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INTERNATIONAL NEWS

CPEM 2006 round table discussion 'Proposed changes to the SI'

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Abstract
This report summarizes a round table session held last July at the CPEM 2006 to discuss recently proposed redefinitions of some base units of the International System of Units (SI) based on defined values of some fundamental constants. The aim of the session was to inform CPEM delegates of the various proposals and to promote a wide discussion of the issues arising from them. An interdisciplinary panel of six experts from national metrology institutes, the academic community and the industrial metrology community briefly presented their views and their concerns. The presentations were followed by a session in which the panel answered questions and heard comments from the audience.

At the CPEM 2006 in July, a round table discussion was held to look at questions arising from recent suggestions concerning the future redefinition of some of the base units of the International System of Units (SI). The participants were Dr Barry Wood (NRC), Dr Franz Josef Ahlers (PTB), Professor Christian Bordé (University Paris XIII and corresponding member of the *Académie des Sciences*, Paris), Mr David Deaver (Fluke Corporation), Dr Michael Gläser (PTB) and Dr Barry Taylor (NIST). The format of the round table discussion allowed an initial presentation of the personal views of the invited experts from different fields concerned by the proposed changes, and the meeting was then opened to questions from the audience.

The chairman, Dr Barry Wood, opened the round table discussion, commenting that its purpose was to inform both the community of electrical metrologists and the wider scientific community about considerations underway to change the SI. He outlined a number of recommendations made by the CODATA Task Group on Fundamental Constants, the Consultative Committees for Electricity and Magnetism (CCEM), Mass and Related Quantities (CCM) and Units (CCU) and most recently, Recommendation 1 (CI-2005) of the International Committee for Weights and Measures (CIPM), 'Preparative steps towards new definitions of the kilogram, the ampere, the kelvin and the mole in terms of fundamental constants' [1].

This recommendation invites the CCM, CCEM, the Consultative Committee for Amount of Substance (CCQM) and the Consultative Committee for Thermometry (CCT) to consider the implications of changing the definitions of the base units of the SI, to solicit input from the wider scientific and technical community, to monitor the results of new experiments relevant to the possible new definitions, to identify necessary conditions to be met before proceeding with changing the definitions, to consider alternative ways of redefining the units and perhaps, most importantly, to submit a report to the CIPM not later than June 2007.

In response to the recommendation of the CIPM [1], the CCEM established a working group to study proposed changes to the SI (WGSI), which is to make a recommendation to the CCEM at its next meeting in March 2007. This working group is chaired by Dr Barry Wood and is composed of Dr Beat Jeckelmann (METAS), Dr François Piquemal (LNE), Dr Ian Robinson (NPL), Dr Edwin Williams (NIST), Dr Brian Ricketts (NMIA), Dr Jürgen Melcher (PTB), and from the BIPM, Dr Thomas Witt and Dr Michael Stock as Secretary and Dr Claudine Thomas as CCU liaison.

The WGSI has met twice and has identified and discussed a number of issues, including the following. The timing and logistics of a possible implementation could be no sooner than 2011; otherwise, implementation would be delayed by increments of four years as it must be approved at a meeting of the General Conference on Weights and Measures

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(CGPM). The fixed values of h, e, k and N_A could be those deduced by the most recent CODATA adjustment. The changes would affect the present values of ε_0 and μ_0 (the permittivity of vacuum and the permeability of vacuum, respectively). There would appear to be increased uncertainties in some quantities, particularly quantities of mass. However, it must be remembered that the stability, and hence the uncertainty, of the mass of the present kilogram in relation to physical constants is unknown. Various wordings of unit definitions have been considered. There would be changes in the interpretation of results of some measurements, such as those based on the quantized Hall resistance, the Josephson voltage and the calculable capacitor. What are the consequences of inconsistency in the present fundamental constant determinations, particularly of h? What publicity and public education will be required in preparation for any change in the SI?

Dr Barry Taylor presented some of the key points of a paper, of which he was a coauthor, proposing an implementation of the CIPM recommendation [2]. Just as the definition of the metre links it to an exactly defined value of the speed of light in vacuum, c, the authors of [2] propose redefining the kilogram, ampere, kelvin and mole so that they are linked to exactly defined values of the Planck constant h, elementary charge e, Boltzmann constant k and Avogadro constant N_A, respectively. The values could be based on the 2010 CODATA least-squares adjustment of the constants, thereby ensuring the continuity of the magnitudes of the SI units, and the new definitions could be adopted by the 24th CGPM in 2011. *Mises en pratique* of the new definitions would be prepared by the appropriate Consultative Committees (CCs) of the CIPM, and the exact wordings of the new definitions would be developed by the CIPM through its CCs, other international bodies and the national metrology institutes. It was emphasized that the redefinitions would proceed only if the data on which the values of h, e, k and N_A rest have sufficiently small uncertainties and are in acceptable agreement.

