1. Introduction

In 2005, the Consultative Committee for Mass and Related Quantities (CCM) was faced with the challenge of dealing with a serious proposal to redefine the kilogram in terms of a constant of nature, within a very short time [1]. The timing would have meant that mass calibrations would, at least initially and possibly for a very long time, need to remain tied to the present definition of the kilogram which is based on an artefact standard, while in parallel; the SI adopted a more ‘modern’ definition of the kilogram. The following briefly describes how the CCM has dealt with the redefinition in order to reach what we believe will be an excellent result for all concerned.

Section 2 introduces the major issues that faced the CCM and the various reactions of the wider international community as reflected particularly in Resolutions of succeeding General Conferences on Weights and Measures (CGPM). Section 3 describes how the CCM organized its coordination work in order to ensure that the wide and diverse mass community was efficiently represented. Of special interest here are the CCM Recommendations that set out what is required technically and operationally of the redefinition of the kilogram in order to maintain continuity with the present definition, to limit inconvenience to secondary laboratories and of course to realize the new definition in practice. A roadmap was also established that shows essential tasks that need to be accomplished (including production of this focus issue of Metrologia) as well as the timetable for accomplishing all essential steps in order to reach the redefinition of the kilogram by the autumn of 2018. Section 4 describes the production of the draft mise en pratique of the (re)definition of the kilogram and contrasts the draft document with the present mise en pratique for the artefact definition of the kilogram. Finally section 5 recalls some, though by no means all, of the major issues that have needed to be resolved collectively in order to reach the final goal.

2. Early stages

2.1. Urgency of the redefinition

The mass of the international prototype of the kilogram (IPK) has defined the unit of mass since the 1st CGPM in 1889,
although the definitive wording did not come until the 3rd CGPM in 1901 [2]. The IPK has thus defined the kilogram for about 130 years and for years has been the only material artefact still defining a base unit. This will change with the redefinition.

International efforts to relate the mass of the IPK to a fundamental or atomic constant had already been initiated about 40 years ago [3]. The efforts of several major National Metrology Institutes (NMIs) were significantly increased about 20 years ago. More recently many additional NMI players have taken up the challenge.

As a consequence of these efforts, more than a decade ago the President of the Consultative Committee for Units (CCU) at that time and four distinguished co-authors declared after serious reflection that the time for the redefinition of the kilogram had come [1]. Even if the redefinition will take place about 14 years later, this controversial paper set the cat among the pigeons and catalyzed events that have led to a revised SI with more sweeping changes than had been envisioned by these authors in their first publication [1].

One of the main reasons not to redefine the kilogram in 2005 or shortly after was the discrepancy of nearly 1 part in \(10^6\) between comparable results obtained from the watt balance experiments and the x-ray-crystal-density (XRCD) method. The mass community under the auspices of the CCM expected both reasonable agreement and low uncertainties of measurement.

### 2.2. A brief history of the CGPM decisions

In the mean time the CGPM was actively following the evolution of the situation.

In 1999, the 21st CGPM [4] recommended in its resolution on the definition of the kilogram that NMIs ‘continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram’ (but see section 5 for an even earlier recommendation on this subject).

In 2007 the 23rd CGPM [5], recommended in its resolution on the possible redefinition of certain base units of the International System of Units (SI) that NMIs and the BIPM ‘pursue the relevant experiments so that the (CIPM) can come to a view on whether it may be possible to redefine the kilogram, the ampere, the kelvin, and the mole using fixed values of the fundamental constants at the time of the 24th CGPM (2011)’.

After some significant progress with the relevant experiments, in 2011 the 24th CGPM [6] prepared in its resolution on the possible future revision of the International System of Units the SI the foundation of the revised SI with a proposed wording for the seven base units. The CGPM also encouraged researchers in (NMIs), the BIPM and academic institutions to continue their efforts and make known to the scientific community in general and to CODATA in particular, the outcome of their work relevant to the determination of (the Planck constant \( h \), elementary charge \( e \), Boltzmann constant \( k \), and Avogadro constant \( N_A \)). We emphasize that for all practical purposes an experimental value of \( h \) is perfectly anti-correlated with its corresponding value for \( N_A \), the correlation coefficient being \(-0.9993\). Therefore a determination of \( h \) has virtually the same information as a determination of \( N_A \). The correlation coefficient between the Planck constant and the mass of a carbon-12 atom has the same magnitude but with a positive sign [4].

