give consistent results.

The achieved uncertainty of the CODATA value is expected to be 1 ppm. Presently, the smallest uncertainty, 1.8 ppm, is achieved by AGT followed by RIGT with 9 ppm. It is expected that only AGT may reach 1 ppm by the end of 2010, which corresponds to an uncertainty of 0.25 mK for the temperature of the triple point of water. The CCT Task Group on the SI will convene after the 4th Boltzmann Constant Workshop, during the third quarter of 2009, to review the perspectives of the thermometry approaches and give a recommendation on a possible redefinition.

Dr Fischer furthermore confirmed that the CCT supports the explicit-constant type of redefinition, and that a *mise en pratique* for the new definition is being drafted.

3.4 Report from the Comité "Science et Métrologie" de l'Académie des Sciences

The President recalled that the Committee "Science and Metrology" was created as the follow-up to the Académie Working Group on "SI Units and Fundamental Constants", which delivered a report to the CCU in 2007. The Committee is co-chaired by Prof. Kovalevsky and Prof. Bordé. The membership of the Committee also includes two Nobel price winners, two persons from the Royal Society (Dr Quinn and Prof. Mills), Prof. Himbert, and Dr Thomas, who acts as the Scientific Secretary. The President also indicated that the document proposed to this CCU meeting was produced by the Co-Chairmen, but was not circulated and agreed among the members of the Committee.

In his report on the discussions of the Committee, Prof. Kovalevsky focused on the unit of time, the second. The stability of optical reference transitions and of optical frequency combs as frequency links between the optical and microwave frequency regions now exceeds the capabilities of caesium clocks. This has been demonstrated with various single-ion or neutral atom set-ups. Thus the Committee suggests beginning the discussion on a redefinition of the second in order to avoid a situation comparable to the quantum realizations of the volt and the ohm since 1990. This discussion was taken up in Agenda item 7.

Prof. Bordé indicated that the question of redefining the second came during discussions held at the BIPM in November 2008 while celebrating the 25th anniversary of the definition of the metre in terms of a fixed value of a fundamental constant.

Prof. Bordé began his report by saying that all SI units should be considered together because they are linked; for instance mass and time are related through the quantity action. He then discussed the link between mass and frequency through the de Broglie-Compton frequency. He indicated that there are some criticisms. The concept is unfamiliar, but one can consider a macroscopic mass as a sum of microscopic masses. The de Broglie-Compton frequency is a very large number, but the watt balance measures it. The validity of the quantum-mechanical concept may be questioned in this range, but he quoted atom-interferometric methods for the determination of the fine-structure constant and of the Rydberg frequency, which allow the establishment of links between mass and frequency at measurable frequencies. Prof. Bordé added that he would not agree on defining the kilogram from the energy of a number of photons, as this would imply that the photons are bounded in a box.

On the subject of the mole, Prof. Bordé conveyed the feeling of a number of chemists of the Académie against the redefinition. This is a rather strong position underlined with two arguments: the fact that the mole would be reduced to a count, and that ultimately chemists weigh and thus turn to mass determination. Prof. Mills, supported by several others, argued for the simplicity of the new definition and recalled that it was well received by all concerned communities. Dr Quinn noted that the relative scale of atomic masses will not be changed by the redefinition. Dr Fischer explained that the Boltzmann constant also acts as a proportionality constant for the kelvin exactly as the Avogadro number does for the mole. Prof. Kühne added that it is no more arbitrary than the choice made for the second, and that a system of units is basically built up on choices. The President concluded by saying that the mole is by no means a number and that the concept of the quantity "amount of substance" is something real for all chemists of the world.

Prof. Bordé indicated that the Committee is basically in agreement with the CCT concerning the redefinition of the kelvin, although he personally would prefer to fix the value of k/h. Dr Fischer answered that this was considered but not retained by the CCT Task Group. In any case, it changes nothing except in the formulation.

Prof. Bordé further reported on the definition of electrical units, summarizing what was already said at the 2007 CCU meeting and stating that the present definition of the ampere is perfectly adapted to the propagation of light in vacuum. In the case where the Planck constant has a fixed value, the elementary charge is known with a very small uncertainty of

a few parts in 10^9. He also questioned the validity of the usual expressions for the von Klitzing and Josephson constants. The President stressed the point that the concept of the quantum of charge is more familiar to most of the communities than the concept of the magnetic constant.

