SI UNITS

Proposed change to the definition of the kilogram: Consequences for legal metrology

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The General Conference on Weights and Measures [CGPM] *invites the CIPM* [International Committee for Weights and Measures], *the Consultative Committees, the BIPM and National Metrology Institutes* [NMIs] *significantly to increase their efforts to initiate awareness campaigns aimed at alerting user communities and the general public to the intention to redefine various units of the SI and to encourage consideration of the practical, technical, and legislative implications of such redefinitions, so that comments and contributions can be solicited from the wider scientific and user communities.*

From Draft Resolution A, "On the possible future revision of the International System of Units, the SI", extract of the Convocation to the 24th meeting of the CGPM (October 2011).

Introduction

The above text is part of Draft Resolution A [1] which has been submitted for consideration and possible adoption by the meeting of the CGPM in October 2011. Note that the title of Resolution A refers only to the "possible future revision" of the SI. Nevertheless, this Resolution, if adopted, would help enlarge the debate on future redefinitions of several of the SI base units: kilogram, ampere, kelvin and mole. Although the structure of the SI will not change (the system will still be derived from the same seven base units), the proposal is that the definitions of a number of the base units should be modified once certain conditions are met. (In due course, after the conditions have been met, a new draft resolution would be presented to the CGPM to adopt and implement the new definitions).

One of these units is the kilogram. It is the purpose of this paper to examine the proposed change to the definition of the kilogram in the context of legal metrology, which is to say in the context of OIML R 111-1 [2] and OIML D 28 [3]. In addition, a brief Appendix explains why the proposed redefinition of the kelvin will have no effect on mass metrology in general and R 111-1 in particular.

This article begins by recalling the present definition of the kilogram and the practical problems it poses for mass metrology in particular and for science generally. Next, the concept of a redefinition of the kilogram based on fundamental constants is presented - this shows that any reasonable redefinition can be realized by at least two different approaches. Then the prospects for a redefinition of the kilogram in approximately five years' time, with an emphasis on the impact, if any, on legal metrology is discussed. This article should be considered to be a progress report.

1 The present definition

In the present SI, 1 kg is defined as exactly equal to the mass of an object known as the international prototype of the kilogram, now commonly abbreviated as IPK. This definition dates from 1889. The definition means that the numerical value in kg of any object, X, is equal to $m(\mathrm{X})/\boldsymbol{m}\mathbf{(IPK)}$:

$$m(\mathrm{X}) = \left(\frac{m(\mathrm{X})}{\boldsymbol{m}\mathbf{(IPK)}}\right)\mathrm{kg}\quad , \quad \text{or}$$

$$m(\mathrm{X})/\mathrm{kg} = \frac{m(\mathrm{X})}{\boldsymbol{m}\mathbf{(IPK)}} \tag{1}$$

where $m(\mathrm{X})$ is the mass of X in kg and $\boldsymbol{m}\mathbf{(IPK)}$ is the mass of the IPK.

The kilogram is the last base unit of the SI [4] which is directly defined in terms of a property - the mass, in this case - of a manufactured object or "artefact". By contrast, the metre, which was also defined in 1889 by an artefact, had already been redefined in 1960, and again in 1983. The IPK is a cylinder made of an alloy of platinum and iridium. It is conserved at the BIPM and has been used extensively during three extended periods in order to provide traceability to national prototypes of the kilogram. The last such occasion was the period from 1989 to 1991. The IPK is mentioned explicitly in OIML R 111-1, in the definition of class E_1 weights:

Class E_1: *Weights intended to ensure traceability between national mass standards (with values derived from the International Prototype of the kilogram) and weights of class E_2 and lower…*[2].

Thus all mass values in legal metrology are ultimately traceable to the mass of the IPK.

This system worked reasonably well throughout the 20th century, but there are clearly some shortcomings for mass metrology:

- the IPK is a unique object, which is stored and used only at the BIPM. (Access to this object is strictly regulated by the CIPM);
- the IPK could, at least in principle, be damaged during use;
- after long periods when it is not used, the IPK must be carefully cleaned in order to remove accumulated surface contamination without removing the underlying alloy;
- the mass of the IPK and similar artefacts might be affected over very long periods of time by chemical or physical processes which are too slow to be easily detected;
- by convention, in the SI the mass of the IPK is always 1 kg; it was exactly 1 kg in 1889 and, after cleaning, its mass would be exactly 1 kg today.