Finally in 2014, the 25th CGPM [7] confirmed in its resolution on the future revision of the International System of Units, the SI, the way forward and recommended ‘to complete all work necessary for the CGPM at its 26th meeting to adopt a resolution that would replace the current SI with the revised SI, provided the amount of data, their uncertainties, and level of consistency are deemed satisfactory’.

### 3. The turning points

#### 3.1. The CCM workshop

The CCM held a Workshop on the mise en pratique of the new definition of the kilogram on 21–22 November 2012 in order to review the status of the draft mise en pratique which was being prepared. The principal objective of the Workshop was to revive and broaden the debate on various issues relevant to the redefinition of the kilogram. Starting with its meeting in 2005, the CCM had regularly presented the CIPM with recommendations for conditions to be met before the redefinition of the kilogram. At the time of the Workshop, the most recent of these had been formulated in 2010 [8] and it was this recommendation that was presented to the attendees for comment.

The status of future primary methods i.e. the XRCD method (sometimes referred to as ‘Avogadro’ because the method was originally used to yield an accurate value for the Avogadro constant) and the watt balance experiments, the European Metrology Research Programme (EMRP) projects on SI Broader scope and other Regional Metrology Organization (RMO) cooperation as well as the preparation work for the redefinition undertaken within the CCM working group on Mass was overviewed. The BIPM work on the calibrations of mass standards traceable to the IPK and on the development of an ensemble of reference mass standards (ERMS) was presented. The instability observed in the mass of some prototypes was questioned.

Positions and concerns on the redefinition of the mass unit from various bodies such as the International Organization of Legal Metrology (OIML), the RMOs and the European Association for National Trade Organisations representing the European Manufacturers of Weighing Instruments (CECIP) were reported and discussed. Views on the long term support of primary methods and the required number of laboratories able

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4 Correlation coefficients can be searched interactively on [http://physics.nist.gov/cuu/Constants/](http://physics.nist.gov/cuu/Constants/). The Avogadro constant has the unit \( \text{mol}^{-1} \). The mass in kg of a single atom of carbon-12 is almost perfectly correlated with the Planck constant, the correlation constant being \( -0.9993 \). This is not surprising because the determination of the mass of a carbon-12 atom is equivalent to the determination of \( N_A \) in the present SI (see also footnote 5).

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^1 Among the first of the modern suggestions is found in the last paragraph of [3].
to realize the methods before and after the redefinition were expressed and argued. A significant number of issues were raised and/or debated such as the way to encourage the development and maintenance of primary methods after the redefinition, the time line of the redefinition, and efforts and ways to raise the awareness and facilitate the understanding of non-initiated users etc. In particular, the robustness of the consistency conditions imposed by CCM Recommendation G1 (2010) \[8\] on the various determinations of $h$ was discussed and the ambiguity of the formulation involving the 95% confidence level was pointed out. The draft of *mise en pratique* document and its various sections were largely commented upon and discussed. The possibility of realizing the mass unit at a level different from 1 kg was clarified. The dissemination scheme after the redefinition, especially the envisaged on-going BIPM comparison \[9\] and the role of the BIPM ERMS \[10\], were intensively debated and a general consensus was reached.

Main decisions and actions taken through the Workshop were as follows; all were invited to comment on the *mise en pratique* and/or to propose alternative wordings. The CCM recommendation of 2010 should be reconsidered with a view to remove the present ambiguity. The need for separate documents, among which might be ‘Frequently Asked Questions’, was reviewed. The protocol for the inter-laboratory comparisons before redefinition needs to be prepared. It was requested that the positions of institutional stakeholders be published on the BIPM website.