3.5 Report from the CCM-WGM

Dr Richard reported that the CCM-WGM had established two Tasks Groups related to the expected redefinition of the kilogram, in order to ensure continuity, reliability and quality of dissemination in case of a redefinition. Task Group 1 focuses on vacuum mass metrology and air-vacuum transfer, while Task Group 2 considers uncertainties of the traceability to the mass prototypes.

The CCM is investigating the requirements for future primary realizations of the kilogram such as the number and quality of watt balances. Furthermore, it is investigating options for and the potential of a pool of artefacts to be kept at the BIPM as a *mise en pratique* for the definition of the kilogram. Dr Richard expressed the concern of the CCM that occasional problems in providing traceability may occur due to a lack of watt balances in operation.

It was pointed out that most precision mass measurements are made in the field of legal metrology. It is assumed that mass standards are traceable to the international prototype of the kilogram, which is considered to have no uncertainty (i.e. the present SI definition). Therefore, if not handled carefully, the proposed redefinition has the potential to inconvenience a large community.

Prof. Wallard explained that the aim of the BIPM would be to establish a pool of mass artefacts based on platinum-iridium alloys, other alloys, and silicon spheres, which should have a short-term stability superior to the realization of the new definition. Travelling artefacts would be circulated to provide traceability to the pool of artefacts maintained at the BIPM. Dr Quinn pointed out that permanently operating watt balances providing traceability will not be required. Instead, a determination of possible drifts of artefacts such as those provided by the BIPM will be needed from time to time. Dr Taylor added that silicon spheres as part of the pool would allow an independent experimental indication of possible drifts with techniques developed in the Avogadro experiment.

One of the basic requirements of the CCM for a recommendation to redefine the kilogram (three experiments based on at least two different methods consistent within a few part in 10^8) has not yet been fulfilled. At its March 2010 meeting the CCM will consider again its recommendation and will discuss a possible wording for the *mise en pratique* for the new definition.

3.6 Report from the CCQM

In his report Dr Milton pointed out that from a chemical point of view the mole is neither just a number nor should it refer to the kilogram, but it is the unit of the quantity *amount of substance* which is relevant in a chemical reaction. Consequently, the CCQM prefers a redefinition of the mole based on a fixed value of the Avogadro constant, with the added condition that the relevant entity must be specified. Some opposing views have been expressed, which would support maintaining the present definition and not reducing the definition of the mole to a count of entities, but the CCQM does not support these arguments. Further debate will take place at the IUPAC General Assembly to be held in Glasgow in August 2009, where the President will present the case[2].

Dr Milton further stressed that the CCQM would prefer an explicit-unit wording for the new definition of the mole, and that the current draft *mise en pratique* should be extended to a very small number of entities.

3.7 Reports from the CCEM and the CODATA Task Group on Fundamental Constants

These reports were presented by Dr Wood. The CCEM met in March 2009. At that meeting, the CCEM reviewed its Recommendation E1 (2007), already presented at the last CCU meeting, and unanimously re-endorsed it, namely recommending the fixing of the values of the Planck constant and the elementary charge, and to define the kilogram and the ampere with respect to these fixed constants. It also re-affirmed that it is ready to proceed as soon as possible. A *mise en pratique* for the ampere and the derived electrical units

[2] Note dated 31 August 2009: At its August 2009 meeting the IUPAC supported the proposal for a redefinition of the mole in terms of an exact value of N_A.

with special names as given in the SI Brochure was approved and is now presented to the CCU.

The CODATA Task Group on Fundamental Constants reviewed the present status of the Planck constant, the Avogadro constant and the Boltzmann constant. Only a few new results have been published since the previous CCU meeting, and it is expected that the values of the relevant constants will change only slightly compared to the 2006 adjustment. The Task Group has also discussed the timing required for its work in view of the possible redefinition of the SI.

3.8 Reports from ISO/TC12, IEC/TC25, IUPAP, and IUPAC

Prof. Thor informed the CCU that the ISO/IEC 80000 standards on "*Quantities and units*" are finished with the exception of parts 1 (*General*), 2 (*Mathematics*), and 10 (*Atomic and nuclear physics*). All the 14 parts it contains are expected to be completed by the end of 2009.

Prof. Borghi reported that the IEC/TC 25 is in favour of the new definitions as proposed by the CCU in 2007, but did not choose between expressing them under the explicit-unit or explicit-constant form.