In addition, the present definition of the ampere, which is an SI base unit, refers to a force between two current-carrying wires [4]. The unit of force contains the kilogram, and thus the kilogram definition affects electrical units as well. The electrical community recommends a new SI where two fundamental constants, the Planck constant and the elementary electrical charge, have exactly defined values [5]. Meanwhile, since 1990, the electrical community has adopted very precise "representations" of voltage and resistance units, sometimes referred to in the scientific literature as conventional 1990 electrical units (see footnote 3 in the Appendix on the need for such conventions).

Regarding the last bullet point above, it has been observed that the masses of the majority of other, similar 1 kg prototypes are increasing with respect to the mass of the IPK [5]. The relative change with time among prototypes is small, roughly 50 µg during a period of 100 years, but it is impossible to tell from measurements made on a mass comparator whether it is the mass of the IPK or that of other prototypes which have changed with respect to some fundamentally constant reference mass - it may be that the masses of all these prototypes made of the same material are also changing together with respect to a fundamental constant of mass. The need to accept the last bullet point is the major motivation in mass metrology for redefining the kilogram. Indeed OIML R 111-1 has something very relevant to say about the stability of reference weights, and the IPK is the ultimate reference weight for mass metrology:

> **The uncertainty due to instability of the reference weight...can be estimated from observed mass changes after the reference weight has been calibrated several times. If previous calibration values are not available, the estimation of uncertainty has to be based on experience** [2].

This, of course, is excellent advice but it is impossible to apply it to the IPK, whose mass must always be exactly 1 kg by definition!

Finally, in modern physics it is illogical to measure perfectly stable physical constants - often referred to as the "fundamental" constants - in terms of some manufactured object whose long-term stability is suspect. Logically, it should be the other way around: the mass of the IPK and of all other reference weights should be traceable to the mass of a fundamentally stable constant of nature. Clearly, many problematic aspects associated with the present IPK would disappear for metrology in particular and science in general if the kilogram were somehow to be redefined in terms of fundamental constants. It must, however, be understood to what extent new problems may arise. This will be discussed in Section 4. First a brief comment is provided of how fundamental constants of mass are measured today and how one of them might serve to redefine the kilogram in the future.

2 Constraints on a new definition of the kilogram

Among the fundamental constants that can be considered, the most obvious are those which are simply masses themselves: $m(\mathrm{X})$, where X is an entity which might be chosen to be a stable atomic isotope such as carbon-12 ($^{12}\mathrm{C}$) or silicon-28 ($^{28}\mathrm{Si}$). At present, the SI value of $m(\mathrm{X})$ in all these cases must be traceable to the mass of the IPK. Say, for instance, that the most recent experimental result of such a measurement is a, so that:

$$m(\mathrm{X}) = a \qquad (2)$$

where both $m(\mathrm{X})$ and a are in kilograms. Based on traceability to the IPK as shown in (1),

$$m(\mathrm{X})/\boldsymbol{m}(\mathbf{IPK}) = a/\mathrm{kg} \qquad (3)$$

Equation (3) is useful for the purposes of this discussion because it shows both the IPK and the kilogram unit explicitly. The quantity a is measured in kg. Therefore, a/kg is dimensionless, as is the ratio on the left hand side of (3). Suppose that the measured quantity a has a standard relative uncertainty $u_r(a)$ ($k = 1$). At present, the standard relative uncertainty of $m(\mathrm{X})$, $u_r(m(\mathrm{X}))$, equals $u_r(a)$ because, by definition, $u_r(\mathrm{IPK}) = 0$.