The benefits of the redefinitions include (i) the guaranteed future ability of the SI to serve as the common measurement language in all fields of endeavour; (ii) the SI base unit of mass could be realized at any time, at any place, by anyone; (iii) the Josephson and quantum Hall effects could be used to realize directly SI electric units—the current system of conventional electric units could be abandoned; (iv) a large number of fundamental constants would become exactly known; (v) a number of 'energy' conversion factors would become exactly known—the mass of a particle would have the same relative standard uncertainty whether its value was expressed in kg, J, $\mathrm{m^{-1}}$, Hz or eV; (vi) the uncertainties of many constants, although still finite, would be significantly reduced; and (vii) the variation in the recommended values of the constants from one CODATA adjustment to the next would be significantly reduced.

The redefinitions would lead to two changes to the SI that are in reality 'non-problems.' First, the permeability of vacuum μ_0 would no longer be exactly $4\pi \times 10^{-7}\,\mathrm{N\,A^{-2}}$ but must be determined experimentally. However, this would have no practical consequences, because it is unlikely that the measured value of μ_0 would ever deviate from its current value by more than the fractional amount 1×10^{-9} and that its relative standard uncertainty would ever exceed 1×10^{-9}.

Second, the calculation of the molar mass M(X) of an entity X would change. The current definition of the mole fixes $M(^{12}\mathrm{C})$ to be exactly $0.012\,\mathrm{kg\,mol^{-1}}$, and $M(X) = A_r(X)M_u$, where $A_r(X) = m(X)/[m(^{12}\mathrm{C})/12]$ is the relative atomic mass of X and $M_u = 10^{-3}\,\mathrm{kg\,mol^{-1}}$ is the molar mass constant [m(X) is the mass of X, hence $A_r(^{12}\mathrm{C}) = 12$]. Based on the new definitions of the kilogram and mole, $M(^{12}\mathrm{C})$ would no longer be exactly $0.012\,\mathrm{kg\,mol^{-1}}$ and M(X) would be calculated from $M(X) = (1+\kappa)A_r(X)M_u$. But since it is unlikely that the value of κ would ever deviate from its current value of zero by more than 2×10^{-9} and that its standard uncertainty would exceed 2×10^{-9}, the existence of the factor $(1+\kappa)$ is inconsequential.

Dr Michael Gläser presented considerations of the mass community concerning new definitions of the kilogram and the mole. He recalled the essential parts of the CCM recommendation G1 to the CIPM of 2005. It states three conditions under which the kilogram may be redefined: (i) there are no significant unresolved discrepancies between results from independent experiments; (ii) the relative uncertainty of the best realization of the definition of the kilogram does not exceed two parts in 10^8 at the level of one kilogram and (iii) the results of a sufficient number of independent experiments are available with the required uncertainty.

He summarized the opinions and wishes of the mass community: (i) that, in general, a new definition of the kilogram based on a fundamental constant is desired; (ii) that a redefinition is not urgent for mass metrology; (iii) that there shall be no offset between the new and the old kilogram; and (iv) that a new definition of the kilogram should be understandable, especially for non-experts.

Dr Gläser presented the currently discussed options for a new definition of the kilogram, which are (i) the kilogram be defined as a multiple of the mass of a $^{12}\mathrm{C}$ atom with a fixed numerical value of the Avogadro constant, N_A, or of the mass of the electron; (ii) the kilogram be defined by a fixed numerical value of the Planck constant, h; (iii) the kilogram be defined by its Compton frequency, which also implies a fixed value of h. In addition, he presented a fourth definition: (iv) 'the kilogram is the mass of $(6.022\,141\,5 \times 10^{23}/0.012)$ free particles at rest and in their ground state whose creation frequency is $[(0.012/6.022\,141\,5\times10^{23}) \times (299\,792\,458)^2/(6.626\,069\,3\times10^{-34})]$ Hz'. The numerical values are those of N_A, $M(^{12}\mathrm{C})$, c and h. This definition fixes both h and the number of hypothetical particles, the mass of the particles being specified by the creation frequency and thus by h. N_A will be defined in the new mole definition. In order to express the creation frequency in terms of the present definition of the second, the simultaneous definition of h and N_A requires the introduction of a correction, the molar mass factor $(1+\kappa)$ already presented by Dr Taylor. Taking account of the value of this factor, the mass of the hypothetical particle is—for all practical purposes—close enough to the mass of the corresponding real particle. He remarked that a paper on new definitions is being prepared by several authors and will discuss this option in more detail. Options (i) and (iv) are preferred because they relate the kilogram to an atomic mass that has the same unit (kg), whereas options (ii) and (iii) relate the kilogram to quantities other than mass (action and frequency) with other units (J s and s^{-1}). Option (iv) would satisfy the wishes of both the mass community and the electricity community, if the numerical value of the elementary charge, e, is fixed in a new ampere definition. The Josephson and quantum Hall effects then can be used to realize the volt and the ohm in SI units.