Dr Flowers reported that the IUPAP had passed a resolution at its 26th General Assembly endorsing the recommendations for redefinition of the SI units made by the CCU to the CGPM at its meeting in November 2007.

Prof. Mills said that he reported the 2007 CCU decisions to the last IUPAC General Assembly in Beijing two years ago, and did not hear any opposition to the proposed redefinition of the mole, or any of the other units [see Note in §3.6 above about the IUPAC decision of August 2009].

The CCU briefly discussed a problem raised in a draft IUPAC paper about the fact that there exists no official definition of the year, and that the symbols "yr", "y" and "a" are all used. The CCU did not come to a solution, but Dr Quinn, supported by Prof. Kühne, suggested that if there is a need, then the CCU and the CIPM should give advice to the CGPM even though the year is not an SI unit. Prof. Mills invited Dr Capitaine and Prof. Obdržálek to form a small group including representatives from ICRU and IUPAP to propose a solution. The group would not need to meet but could work on the basis of email correspondence. Dr Thomas could also participate in close contact with Dr Arias. This issue could then be

considered again at the next CCU meeting. The President added that he would try to delay the publication of the IUPAC draft document on the year when he attends the IUPAC General Assembly in August 2009.

4 REVIEW OF PROPOSALS FOR REDEFINING THE BASE UNITS KILOGRAM, AMPERE, KELVIN AND MOLE

The President reminded the CCU of its decision made at the last meeting in June 2007 to recommend a redefinition of the kilogram, ampere, kelvin and mole to fix the values of the Planck constant h, elementary charge e, Boltzmann constant k, and the Avogadro constant N_A, respectively. These recommendations were approved in principle by the CGPM, unequivocally by the IUPAP, and also by other institutions. There appear to have been no significant developments in the meantime which would give reason to open the discussion again, but it is the duty of this CCU meeting to review any new arguments.

Dr Davis explained that mass metrologists have no preference concerning redefining the kilogram to fix the value of the Planck constant or the value of the mass of a carbon 12 atom, $m(^{12}C)$, since the ratio $m(^{12}C)/h$ is independent of the kilogram and the mole, and has an uncertainty much smaller that the uncertainty of either $m(K)/h$ or $m(K)/m(^{12}C)$ for any macroscopic mass K.

Prof. Thor repeated the preference of the ISO/TC 12 to fix the mass of ^{12}C for the kilogram, μ_0 for the ampere, and N_A for the mole. He added that a definition of the kilogram based on a fixed value of the Planck constant cannot be easily understood by laymen, which the CGPM explicitly noted as desirable. Prof. Obdržálek objected to the meaning of "easily understandable".

Although summarized here, much of this discussion took place following Prof. Bordé's report under Agenda item 3.4.

Prof. Thor also suggested renaming the kilogram to avoid the prefix kilo, and to give to the gram the same status as the litre has at present. The President recalled that the prefix issue for the name of the kilogram had been previously decided by not recommending any change, realizing that this issue

does not seem to cause problems, whereas changing the name would give rise to a great deal of confusion, even in everyday life.

The CCU discussed the need to clearly distinguish quantity from unit. Whereas quantities are related by the laws of physics, units are essentially free to be chosen. The choice of units does not affect the equations relating quantities.

To conclude, the meeting re-endorsed the recommendations it made to the 23rd CGPM in 2007.

5 DRAFT WORDING OF NEW DEFINITIONS

The President put the explicit-constant versus explicit-unit wording for the definition of the units up for discussion. The CCU in its majority supported the explicit-constant wording for the definitions of the units, each to be followed by a more practical, explicit-unit type explanation.

The CCU furthermore agreed in its majority that in Chapter 2 of the SI Brochure, the definitions of the base units should be introduced by an explanation of the basic principle of the redefinitions:

- fixing the values of a set of constants, i.e. $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$, c, h, e, N_{A}, k, K, no matter which SI unit is defined in terms of which constant, in order to scale (to be translated into French as “dimensionner”) the whole system of units; and
- emphasizing history and continuity at the time of the redefinition.