One possibility to redefine the kilogram would be to specify that a is the exact numerical value of $m(\mathrm{X})$ when this mass is expressed in kg. If that were to happen, $u_r(m(\mathrm{X})) = 0$ and the value of $m(\mathrm{X})$ would forever be $\boldsymbol{a}$, its measured value just before the redefinition took effect. In this case, immediately after the redefinition takes effect, (3) would be rearranged to become:

$$m(\mathrm{IPK})/\boldsymbol{m}(\mathbf{X}) = \boldsymbol{a}^{-1}/\mathrm{kg} \qquad (3')$$

The value of $\boldsymbol{m}(\mathbf{X})$ in kg is defined for all time to be exactly $\boldsymbol{a}$. Remember, $m(\mathrm{X})$ is a fundamental constant of physics. Its mass will not change. Suppose that sometime after the redefinition of the kilogram a new measurement of $m(\mathrm{IPK})/\boldsymbol{m}(\mathbf{X})$ does not equal $\boldsymbol{a}^{-1}$/kg. Suppose this ratio now is measured to be b^{-1}/kg and that $\boldsymbol{a} \neq b$ within the measurement uncertainty. One would conclude that $m(\mathrm{IPK})$ has changed since the time it was used to determine $\boldsymbol{a}$. A change in an artefact's mass is certainly possible, and even expected (that is why they are recalibrated). With the present definition of the kilogram it would be suspected that $\boldsymbol{m}(\mathbf{IPK})$ has changed with respect to the physical constants but the present definition of the kilogram nevertheless constrains $\boldsymbol{m}(\mathbf{IPK})$ to be 1 kg exactly.

To summarize, the most important features of a new kilogram definition based on a fixed value of a fundamental constant of mass are:

- The mass of X, $\boldsymbol{m}(\mathbf{X})$, which is a fundamental constant such as the mass of a conveniently chosen atom such as carbon-12 (^{12}C) or silicon-28 (^{28}Si), will be a perfectly stable reference into the future.
- There will be no jumps in mass values measured just before and just after the redefinition. Equations (3) and (3') ensure this important feature. (Thus previous mass values traceable to the IPK are unchanged just after the redefinition).
- The mass of the IPK in kg, which by convention had zero uncertainty, acquires a known standard uncertainty, $u_r(a)$. In the future, $m(\mathrm{IPK})$ must be recalibrated just as the mass of any other reference weight, i.e. the value $m(\mathrm{IPK})/\boldsymbol{m}(\mathbf{X})$ can change with time and this is now interpreted as a change in $m(\mathrm{IPK})$.
- The recommendations in OIML R 111 for estimating an uncertainty component for the mass instability of a reference weight will be valid for the IPK as they are for all other reference weights. (Note however, the uncertainties of mass values which were traceable to the IPK acquire a new uncertainty component. In a sense, this component was always there but it could not be estimated accurately and, by convention, the present SI conveniently defines this uncertainty component to be zero).
- The experiment which resulted in the measurement of $\boldsymbol{a}$ can, in principle, be reproduced, and perhaps improved, wherever and whenever needed. This is important because reference weights remain artefacts and will thus need periodic recalibration.

The relative uncertainty component, $u_r(\boldsymbol{a})$ measured just before redefinition of the kilogram, will transfer to all macroscopic masses just after the redefinition. This is a crucial consideration for mass metrology and will be discussed in more detail in Section 4, below. Here it should be added that, if $m(\mathrm{IPK})$ has changed over time with respect to fundamental constants of mass, then measured values of the fundamental constants of mass may appear to have changed over time with respect to $m(\mathrm{IPK})$. It is important to note that no such evidence has been found. Nevertheless, experimental accuracies are continuously being improved.

3 Methods to redefine the kilogram and to provide traceability to the new definition

The previous section has introduced the basic scheme for redefining the kilogram in terms of a fixed numerical value of a fundamental constant. The example of the mass of an atom has been taken but, as will now be shown, there is another possibility. Two principal types of practical experiments which are being used to provide the necessary metrological underpinning of a new definition are described. The two methods in some ways resemble the methods a) and b) mentioned in Section 9 of OIML D 28:

> *In general, the mass of a body can be determined either:*
>
> *a) By comparison with a weight or a mass standard as a reference, using a balance or weighing instrument as a comparator, or*
>
> *b) By using a weighing instrument as a reference instrument.* [3]

3.1 Traceability of $m(^{28}\mathrm{Si})$ to $m(\mathrm{IPK})$ - type (a) experiment

This experiment is usually referred to as measuring the Avogadro constant, N_A. For our purposes, however, it is preferable to view this experiment simply as a determination of the mass of one silicon-28 atom, $m(^{28}\mathrm{Si})$, in kg[(1)]. The challenge is to compare two masses as in (2) above, where a/kg is nominally about 5×10^{-26} and to carry out this comparison with a relative uncertainty that is much smaller than, for example, the class E_1 maximum permissible error (mpe) at 1 kg. This remarkable feat has required a world-wide collaboration