### 3.2. The CCM Recommendation G1 (2013)

The CCM Recommendation G1 (2013) \[11\] defined four main conditions to be met before redefinition. The conditions relate to consistency, uncertainty, traceability and validation of the future definition. In detail, the CCM:

- recommends that the following conditions be met before the International Committee on Weights and Measures (CIPM) asks CODATA to adjust the values of the fundamental physical constants from which a fixed numerical value of the Planck constant will be adopted,

1. **Consistency**:
   - at least three independent experiments, including work from Watt balance and XRCD experiments, yield consistent values of the Planck constant with relative standard uncertainties not larger than 5 parts in $10^8$,
2. **Uncertainty**:
   - at least one of these results should have a relative standard uncertainty not larger than 2 parts in $10^8$,
3. **Traceability**:
   - the BIPM prototypes, the BIPM ensemble of reference mass standards, and the mass standards used in the watt balance and XRCD (x-ray crystal density) experiments have been compared as directly as possible with the international prototype of the kilogram’,
4. **Validation**:
   - the procedures for the future realization and dissemination of the kilogram, as described in the *mise en pratique*, have been validated in accordance with the principles of the CIPM MRA (Mutual Recognition Arrangement)”.

### 3.3. The CCM and CCU joint roadmap

In order to achieve the challenging objective; to redefine the kilogram by 2018, the CCM already established a roadmap in 2013. The CCM roadmap toward a redefinition in 2018 was presented by the CCM President for the first time in 2013 to the CIPM, then to the CCU and finally to the Directors of NMIs and representatives of the States Parties to the Metre Convention. This roadmap includes a schedule of the major steps necessary to fulfil the CCM criteria. It sets out realistic steps leading to a redefinition in 2018.

The roadmap shows the timing of the most relevant meetings of the CCM, of the CCU, of the CIPM and of the CGPM. The four red diamonds in figure 1 represent the milestones where the CCM conditions could be reached. Progress of the major tasks of the roadmap is reported in other papers of this focus issue \[9, 10, 12–16\] or in other issues of *Metrologia* \[17, 18\].

After the latest meeting of the CCM in February 2015, the CCM roadmap was approved by the CCU President and the CCM roadmap became the joint CCM and CCU roadmap.

The CIPM decided in 2015 that new experimental results pertinent to the revised SI should be accepted for publication by 1 July 2017 \[19\]. This will leave sufficient time for CODATA to recommend final values of the four fundamental physical constants prior to the CGPM fixing their numerical values.

### 4. The *mise en pratique*

In order to redefine the kilogram in terms of a physical constant, one must decide on a particular constant (since 2011 the CGPM made the choice of the Planck constant $h$) that at present is measured in terms of the IPK, formulate a definition of the kilogram based on this constant and write the *mise en pratique* of the definition. As fixing the value of $h$, which has the unit kg m$^2$ s$^{-1}$, does not tell how to realize the unit of mass from measurements of length and time, the *mise en pratique* is above all a recipe which describes how the kilogram can be realized experimentally by means of high-accuracy methods like the XRCD method or the watt balance. The draft *mise en pratique* of the new definition of the kilogram also includes the first steps to disseminate the redefined kilogram.

The work on the *mise en pratique* of the new definition of the kilogram was initiated at the BIPM in 2010 and has since then been actively pursued under the responsibility of the CCM working group on the realization of the kilogram.

The latest version of the *mise en pratique* \[20\] was provisionally approved at the 15th meeting of the CCM in 2015. The definitive version of the *mise en pratique* will take into account the lessons and experiences derived from the pilot study (see also section 3.3 on the CCM and CCU joint roadmap) and is planned to be adopted by the CCM at its 16th meeting in May 2017.
4.1. The mise en pratique of the present definition of the kilogram

The mise en pratique of the present definition of the kilogram, based on the mass of the IPK, dates from 2005 [21]. It will be instructive to examine this brief document in order to compare it with the draft mise en pratique for the new definition of the kilogram. All current mises en pratique for the SI base units appear in appendix 2 of the SI Brochure. Appendix 2 is web-based so that any of the mises en pratique can be updated without the delay of waiting for a new edition of the parent document.