Because both the Avogadro constant and the mole are, in fact, ratios between quantities with the same units, he proposed to consider henceforth the Avogadro constant as a number (with unit one) and to define the mole as a number, $\{N_A\}$, of entities, where 'mole' is only another name for the unit one.

Professor Christian J Bordé spoke on behalf of the working group on base units and fundamental constants of the *Académie des Sciences*, Paris. This group had sent a communication to the CCU in June 2005 [3], recommending a redefinition of the unit of mass based on the de Broglie–Compton frequency of the kilogram, which amounts to fixing the Planck constant. This frequency can be measured either directly with the watt balance or indirectly as the product of the Avogadro number and the de Broglie–Compton frequency of atoms, the latter being determined by atom interferometry [4]. Unfortunately, these two measurements at present differ at the 10^{-6} level, and it is generally agreed that no change in the definitions can occur before this inconsistency has been resolved.

A discussion is still going on within the working group on base units and fundamental constants concerning the redefinition of electrical units following the fixing of the Planck constant. A first choice, compatible with the present definition of the ampere, would be to fix the Planck charge $q_P = (2\varepsilon_0 hc)^{1/2}$. A second choice would be to fix the elementary charge e, since the ratio of these two charges is the square root of the fine structure constant, which cannot be fixed but has to be determined experimentally. These two choices are mutually exclusive with pros and cons in each case. The advantage of the first choice is to keep the permeability, permittivity and impedance of the vacuum fixed, in continuity with the present definition. The fine structure constant appears in this case as a property of the electron. The advantage of the second choice is the possibility of accommodating a space-time varying fine structure constant, which appears then as a property of the vacuum and, in this case, an easier implementation of gauge invariance. Advanced string theory points in this direction for the future [5]. The price is a 'floating' vacuum and an electric energy density whose expression depends on the fine structure constant in the absence of any charge. This second choice would allow one to fix the Josephson and von Klitzing constants but, unfortunately, the corresponding theoretical expressions are not yet validated experimentally to a sufficient accuracy (a few parts in 10^7 for K_J and a few parts in 10^8 for R_K). As a consequence, there appears to be no real practical advantage in the near future in fixing e rather than μ_0 or Z_0. If we choose to keep the vacuum properties fixed, the chain for the *mise en pratique* would include, as a primary realization of the definition, the Thompson–Lampard calculable capacitor. This is at present the best direct measurement based on the vacuum properties, especially on the vacuum impedance Z_0 (with a relative uncertainty equal to a few 10^{-8} today and to 10^{-8} in the near future). From there, one can determine not only R_K by direct comparison with Z_0 (calculable capacitor experiment) but also determine K_J thanks to the watt balance used with Z_0 instead of R_K, without depending upon the veracity of the formulae connecting these constants to e, h and α.

The working group has also expressed a favourable opinion about fixing the Boltzmann constant to redefine the kelvin and to maintaining an arbitrarily fixed Avogadro number to keep the mole as a base unit independent of the new unit of mass.

Dr Franz Josef Ahlers recalled the CCEM Recommendation E1 (2005) to the CIPM. Its central statement is that *'at the time when the kilogram will be redefined,... consideration be given to fixing the values of both the Planck constant and the elementary charge.'* This Recommendation is based on a general agreement on the advantages of fundamental constant-based unit definitions over artefact-based standards, which include the absence of drifts, independence from environmental conditions and comparatively easy availability.