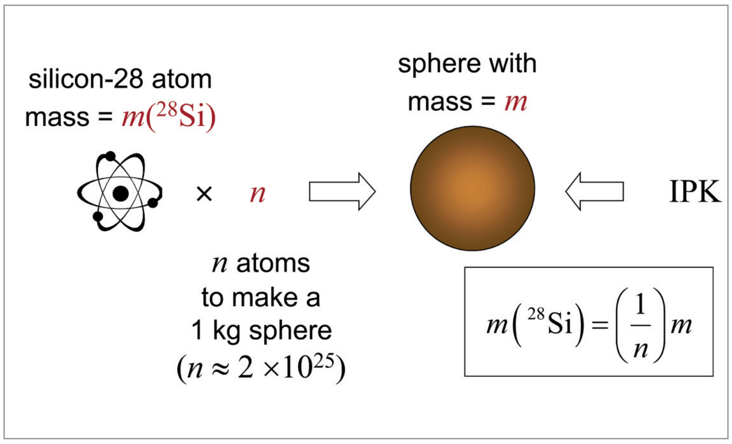

Figure 1. Linking the mass of a silicon-28 atom to the IPK. A sphere, with mass approximately 1 kg, is manufactured from a perfect crystal of silicon. Only the isotope silicon-28 is used to grow the crystal. The number of atoms, n, in the sphere is found by dividing the volume of the sphere by the average volume occupied by a single atom. Comparing the mass of the sphere to the mass of a 1 kg reference weight traceable to the IPK establishes the link between the mass of a silicon-28 atom and the IPK. There are many experimental challenges to achieving high accuracy [7].

involving many NMIs and other laboratories. The procedure was to create a nearly perfect crystal, with a mass close to 1 kg, composed entirely of silicon-28 atoms. The perfection of the crystal allows the experimenters to determine the number of atoms, n, in the crystal by a combination of innovative techniques. Thus the mass of the crystal is $n \times m(^{28}\mathrm{Si})$. The crystal is manufactured to be a sphere with mass of approximately 1 kg. Its actual mass, m, is found with respect to a reference standard, m_r, by performing a series of weighing cycles. Of course the value of m_r is traceable to the IPK (Fig. 1). Thus the ratio $m(^{28}\mathrm{Si})/\boldsymbol{m}(\mathbf{IPK})$ is known from this experiment:

$$\frac{m\left(^{28}\mathrm{Si}\right)}{\boldsymbol{m}(\mathbf{IPK})} = \left(\frac{1}{n}\right) m/\mathrm{kg} \qquad (4)$$

Note that (4) has the same form as (1) and (3). The experiment consists of measuring m/n to high accuracy, and this is extremely challenging [7].

The Avogadro collaboration has determined the average of m/n in two different crystalline spheres to a standard relative uncertainty of 30×10^{-9}, or 30 µg/kg, and work continues to reduce this uncertainty even further.

3.2 Traceability of h to m(IPK) using a watt balance - type (b) experiment

Simply put, the watt balance is a weighing instrument which, after a future redefinition of the kilogram, can serve as a reference instrument to determine the mass of a weight piece. The operation of a watt balance has two parts, often referred to as "weighing" and "moving" experiments [8]. The weighing experiment is very similar to that which occurs in an analytical balance of the type well known in legal metrology. As shown schematically in Fig. 2-1, the gravitational force, $m_r g$, is balanced by an electro-magnetic force. The latter is produced by an electrical current, I_r, flowing through a length, L, of wire that is in a magnetic field, B. The current can also be thought of as the balance indication:

$$m_r = (BL/g)I_r \qquad (5)$$

In an analytical balance, (BL/g) is determined by the ratio m_r/I_r. In a watt balance, however, the gravitational acceleration, g, is measured and BL is eliminated by carrying out the "moving" experiment. As shown in Fig. 2-2, BL is the ratio of a voltage, U, to a velocity v:

$$BL = U/v \qquad (6)$$

so that:

$$m_r = (U/vg)I_r \qquad (7)$$

or:

$$m_r vg = UI_r \qquad (7')$$

The left hand side of (7') is a mechanical power and the right hand side is an electrical power. Both powers are measured in watts, hence the name "watt balance". But (7') does not yet contain a fundamental constant.