There was much discussion on the advantages and disadvantages of the so-called “radical approach” in which only the set of values of the constants is given, and base and derived units are no longer introduced. As an illustration, the electrical units ampere, volt and ohm would be experimentally linked to h, e, and $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$ by single-electron tunnelling and Josephson and quantum-Hall experiments, respectively, making the distinction between base units and derived units unnecessary. In addition, no specific “recipe” to define the units would be given in this presentation. However, the CCU argued that the system of the seven base units and derived units should be preserved for historical reasons, and in order to document the smooth

transition of the SI to the new definitions. Furthermore, the Brochure should be valuable and readable for non-expert users and the general public.

The majority of the CCU was of the view that the world was not yet ready for the radical approach, despite it having many advantages. The CCU agreed that the way in which the new definitions should be presented, while maintaining the structure of the base units and the derived units as well as giving the set of values of the defined constants, was as follows:

- Following the general introduction to Chapter 2, a list of the seven constants with their chosen fixed values would first be given, followed by the set of corresponding definitions of the seven base units. Each of these seven definitions would be presented in a standard format, based on an explicit-constant wording, beginning "The [unit], unit of [quantity], is such that…".
- Each explicit-constant definition should be followed by an explicit-unit wording of the same definition.

With respect to the metre, Dr Quinn suggested the definition should refer to light travelling in an *unbounded* vacuum or in a *void* ("dans le vide" in French).

Dr Bastie pointed out that the definition of the candela does not refer to a defined constant, in contrast to the new definitions of the other base units, but to a coefficient linking a physiological quantity to a physical quantity. He added that the frequency of 540 THz is not exactly equal to the wavelength of 555 nm. Consequently, the definition should refer to K or K_m instead of $K(\lambda_{555})$ to be in agreement with the present definition of the candela. The President asked Dr Bastie to offer revised words for the definition of the candela.

With regard to the possible dropping of the candela from the set of base units, it was clearly stated that this unit is very important for society, because of the lighting industry. The CCPR has already discussed this at length and is strongly in favour of keeping the candela as a base unit.

The President invited a "drafting team" consisting of himself, Dr Quinn, Prof. Himbert, Dr Davis, Dr Stenger, and assisted by Dr Thomas for the revision of the draft of Chapter 2 of the Brochure. He offered to formulate a first draft by the end of June 2009. The drafting team should meet

in August 2009, and the draft should be finalized for circulation to the CCU by the end of August 2009[3].

The President also proposed to change the order of the base units to second, metre, kilogram, ampere, kelvin, mole and candela. The majority of the CCU supported that idea.

The CCU was unanimous about the need to publish the recommended changes in the SI, as widely as possible, such as in Wikipedia.

6 PRACTICAL REALIZATIONS OF THE DEFINITIONS

The President explained his preference for keeping the *mises en pratique* (Appendix 2 of the Brochure) separated from the definitions and to publish them on the BIPM website since a more rapid change of *mises en pratique* in relation to the definitions must be expected. Dr Thomas said that all *mises en pratique* currently published are up to date: in particular the text on time was revised in April 2009, and links were given to the latest recommended transitions for the metre and the secondary representations of the second.

After some discussion the CCU agreed with the CIPM (2008) wording that the expression "*mise en pratique*" means the realization of the definitions of the units at the highest, primary level. The wording in the Brochure in each case should read: "*mise en pratique* for the definition of the [unit]....", translated into French as "mise en pratique de la définition de [l'unité]". The case of electrical quantities, where the ohm and the volt can be realized with smaller uncertainties than the base unit ampere, implies that the expression *mise en pratique* is not reserved for the base units, but may also be used with derived units. One could then use the expression "*mise en pratique* for the definition of the ampere and various electrical units". This approach is in line with the basic concept behind the redefinition effort which dilutes the distinction between base and derived units.

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[3] Note dated 28 August 2009: The group met in Reading (United Kingdom) on 7 August 2009, and the resulting text was distributed to the full CCU on 25 August 2009.

The Consultative Committees are now asked to draft the *mises en pratique* (details on their statuses are mentioned under Agenda item 3). Dr Richard informed the CCU that the CCM intends to present a *mise en pratique* for the definition of the kilogram after its March 2010 meeting. However, a certain hesitation to proceed quickly has been observed in the CCM, due to the fact that the requirements for the redefinition are not yet fulfilled.