These advantages can be fully exploited when macroscopic quantum effects provide a direct link between the microscopic realm of the fundamental constants and the macroscopic realm of practical metrology. Prototypical examples in electrical metrology are the Josephson and quantum Hall effects. They involve combinations of the Planck constant h and the elementary charge e and allow reproduction of the units of voltage and resistance with an uncertainty which is at least two orders of magnitude smaller than in the non-quantum SI. Such a win–win scenario strongly suggests that a unit should be defined which is based on the respective fundamental constant.

In electrical metrology these effects have been used on a routine basis since 1990, employing conventionally fixed values for the relevant fundamental constant combinations $K_J = 2e/h$ and $R_K = h/e^2$. The impressive advancement brought to electrical metrology by the quantum effects was demonstrated by comparing the drifts of voltage or resistance artefacts in the pre-quantum era with a currently available reproducibility of around 1 ppb. Strictly speaking, however, the electrical units presently disseminated via the Josephson and quantum Hall effects are not SI units. A new SI with fixed values of e and h would remedy this and allow one to perform voltage and resistance calibrations with extremely small uncertainty contribution from the standard.

Presently, the electrical quantum effects are advancing in many areas. With the availability of switchable Josephson arrays and of quantum Hall arrays nearly arbitrary voltages and resistances, as well as the corresponding ac quantities, can directly be derived from a quantum standard. In addition, a third quantum effect, single electron tunnelling, may allow one to check the internal consistency of the other effects by purely experimental means, thus testing underlying theoretical models. Lastly, the combination of the electrical quantum effects with a unique electro-mechanical instrument, the watt balance, provides a way of determining the Planck constant or, interpreted the other way round, defining the unit kilogram based on the Planck constant (if its value were fixed in the future). Worldwide, about 50 Josephson experiments and 30 quantum Hall experiments are already in operation. This demonstrates the easy availability of standards based on the fundamental constants. Five watt balances are in operation or in development.

In summary, from the point of view of the electrical community, the values of the fundamental constants h and e should be fixed in a future SI to secure all the advantages this has for practical metrology. If the mass community will consider fixing h, as proposed by Dr Gläser and other authors of a forthcoming publication, there is no controversy about fixing h, e and N_A to define the units kilogram, ampere and mole, respectively.

Mr Deaver pointed out that although many manufacturers understand the concept of the SI, from a practical perspective their traceability is not to the SI but to a national metrology institute (NMI). Historically, manufacturers view their responsibility as being able to provide traceability to an NMI and that it is the NMI's responsibility to provide the traceability to the SI units. As a result, the NMI's measurements and the quality of their traceability to the SI were rarely questioned.

In recent years, some manufactures have begun to give more attention to traceability to the SI because

- differences are found between NMIs when dealt with globally,
- more manufacturers are using primary standards (or intrinsic standards) to realize some of the SI units directly, as in thermometry, or to realize primary voltage and resistance standards based on K_{J-90} and R_{K-90},
- ISO 9000 and ISO/IEC 17025 have encouraged scrutiny of the quality of the traceability to the SI, not just to a particular NMI, and
- historical behaviour of some standards would indicate that the measurements of some NMIs are better than those of others.

Nevertheless, this shift in perspective from the NMI to SI is taking place slowly. Most manufacturers still rely on their NMI to provide measurement units. Redefinition of the measurement parameters without shifts in their values will have little impact on industry. If shifts in the measurement parameters do occur, and if they are of the sizes presently under discussion, some industrial laboratories will notice them but it is anticipated that the impact will be insignificant once one moves only a little down the traceability chain.

Even though the impact will be small, the uncertainty and doubt will be great when the announcement is made that some of the SI units are being redefined. Industry, governments, accreditation bodies and those responsible for legal metrology will be unsure about how they need to react to the changes. There will be concerns about the legality of existing calibration certificates.

It is recommended that many of the processes used in the 1990s for the introduction of electrical measurements based on K_{J-90} and R_{K-90} be used when the proposed SI redefinitions are decided upon. The working groups must first publish their documents. These will be used by the NMIs and a few in industry that will directly realize the SI units. Next, the NMIs need to issue a document that explains the changes in layman's terms that the manufacturers can readily understand. In 1989, the document issued by the US National Institute of Standards and Technology (NIST), Technical Note 1263, was about 70 pages in length. One manufacturer, Fluke Corporation, was then able to issue an application note of about 7 pages to its customers explaining the impact and which specific models would be affected by the change. These guidance documents will be very helpful in communicating the impact of future changes. If there are only small changes to the assigned values, the notes needed for wider communication need only be short, but they will be critical in communicating to users that there is little that needs to be done.