Many NMIs now calibrate voltage and resistance standards not in terms of the SI definitions of these units, but in terms of quantum electrical devices. Hence the 1990 conventions mentioned briefly in Section 1 which are commonly used at the highest levels of electrical metrology [5]. Voltage standards are based on the "Josephson effect" and resistance standards are based on the "quantum Hall effect". (A Nobel prize was awarded for the discovery of each effect). For this article it is sufficient to state that (7) becomes:

(1) m(X) of any atomic entity X is related to the Avogadro constant, N_A, through the molar mass of X, M(X): $M(\mathrm{X}) = m(\mathrm{X})N_A$. In the present SI, the value of $M(^{12}\mathrm{C})$ is defined as exactly 0.012 kg/mol. Thus a measurement of $m(^{12}\mathrm{C})$ with relative uncertainty $u_r(m(^{12}\mathrm{C}))$ can be reported as a measurement of N_A having the same relative uncertainty. From measurements in atomic physics, the mass ratio $m(^{28}\mathrm{Si})/m(^{12}\mathrm{C})$ is already known with a negligible uncertainty. Therefore a measurement of $m(^{28}\mathrm{Si})$ can easily be converted to a value of $m(^{12}\mathrm{C})$, and hence to a measured value of N_A. (Note: In the "new" SI, it has been proposed that N_A have an exactly defined value in mol^{-1} and that, consequently, $M(^{12}\mathrm{C})$ will acquire a very small uncertainty.)

$$m_r = h\frac{f_{J,1}f_{J,2}}{vg}C_{wb} \tag{8}$$

where the constant, h, the two measured frequencies $f_{J,1}$ and $f_{J,2}$ and a dimensionless factor, C_{wb}, all arise from the use of quantum effects for measuring voltage and resistance, as shown in [8]. The constant, h, which now appears is the Planck constant, the fundamental constant of quantum physics. Its unit, kg m^2 s^{-1}, contains the kilogram. On the right hand side of (8), the kilogram unit appears only in the units of h.

At present, watt balance experiments described in (8) have already been used to measure the Planck constant with great accuracy. In analogy to (1), (3) and (4) it is seen that, in the present SI, the watt balance is a means to relate h to the IPK:

$$\frac{h}{m(\text{IPK})} = \left(\frac{vg}{f_{J,1}f_{J,2}C_{wb}}\right) m_r / \text{kg} \tag{9}$$

In the future, the kilogram could be redefined in terms of a fixed numerical value for h and (9) could be rearranged to represent a realization of the new definition.

The National Institute of Standards and Technology (NIST, USA) has been steadily improving its watt balance over the years and has continued to reduce its uncertainty. The new NIST-measured values of h remain consistent with its own historical values. At present, NIST has also achieved the lowest uncertainty of any watt balance experiment. The most recently published NIST value for h has a relative standard uncertainty of 36×10^{-9}. A number of other NMIs and the BIPM are also working actively on the "electronic kilogram" but have not yet achieved uncertainties comparable to that of NIST. However, low-uncertainty results can reasonably be expected from several of these laboratories in the near future.

3.3 Relation between $m(^{28}\text{Si})$ and h

One might think that the choice of whether to redefine the kilogram through an atomic mass, or through an exact value of the Planck constant would be a crucial decision for mass metrology. However, this is not the case. Various experimental results obtained in the realm of atomic physics can be combined to provide a value of the ratio $h/m(^{28}\text{Si})$ to a relative uncertainty less than 1×10^{-9}, (i.e., a relative uncertainty corresponding to less than 1 µg/kg). This uncertainty component is so small that both the NIST watt balance experiment to determine h and the Avogadro experiment to determine $m(^{28}\text{Si})$ provide equivalent values of h. Thus the kilogram can be redefined in terms of h but traceability of mass standards to h can in principle be achieved through $m(^{28}\text{Si})$ or through h.