7 DISCUSSION ON A REDEFINITION OF THE SECOND

Dr Arias reviewed the state of the art in time and frequency metrology. Currently eight caesium fountains contribute regularly to ensure the accuracy of International Atomic Time (TAI). Two-way time and frequency transfer via satellite allows a relative uncertainty of less than one part in 10^{15} with a foreseeable limit of a few parts in 10^{16}. There is much work to be done to reach time and frequency transfer performance that would be appropriate for comparing optical clocks.

Prof. Riehle reported on the discussions in the CCL-CCTF Frequency Standards Working Group. The uncertainties which can be achieved by optical clocks consisting of an optical reference transition and a femtosecond frequency comb presently surpass the uncertainties achievable with caesium fountains at a few parts in 10^{16}. The decrease of the uncertainties achieved over the last decade indicates a potential for a significantly lower uncertainty for optical clocks in the next few years, down to below 10^{-17}, whereas caesium clocks are not expected to reach significantly less than 10^{-16}. At the moment, however, the *absolute* uncertainty of an optical frequency can not be less than the uncertainty of the realization of the second as given by caesium clocks. Prof. Riehle pointed out that adopting a reference transition as a secondary representation of the second helps with the detailed evaluation of the reproducibility of these standards at the highest level.

Two options need to be discussed for a possible redefinition: to fix the value of a fundamental constant such as the Rydberg constant, which is currently known with an uncertainty of a few parts in 10^{12}, or to choose a specified optical reference transition. The discussion quickly made it clear that no fundamental constant has the potential for a definition of the second better than a specific, chosen optical reference transition in an atom or ion.

Dr Karshenboim pointed out the unprecedented accuracy of measurement of optical frequency ratios and Dr Thomas expressed her concern that uncertainties of optical clock measurements are no longer referred to the SI second based on caesium.

The CCU discussed options for reference transitions and experimental limitations such as that due to black-body induced AC Stark shifts. Apparently there is still no clear optimum candidate. It is not even known yet whether neutral atoms or ions have the greatest potential. At this stage, optical clock comparisons in the laboratory are the only way to get a clearer view of the best candidate.

The President concluded the discussion. There is consensus in the CCU that the experimental situation implies a discussion of a redefinition in the coming years. The time and frequency community is encouraged to pursue the experimental work both on reference transitions and on time and frequency transfer via satellites and optical fibres. Clock comparison experiments and frequency ratio measurements are crucial for further developments. No immediate need for a redefinition is seen from the users' point of view.

Dr Capitaine argued that astronomers have difficulty in selecting the units to be used for coordinate quantities in General Relativity, such as Barycentric Dynamical Time (TDB) and Terrestrial Time (TT). There are several options such as using the SI second or introducing a dedicated second for each quantity. No consensus has been reached because the SI second is considered to be a proper unit in the framework of General Relativity, and the form of its definition is based on its realization. Dr Capitaine also commented that the SI Brochure should mention more clearly that the second is "the unit of time" and also the unit of all quantities with the dimension of time, recognizing the fact that only proper time is a measurable quantity.

The CCU came to the conclusion that a separation between the definition and its realization is not possible as long as the definition is based on a specific atom or ion, because the magnitude of the unit would then be missing. Instead, working in the framework of General Relativity implies a careful definition of the quantity being measured. The CCU also noted that the expression "unit of time" should be inserted in the wording of the definition of the second. This will be taken into account when the definitions of all base units are reworded in a unified way.

Dr Capitaine also reported on a possible change in the definition of the astronomical unit of length, which is being discussed by the IAU Working

Group on Numerical Standards for Fundamental Astronomy. The proposal is to move at the time of the IAU General Assembly in 2012, to a fixed relationship to the SI metre through a defining number determined by continuity. The astronomical unit of length would then no longer be determined experimentally and would be listed in Table 6 of the SI Brochure (instead of Table 7). After discussion, the CCU declared its support for such a change and suggested that the astronomers should decide upon an appropriate symbol for this unit independently of the language, "ua" and "au" being presently in use ("ua" is currently indicated in Table 7 of the SI Brochure).

8 REPORT FROM THE CCU TO THE CIPM

The CCU discussed the conditions to be met before the change to the new definitions is implemented.