In fewer than 300 words, the mise en pratique

- recalls the definition of the kilogram and essential features of the IPK that are referred to the rest of the document;
- states that
  - the mass of the IPK is exactly one kilogram immediately following its having been cleaned and washed by a specified method in order to remove reversible surface contamination accumulated at a rate of order 1 $\mu$g yr$^{-1}$;
  - comparisons between the IPK and secondary 1 kg standards of the same alloy can be made using balances with an uncertainty of about 1 part in $10^9$;
  - comparisons between platinum-iridium and stainless steel 1 kg standards involve a correction for air buoyancy that increases the uncertainty in the determination of the mass of the stainless steel standard to about 1 part in $10^8$;
  - calibrations of mass standards that are multiples or sub-multiples of 1 kg can be carried out by ‘a conceptually simple procedure’.
- Although the present mise en pratique is concise and easily understood by mass metrologists, the weakness of the artefact definition of the kilogram is exposed by the various assumptions, obvious and subtle, required to support the second bullet point.

4.2. The mise en pratique of the new definition of the kilogram

The latest draft of the mise en pratique of the new definition of the kilogram is 18 pages long [20]. Stylistically, the draft is written as if the present definition has been abrogated and the new definition adopted. Therefore when the draft refers to ‘the definition of the kilogram’, it means the definition based on the Planck constant, $h$.

The greatest difference between [20, 21] is that the definition of the kilogram is no longer based on a unique artefact, the IPK, which is conserved and used at the BIPM. The IPK is the only possible primary standard of mass in this arrangement. The draft mise en pratique makes clear how the kilogram definition based on $h$ changes previous notions of primary methods and standards. This is shown in figure 2 (figure 1 of [20]).

The primary methods result in primary mass standards which are then used to disseminate the unit of mass to secondary mass standards, similar to the dissemination step from the IPK. However, as the system admits many primary
The kilogram to primary and secondary mass standards. The unit of mass standards derived from two completely different primary methods, any NMI with a primary method can in principle disseminate the mass unit directly or in collaboration with other NMIs with similar capabilities. Of course it will be impractical for the majority of NMIs to have any capability to derive their own primary standards. The draft *mise en pratique* accepts that the CIPM MRA already deals with these situations in general and therefore [20] adapts the procedures and discipline of the CIPM MRA to the definition of the unit of mass based on a fixed value of $h$. Other articles in this focus issue discuss these issues in greater detail [13–16]. There are placeholders for these and similarly relevant references in [20].

The draft *mise en pratique* concludes with a section that describes how continuity with the mass unit based on assigning the mass of the IPK an exact value of 1 kg, and the mass unit based on assigning a fixed value to $h$ has been achieved.

5. Debate, discussion

The proposals set forth in [1] were immediately controversial within the mass community. Of course the idea of redefining the kilogram based on a physical constant was welcome. In fact this idea had already been advanced by the CCM a decade before, resulting in CIPM Recommendation 4 (1993) and CGPM Resolution 5 (1995) [22], both of which have virtually identical wording. Resolution 5 ‘recommends that laboratories pursue their work with a view to monitoring the stability of the international prototype of the kilogram and in due course opening the way to a new definition of the unit of mass based upon fundamental or atomic constants.’ The 1995 Resolution is not cited again in subsequent resolutions of the CGPM (note its absence from [4–7]). The problem for the mass community with [1], aside from its provocative title, was the suggestion to redefine the kilogram immediately by fixing the value of either the Planck constant or the Avogadro constant while mass metrologists would continue to use the IPK, defined to have a mass of 1 kg. But in so doing, the mass of the IPK would have what they termed a ‘conventional mass’, although its SI mass would only be known within specified uncertainty limits which would have been rather wide at that time. The authors of [1] did not equivocate: ‘We strongly believe that there is no reason to postpone this decision, for example, to wait until the mass of the international prototype can be related to (physical) constants with a relative standard uncertainty $u \approx 10^{-8}$.’ The CCM Recommendations of 2010 and 2013 crystallized opposition to the point of view expressed in [1].