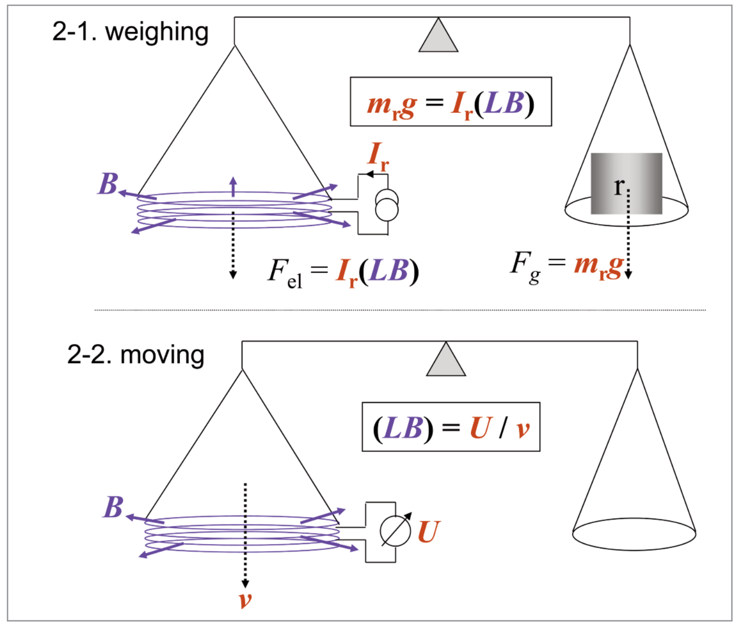

Figure 2. Linking the Planck constant to the IPK. 2-1: The "weighing" experiment is similar to the operation of a modern analytical balance: The gravitational force on a reference weight, r, is balanced by the electrical current, I_r, flowing through a coil (of length, L) placed in a magnetic field of flux density, B. 2-2: In the "moving" experiment, the same coil is made to move at constant velocity, v, through the same magnetic field. This induces a voltage U at the ends of the coil. Combining both experiments eliminates (BL) from the model equation. From (7') and (8), measuring the electrical quantities, U and I_r, by means of the Josephson and quantum Hall effects establishes a link between h and the IPK [8].

Results of the Avogadro experiment to determine $m(^{28}\text{Si})$ can easily be compared with results of watt balance experiments to determine h, with which they should agree within their combined uncertainties. Again, this is because the value of $(h/m(^{28}\text{Si}))$ is already known to 1 part in10^9. Thus a measurement of $m(^{28}\text{Si})$ to a relative uncertainty of, say, 10×10^{-9}, when multiplied by the recommended value of $(h/m(^{28}\text{Si}))$ provides a value of h to the same relative uncertainty of 10×10^{-9}. Conversely, a measurement of h made on a watt balance can easily be converted to a value of $m(^{28}\text{Si})$ or, indeed, to a value of the Avogadro constant, N_A, as explained in the footnote referenced at the beginning of 3.1.

4 The proposed new definition of the kilogram

After considering the various recommendations of its relevant consultative committees - namely the Consultative

Committee for Mass and Related Quantities (CCM), the Consultative Committee for Electricity and Magnetism (CCEM), the Consultative Committee for Metrology in Chemistry (CCQM) and the Consultative Committee for Units (CCU), the International Committee for Weights and Measures (CIPM) has concluded that a redefinition of the kilogram based on a fixed value for *h* combined with the existing definitions of the metre and the second is the optimum choice.

In large part, this decision was motivated by: (i) the central role of *h* in modern science; (ii) the fact that defining an exact value for *h*, along with an exactly defined value for the charge on the electron, would bring the quantum electrical standards (see Section 1) within the SI [5]; and (iii) the fact that the kilogram can be disseminated equally well from a new definition based on *h*, $m(^{28}\mathrm{Si})$ or $m(^{12}\mathrm{C})$. Thus the proposed draft recommendation for consideration at the October 2011 meeting of the CGPM, as cited at the start of this paper, proposes the following redefinition of the kilogram based on an exact fixed value for *h* :

...the SI will continue to have the present set of seven base units, in particular