The major discrepancy of about one part in 10^6 between the experimental results for the Planck constant h from the XRCD measurement of the Avogadro constant using a natural silicon sphere and from the best of the watt balance measurements appears to have been resolved through the discovery of an error in the value used for the molar mass of natural silicon; the Avogadro and the watt balance results now agree within their uncertainties, although this result is not yet published and must still be treated as preliminary. Moreover the preliminary results from the international Avogadro project using a pure silicon 28 sphere promise close agreement with the CODATA 2006 results and the best watt balance results, with the XRCD results achieving a relative uncertainty of less than one part in 10^7. The only slight discrepancy at present remains the recent NPL watt balance result, which deviates from the CODATA value by about 3 parts in 10^7. As reported earlier by Dr Stock, several watt balances are at present under construction in various national metrology institutes and at the BIPM. Results from these new experiments with uncertainties of a few parts in 10^8 may be expected over the next few years.

Dr Stenger stressed the necessity to correctly define the constants under consideration since they are over-redundantly linked by the laws of physics. Undiscovered systematic shifts entering the fixed values would eventually

lead to contradictions in experiments. Prof. Wallard and Prof. Kühne added the necessity to have more than one watt balance available to have a robust enough dissemination system for the kilogram. Dr Quinn pointed out that the redefinition will have no impact on dissemination, which will be achieved through the use of kilogram artefacts. Thus, having the pool of artefacts with an expected drift far smaller than is relevant for dissemination, it is not necessary to have several watt balances for frequent calibration.

The President considered that a standard uncertainty of 3×10^{-8} in the Planck constant would be sufficient to support the redefinition of the kilogram. The pool of kilogram artefacts being planned at the BIPM will preserve the continuity once the redefinition has taken place[4].

The next 2010 CODATA least-squares evaluation of the fundamental constants, with a closing date for new data of 31 December 2010, will be available early in 2011. After this, a final decision can be taken by the CIPM as to whether the experimental results will support a change to the new definitions by the 24th CGPM, which will meet in October 2011.

Dr Wood, Dr Mohr, Dr Taylor, and Dr Newell offered to give a preview of the CODATA 2010 adjustment in advance of the CIPM meeting in October 2010. In addition, the CODATA Task Group may consider another closing date for the adjustment if the CIPM requests it, based on the expected final results of ongoing experiments.

Prof. Wallard explained that the redefinitions have to be approved by the CIPM in October 2010. The decision would then go to the Member States at the beginning of 2011, and the final decision would be taken by the 24th CGPM in October 2011. The *mises en pratique* need to be in place by the end of 2010, and this will require a concerted effort from the CCM.

In summary, the President will report to the 2009 meeting of the CIPM that the CCU reviewed and endorsed the decisions taken at its previous meeting in June 2007, which were reported to the CGPM in November 2007. These were to redefine the kilogram, ampere, kelvin and mole to fix the values of the Planck constant h, elementary charge e, Boltzmann constant k, and the Avogadro constant N_A, respectively. In addition, he will report that the CCU is strongly in favour of explicit-constant definitions, which were felt to be

[4] The BIPM points out that an additional requirement to preserve continuity is the long-term availability of realizations of the SI kilogram to this uncertainty, or below.

simpler and more fundamental, followed by words interpreting the definition in the explicit-unit form. He will also present to the CIPM the Draft Chapter 2 of the SI Brochure, based on the CCU endorsement of the initial statement that the SI is scaled by fixing the values of a set of fundamental constants.

The CCU will then have to draft a new Resolution at its September 2010 meeting for the CIPM to consider at its October 2010 meeting, abrogating the present definitions of the seven base units and proposing the new definitions. This Draft Resolution would be put forward to the 24th CGPM in 2011. It is up to the CIPM to decide whether the quality of the experimental data is sufficient for the constants to be fixed. It is possible that the CIPM asks for better data before endorsing the decision to redefine.

9 DECIMAL MARKER

Dr Thompson brought the CCU's attention to an inconsistency in the usage of the dot on the line or comma on the line as decimal marker. A number of international organizations such as the OIML make use of the decimal comma and – in the English language – of the decimal dot, in agreement with Resolution 10 of the 22nd meeting of the CGPM in 2003. The ISO/IEC directives, however, prescribe the use of the decimal comma only.

After discussion the CCU was unanimous in endorsing its previous view to allow the use of either the comma or dot, following the customs depending on country and language, but to strongly suggest the use of the decimal dot on the line as the decimal marker in official documents in the English language. Prof. Mills and Prof. Wallard will again write a letter to the ISO/IEC explaining this policy. The situation will then be further reviewed in 2010 keeping in mind the possibility of submitting a Draft Resolution to the 24th CGPM in 2011.