Finally, if there are shifts in the assigned SI values, an internationally recognized adhesive logo, such as the one made available by NCSL (now NCSL International), would be very helpful to identify in the laboratory standards that have been calibrated to the new values.

After the initial statements and comments from the members of the Round Table, the meeting was opened to questions. The following represents a selection of the resulting discussion, which amplifies the subject under discussion.

Q: What is the sufficient number of independent results needed for a redefinition of the kilogram?

A: Dr Gläser explained that this was not defined in detail in the CCM Recommendation. The question was discussed during the first meeting of the CCM Ad-Hoc Working Group on Changes to the SI directly before the CPEM; there seems to be a consensus that three results with uncertainties of about 2 parts in 10^8 would be sufficient. A proposal will be made to the CIPM in the near future.

Professor Bordé commented with respect to the proposal presented by Dr Gläser that N_A and h cannot be fixed independently to redefine the kilogram, because otherwise the unit of time would be redefined as well. Dr Gläser confirmed that the independent definition of N_A and h requires the introduction of a correction factor in the equation linking the molar mass with the relative atomic mass. Dr Taylor remarked that one cannot fix both h and N_A in a single definition of the kilogram. One needs to fix N_A in a separate definition of the mole.

Dr Peter Mohr (NIST) commented that a very attractive feature of the proposal made by Mills *et al* [2] is to give up the artificial distinction between SI base units and derived units by only specifying the values of seven fundamental constants upon which the whole system would be based. This possibility is surprising at first sight but can be easily understood; clearly, the currently used seven base units can be defined by fixing the values of seven fundamental constants. All other units can be derived from the base units. By omitting the first step, all units can be based directly on seven fundamental constants.

Q: What would be the minimum number of realizations needed after an eventual redefinition?

A: Dr Gläser replied that continuity is needed. It is hoped that the BIPM would operate an experiment, most probably a watt balance, to realize the new definition on a long-term basis. Other laboratories should be encouraged to do the same to guarantee some redundancy. Dr Wood commented that he did not agree with the absolute need for redundant mass realizations to replace a single artefact. Dr Gläser replied that in this case, mass metrology would still be relying on artefacts, as before. Dr Terry Quinn explained that artefacts are stable in the short term and will be maintained for practical mass metrology. A small number of watt balances would be needed to guarantee the long-term stability. Professor Bordé commented that several watt balances are needed to verify the physics, especially the relationship $K_J = 2e/h$.

Q: What is the influence of a possible difference between the elementary charge in free space and in a solid?

A: Professor Bordé explained that a difference is possible due to many-particle effects. Dr Wood said that the discovery of new physics would not change the definition of the new SI but only the physics of the Josephson and quantum Hall effects. The values of e and h would not change. Dr Taylor said that in his opinion there is much evidence implying that the relations $K_J = 2e/h$ and $R_K = h/e^2$ are exact, but if at some future date some corrections are discovered, they can be dealt with in a straightforward way by revising the *mises en pratique* of the kilogram and ampere. He expects that if such corrections are ever found, they will be so small that they will have no practical consequences. Dr Edwin Williams (NIST) said that one should assume the correctness of known physics and use this for the new SI. If necessary, the SI would have to be adapted to new physics. Professor Bordé replied that fixing e might be (mis)understood as fixing R_K and K_J. Dr Ahlers said that the quantum Hall effect (QHE) is very reproducible in different systems and that tests are continuing to guarantee that the effective charge in the QHE is identical to the elementary charge in free space. Professor Bordé replied that reproducibility in different systems does not guarantee knowledge of the correct equation. Dr Ahlers replied that if corrections were identified, they should be applied but they would be smaller than the presently established relative uncertainty of the SI value of R_K, which is 3 parts in 10^8.

Q: Why should the mole continue to be a base unit, if it will just be a number in the new SI?

A: Dr Taylor replied that the mole was introduced in the SI in 1971 at the request of the chemistry community and there is no reason to abandon it now. The redefinition would clarify that amount of substance does not depend on mass.

It was commented that the introduction of the correction factor between the molar mass and the relative atomic mass would destroy the beauty of the current system. Dr Taylor replied that there would be no practical impact and Dr Quinn added that the origin was the decision in 1971, which was right at the time, to define the mole in terms of the mass of a certain amount of ^{12}C. By breaking this link now between amount of substance and mass we inevitably introduce the correction factor.

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