- *the kilogram will continue to be the unit of mass, but its magnitude will be set by fixing the numerical value of the Planck constant to be equal to exactly 6.626 06X × 10^{-34} when it is expressed in the SI unit $m^2\ kg\ s^{-1}$, which is equal to J s,...*[1]

It should be noted that the "X" in the numerical value of the Planck constant refers to digits that have yet to be determined because high-accuracy experimental work is still ongoing. As discussed above, defining the numerical value of *h* to be equal to that of its recommended value in the present SI will ensure that there will be no discontinuity in mass measurements caused by the redefinition (see Section 2). The same procedure has already been followed for successive redefinitions of the metre. It is interesting to note that since 1983 the metre has not been defined by a fundamental constant of length but by a combination of a fixed value of the speed of light in a vacuum and the SI definition of the second. Similarly, the proposed new definition of the kilogram would not be based on a fundamental constant of mass but rather on a fixed value for the Planck constant and the existing SI definitions of the second and the metre.

4.1 Our present knowledge of the value of *h* in SI units

The present values of *h* which have been determined from the Avogadro experiment and the NIST watt balance experiment do not agree as well as could be hoped. The CODATA Task Group on Fundamental Constants, which traditionally recommends values and uncertainties for the fundamental constants of physics, has examined the highly precise NIST and Avogadro determinations along with other relevant measurements.

To summarize the present situation, the available data led the Task Group to recommend a value of *h* with relative standard uncertainty of 44×10^{-9} (k = 1)[9]. This uncertainty takes account of the as-yet unexplained difference between *h* derived from the Avogadro measurement of $m(^{28}\mathrm{Si})$ and *h* derived from the NIST watt balance. Not surprisingly (see footnote (1) at the bottom of page 8), the same relative standard uncertainty, 44×10^{-9}, applies to the recommended values of N_A and $m(^{12}\mathrm{C})$. This means that these expanded relative uncertainties (k = 2) correspond to 88 µg/kg, which is already less than 1/5 the mpe for 1 kg class E_1 weights [2], and further experimental improvements can be expected relatively soon.

4.2 Practical realization of the "new" kilogram definition

At its previous meeting in November 2007, the CGPM had already recognized the importance of establishing practical realizations for the redefined units. Their view was formally expressed as part of Resolution 12:

The 23rd General Conference...

Recommends that National Metrology Institutes and the BIPM...should, together with the International Committee, its Consultative Committees, and appropriate working groups, work on practical ways of realizing any new definitions based on fixed values of the fundamental constants, prepare a mise en pratique for each of them, and consider the most appropriate way of explaining the new definitions to users,...[10].

The *mise en pratique* for the definition of a unit is a set of instructions that allows the definition to be realized in practice at the highest level of accuracy.

A number of questions naturally arise:

- When will the new definition of the kilogram take effect?
- What will be the *mise en pratique* for the proposed new definition of the kilogram?
- Who is responsible for developing the *mise en pratique*?
- What will be the uncertainty with which the new kilogram can be realized in practice?
- How will the new kilogram be disseminated?
- Does every NMI need to have a watt balance?
- And finally, what will be the effect on legal metrology?

4.2.1 *When will the new definition of the kilogram take effect?*

Operationally, the new definition of the kilogram will take effect when the General Conference (CGPM) gives its final approval. Since the CGPM traditionally meets every four years, approval could come as early as October 2015. However, a certain number of criteria must be met. Technical difficulties in realizing the new definitions must be overcome, user communities must be informed and their views considered, and as many as four redefined base units of the SI should be ready for implementation at the same time. Thus the launch date is not yet certain.

Specifically regarding redefinition of the kilogram, the CCM has been involved at least since 2005. Its most recent Recommendation, dated 2010, is available on the BIPM website [11]. In part, the CCM recommends that the following technical conditions be met before the kilogram is redefined in terms of fundamental constants of physics:

- at least three independent experiments, including work both from the watt balance and from international Avogadro collaboration projects, yield values of the relevant constants with relative standard uncertainties not larger than 5 parts in 10^8. At least one of these results should have a relative standard uncertainty not larger than 2 parts in 10^8,
- for each of the relevant constants, values provided by the different experiments be consistent at the 95 % level of confidence,
- traceability of BIPM prototypes to the international prototype of the kilogram be confirmed.