10 RECONSIDERATION OF SOME LONG-STANDING PREVIOUS DISCUSSIONS

The President raised the question of changing the prefixes deca-, hecto-, and kilo-, from da, h, and k to Da (or D), H, and K.

Dr Leitner pointed out that in legal metrology the use of the current lower-case letters is agreed world-wide and a change would hardly be accepted. Other participants, such as Prof. Thor and Prof. Borghi, confirmed the refusal of such a recommendation or even a recommendation to allow both lower-case and capital letters. The President concluded that the CCU will not suggest any change in the prefixes da, h, and k.

The CCU discussed quantities with dimensionless units such as plane angle and solid angle, and quantities with unit 1/s which are sometimes specified according to application such as revolutions, cycles/s, rad/s, etc. Dr Mohr expressed the opinion that the units rad and sr for the quantities plane angle and solid angle are not just equal to the number 1. In his view the relation to the base units should be expressed as rad = m/(m/rad), which would imply, however, that rad and sr can not be expressed from the present base units.

The feeling of the CCU was not to recommend a change but to explain the importance of specifying the quantity to be measured in order to avoid confusion that might follow, if for example 1/s is used as a unit for a revolution speed, a frequency, a decay rate, or an angular frequency. The feeling of the CCU was not to add the rad to the set of base units.

In addition, the CCU agreed that the use of ppm and ppb for 10^{-6} and 10^{-9} cannot and should not be forbidden by the CCU. Even if desirable from a metrologist's point of view, such a recommendation would not be implemented by the users. Generally, the unanimous feeling in the CCU was not to forbid the use of units outside the SI, but rather to convince the world of the advantages of the SI.

Prof. Kovalevsky mentioned the developments in astronomy which have led to the more frequent use of milliarcsecond and microarcsecond for small angles. It was decided that they would be moved from footnote (*d*) of Table 6 of the Brochure to Table 6 itself.

Prof. Obdržálek suggested making the units litre and tonne more visible. The President suggested the addition of a phrase in footnote (*f*) of Table 6, which reads "the litre is a special name for dm^3".

Prof. Lu explained that the use of the units erg and dyne are not allowed for use in legal metrology in China. He suggested preparing a document explaining the content and how to use Table 9 of the SI Brochure, with the aim of improving international scientific exchange. No decision was taken on this subject.

Dr Fujii raised the problem of the use of Greek letters, which are sometimes not easily available on computers. A solution could be the use of u instead of μ. The feeling of the CCU was not to change the use of Greek letters.

Dr Fujii draw attention to an inconsistency in the use of the signs = (equal to), := (equal to by definition), and ≈ (approximately equal to) in document ISO/FDIS 80000 Part 9 on page 12. Prof. Thor recognized that indeed there was a mistake. The feeling was that the CCU should not be too restrictive about the use of these signs and should not become involved in the topic.

Dr Thompson reported on the development of the Extensible Markup Language (XML) for Units to encode scientific units. The NIST has set up a working group on the subject and is developing a related database. He recommended that CCU participants hand out document CCU/09-18 in their institutions and invited them to contact him if they were interested in participating in the working group.

11 STATUS REPORT ON PHYSIOLOGICAL QUANTITIES

Prof. Kühne reminded the CCU of the Workshop on "Physiological Quantities and SI Units", which will be held on 16 and 17 November 2009 at the BIPM. Further information is posted on the BIPM website at the address: http://www.bipm.org/en/events/physiological_quantities/.

12 ANY OTHER BUSINESS

The next meeting of the CCU will be held from 13 to 15 September 2010.

The President closed the meeting, and expressed his warm thanks to Claudine Thomas, the Executive Secretary of the CCU, for all her work in support of the CCU and his tasks as president.

Prof. Obdržálek expressed his thanks to Prof. Mills on behalf of the Committee.

10 September 2009

APPENDIX U 1.
Working documents submitted to the CCU at its 19th meeting

Access to working documents of the CCU is restricted to CCU members.