The CCM Recommendations also took on board the concerns of the weighing industry represented by CECIP, and more widely the concerns of the Legal Metrology community represented by the OIML. These concerns motivated the uncertainty requirements of the CCM Recommendations, as documented by Gläser et al [23].

There was also much debate over whether the kilogram should be redefined in terms of a fixed value of $h$ or a fixed value of $m_a$ (see footnote 5; if the value of $m_a$ were fixed, the definition of the mole would ensure that the values of $N_A$ and $M_n$ would also be fixed). However, it was obvious that a measurement of $N_A$ could be converted to a measurement of $h$ (and vice versa) through a conversion factor having finite but completely negligible uncertainty. It thus made no practical difference to mass metrology whether the kilogram was redefined by fixed $h$, fixed $N_A$ and $M_n$, or fixed $m_a$. Of course there were individual preferences within the CCM for having a mass (e.g. by a fixed value of $m_a$) but the electrical community as represented by the Consultative Committee for Electricity and Magnetism argued strenuously that they would make good metrological use of a fixed value of $h$.

The CCM ultimately decided to focus on realizing the new definition of the kilogram with whatever constant the CIPM decided. There nevertheless remains a tendency for XRCD reports to display graphs of various experimental values of $N_A$, including watt balance results converted to measurements of $N_A$, while CODATA does just the opposite. The relative uncertainty bars of all plotted points are indistinguishable between these two ways of displaying the experimental results.

Although the draft *mise en pratique* focuses on the realization of 1 kg, it mentions the possibility of including primary methods at different nominal mass values. One reason for not including such information in [20] is the following: already in the CODATA 2002 least squares adjustment [24], the value of $h$ was known to a relative uncertainty of 1.7 parts in $10^7$. We now know that the 2002 value agrees to 1.7 parts in $10^7$.

5 It might seem strange to redefine the kilogram by fixing the value of a constant that does not have the kilogram in its unit. The Avogadro constant $N_A$ has the unit mol$^{-1}$, but since the molar mass constant $M_n$ was already fixed by the definition of the mole to have the exact value 0.001 kg mol$^{-1}$, the combination of $M_n$ with an exact value of $N_A$ would indeed serve to redefine the kilogram. The atomic mass constant $m_a$ equals $M_n/N_A$, and has a mass defined as 1/12 the mass of a carbon-12 atom. Clearly, $m_a$ and $N_A$ are perfectly anticorrelated in the present SI.

6 Notwithstanding that conventional mass, having a completely different meaning, was already widely used in Legal Metrology.
with the CODATA 2014 value [25], which itself has a relative uncertainty of only 0.12 parts in 10^7. Thus, for example, at any time since the publication of [24], it would have been conceivable to make force measurements on, say, nanostuctures using a method traceable to the CODATA value of \( h \), which itself is traceable to the mass of the IPK, and this would have incurred an uncertainty component of less than 5 parts in 10^7 due to the experimental value of \( h \). There is no evidence that the present definition of the kilogram has been an impediment to this approach. However, the mise en pratique can easily be amended as thought necessary.

Relative atomic masses (referred to as atomic weights in chemistry) are mass ratios and hence unchanged by the revised SI. Other implications for mass at the molecular, atomic or subatomic levels are discussed in Annex A.2.4 of [20].

6. Summary

The mass of the IPK has defined the kilogram for about 130 years. This is longer than any other artefact-based definition of a metric unit and attests to the excellent decisions taken in the 1870s to specify the physical properties of the artefact which became the international prototype of the kilogram. Nevertheless, the change to a kilogram definition based on a physical constant was seen as the next step about 40 years ago. However, many of the practical considerations summarized by the CCM conditions on consistency, uncertainty, traceability and validation of the mise en pratique have only been met relatively recently. Others are still being completed. We have shown how the process to meet all CCM conditions has been guided by the joint CCM and CCU roadmap. This has been an important period of change accompanied by intense scientific efforts which are planned to be crowned by the revision of the SI at the 26th CGPM in 2018.

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