A recent publication by authors at the Physikalisch-Technische Bundesanstalt (PTB, Germany)[12] makes a detailed case that, if these recommendations are met, the added uncertainty component due to traceability to the new definition will have minimal impact on the calibration of class E_1 weights by accredited laboratories. Legal metrology will be unaffected, and the long-term stability of the kilogram unit will be assured. The importance of the uncertainties obtained by different experiments, their statistical agreement and their traceability to the IPK - all mentioned in the CCM Recommendation - have been explained in Sections 2 and 3.3 above.

4.2.2 *What will be the mise en pratique for the new kilogram? Who is responsible for the document?*

Remember that the *mise en pratique* will be a set of instructions which lead to a realization of the new kilogram to the smallest practical uncertainty. The CCM working group on changes to the SI kilogram, CCM WG-SI kg, is preparing the first draft of this document but it is premature to give further details. The terms of reference of the WG-SI kg are publicly available [13]. These include "To solicit and collate comments from a wider scientific community on the wording of the future definition and on the *mise en pratique*"(2).

4.2.3 *What will be the uncertainty with which the new kilogram can be realized in practice?*

This depends on the results of experiments that are still under way. If the minimum conditions recommended by the CCM can be achieved, then there should be no transitional problems when the redefinition takes effect [11, 12]. After that, one would expect the uncertainty of the realization to decrease with time as experiments are improved.

4.2.4 *Does every NMI need to construct a watt balance or a crystal of ^{28}Si?*

The answer to this question is no. At present, both the watt balance approach and the silicon crystal approach to a realization of a future definition of the kilogram are relatively costly, time consuming and metrologically demanding. The kilogram can be disseminated from any recognized source that realizes the definition of the kilogram. This will not change. For example, the BIPM plans to continue to disseminate the kilogram to its Member States whether or not the BIPM watt balance is operational at the time of the redefinition. The BIPM plans to rely on a weighted average of the realizations available at the time of the redefinition. However, a detailed dissemination scheme has not yet been defined because many experiments that have the potential to realize the new definition are still under development. Any NMI wanting to disseminate the kilogram directly from its own realization of the new definition, such as

(2) Of interest to the readership of the *OIML Bulletin* is the fact that the Chair of WG-SI kg is currently a member of the CIML Presidential Council, and a member of the WG-SI kg is currently the contact person for the Secretariat of OIML TC 9/SC 3. This Secretariat has technical responsibility for both R 111-1 and D 28.

its own watt balance, will presumably be constrained by the rules of the CIPM MRA for the international acceptance of its calibration and measurement capabilities. The BIPM will be under similar constraints.

Conclusion – What will be the effect on legal metrology?

The redefinition of the kilogram in terms of a fundamental constant of physics is still a work in progress. The BIPM has centralized much of the important information on progress towards a new SI at a publicly accessible URL [1]. The site is, of course, kept current. The redefinition of the kilogram, when it occurs, will take the needs of legal metrology into account (e.g. discussion in Section 4.2.1) so that any impact will be minimal. Nevertheless, it is important for the legal metrology community to be aware of the efforts underway and to contribute as it sees fit to this enterprise.

Appendix: mass metrology, legal metrology and the new kelvin

OIML R 111-1 specifies many temperature measurements. These are needed in calculations of air density (for buoyancy corrections) and of water density (for density determinations of weight pieces). As Section 3 of R 111-1 explicitly states, the temperature in kelvin or in Celsius referred to is derived from the International Temperature Scale of 1990 (ITS-90). This is generally true for all temperature measurements required by mass metrologists. The ITS-90 is a conventional scale which is a very close approximation to "thermodynamic temperature". The advantage of the ITS-90 is that temperatures defined on this scale can be efficiently disseminated with high precision and reproducibility(3). Continued use of the ITS-90 is independent of the redefinition of the kelvin [14], which is the SI base unit of thermodynamic temperature. Therefore legal metrology should be unaffected by the redefinition of the SI kelvin.

(3) In 1995 the directors of the PTB and the BIPM published an article which acknowledged that "in many fields where precise metrology is applied, for example, in industry, the uniformity and reproducibility of measurements are of greater immediate interest than compatibility with the SI" [15].

References

Note: To the extent possible, references are given as the URL addresses of freely-available sources.

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