Document CCU/	
09-01	Updated Draft Agenda (20 May 2009), I.M. Mills, 3 pp.
09-02-1	LNE-SYRTE (France). — The Astronomical Units, N. Capitaine and B. Guinot, 2 pp.
09-02-2	Units of relativistic time scales and associated quantities, S. Klioner *et al.*, 7 pp.
09-03	Drafts of possible CGPM resolutions relating to redefining the kilogram, ampere, kelvin, and mole based on explicit-constant definitions, I.M. Mills *et al.*, 7 pp.
09-04	Drafts of possible CGPM resolutions relating to redefining the kilogram, ampere, kelvin, and mole based on explicit-unit definitions, I.M. Mills *et al.*, 5 pp.
09-05	NIST (United States). — On choosing the number of digits for the constants h,e, k, and N_A in the new definitions of the kilogram, ampere, kelvin, and mole, P.J. Mohr *et al.*, 5 pp.
09-06	University of Reading (UK). — Thoughts for the next, 9th, edition of the SI Brochure, I.M. Mills, 14 pp.
09-07	NIST (United States). — A numerically and conceptually simple explicit-unit definition of the kilogram that fixes the value of the Planck constant h, B.N. Taylor, 3 pp.
09-08	University of Reading (UK). — Explicit-constant versus explicit-unit definitions, I.M. Mills, 2 pp.
09-09-R10-2003	CGPM. — Resolution 10 of the 22nd meeting of the CGPM (2003), 1 pp.
09-09-R12-2007	CGPM. — Resolution 12 of the 23rd meeting of the CGPM (2007), 2 pp.
09-10	CCEM. — *Mise en pratique* for the ampere and other electric units in the International System of Units (SI), 6 pp.
09-11	BIPM. — h or N_A? Amplification of the CCM position, R.S. Davis, 4 pp.
09-12	PTB (Germany). — Report on experiments to measure the Boltzmann constant , J. Fischer, 3 pp.
09-13	NIST (United States). — On the new SI, P.J. Mohr and B.N. Taylor, 6 pp.
09-14	University of Reading (UK). — Report to the 23rd CGPM from the CCU, I.M. Mills, 11 pp.
09-15	Draft outline of the *mise en pratique* for the definition of the kelvin, CCT WG1, 4 pp.
09-16	Comments on items to be handled during the CCU meeting 26 to 28 May 2009, A.J. Thor *et al.*, 4 pp.

09-17 LNE-SYRTE (France). — Note sur la définition de la seconde – Note on the definition of the second, N. Capitaine and B. Guinot, 4pp.

09-18 NIST (United States). — Development of Units Markup Language, R.A. Dragoset, 2 pp.

09-19 Resolution by IUPAP concerning redefinitions in the International System of Units, J.L. Flowers and P.J. Mohr, 1 pp.

09-20 Independence of the International System of Quantities on the definitions of SI Units, I.M. Mills *et al.*, 5 pp.

09-21 Report from the CCM-WGM on developments since the 18th CCU meeting in 2007, P. Richard and R.S. Davis, 6 pp.

09-22 CCQM. — Recommendation Q1 (2009): On the possible redefinition of the mole and the kilogram, 1 pp.

09-23 INRIM (Italy). — Thoughts on a changing SI, F. Cabiati and W. Bich, 18 pp.

09-24 Remarks based on discussions at the Committee on Science and Metrology of the French Academy of Sciences, J. Kovalevsky and C.J. Bordé, 11 pp.

09-25 PTB (Germany). —Present status of the Avogadro project, P. Becker, 2 pp.

09-26 NIST (United States). — Decimal marker status in ISO and IEC, A. Thompson, 2 pp.

09-27 METAS (Switzerland). — There is no rationale for a redefinition of the mole (also document CCQM/09-06), H. Andres *et al.*, 5 pp.

09-28 NIST (United States). — Why the mole should be redefined in term of an exact value of the Avogadro constant N_A: A reply to document CCQM/09-06 by Andres *et al.* (also document CCQM/09-07), W.E. May *et al.*, 4 pp.

09-29 Amount of substance and the proposed redefinition of the mole (*Metrologia*, 2009, **46**, 332-338), M.J.T. Milton and I.M. Mills, 7 pp.

09-30 CCQM *ad hoc* WG on the mole. — Draft re-wording of the *mise en pratique* for the mole, 3 pp.

09-31 On a new definition of the second, P. Gill and F. Riehle, 15 pp.

09-32 University of Reading (UK). — Draft words for defining the kilogram, I.A. Mills, 1 pp.

09-001 University of Reading (UK). — Draft Chapter 2 of the next (9th) SI Brochure, dated 23 August 2009, I.A. Mills, 14 pp.