Maintaining and disseminating the kilogram following its redefinition

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Abstract
The new definition of the kilogram, which is expected to be adopted by the General Conference on Weights and Measures in 2018, will bring some major changes to mass metrology. The most fundamental change will be the replacement of the present artefact-based definition with a universal definition, enabling in principle any National Metrology Institute (NMI) to realize the kilogram. The principles for the realization and dissemination of the kilogram in the revised SI are described in the mise en pratique of the definition of the kilogram. This paper provides some additional information and explains how traceability can be obtained by NMIs that do not operate a primary experiment to realize the definition of the kilogram.

Keywords: kilogram, redefinition, SI units

(Some figures may appear in colour only in the online journal)

1. Introduction

The expected adoption of a new definition of the kilogram by the 26th General Conference on Weights and Measures (CGPM) in November 2018 will bring to an end the period during which the kilogram was defined by a material artefact. This period started in 1799 with the Kilogram of the Archives and was continued in 1889 with the adoption of the international prototype of the kilogram (IPK) [1]. The present definition has served all scientific, technical and commercial purposes well for more than a century and has the advantage of great conceptual simplicity. During this period national mass standards have been sent for calibration to the BIPM, where the work of providing calibrations with results traceable to the IPK has been carried out. Traceability to the IPK as one single reference standard has underpinned the equivalence of mass measurements throughout the world, as demonstrated successfully by international comparisons of calibrations of stainless steel mass standards [2, 3].

It has been difficult to assess the stability of the mass of the IPK over time. Observations made during the 2nd and 3rd Periodic Verifications of National Prototypes (around 1946 and 1990 respectively), appeared to indicate that the mass of several other reference mass standards had increased with respect to the IPK. This could be interpreted as evidence that the IPK had lost several tens of micrograms, although it had not been used for any weighings in-between the verifications [4]. The results of the Extraordinary Calibration Campaign using the IPK in 2014 [5] indicated that the masses of the IPK and of its six official copies had remained stable with respect to each other to within a few micrograms since 1992. The fact that the IPK was only available for measurements very rarely (in an effort to protect it against mass changes) and that no higher-order reference exists has made it impossible to
quantify possible changes in its mass accurately. The determination of physical constants with reference to the kilogram over long periods of time would in principle elucidate such changes, but the uncertainties of such experiments are so large that this has not been feasible [6, 7]. This is an example of the difficulty of establishing the limitations of the present definition based on a unique artefact.

The new definition of the kilogram will be based on a fixed numerical value of the Planck constant and will overcome the limitations related to the use of a material artefact to define the kilogram. It will open the possibility for National Metrology Institutes (NMIs) to develop their own realization experiments. In practice, such experiments are complex and require significant resources. Although the number of NMIs operating realization experiments after the redefinition cannot be predicted with certainty, it is expected to be quite limited. It is therefore important to develop a means to ensure that the kilogram can be disseminated during periods when few or, in the worst case, no realization experiments are accessible.

An important change with respect to the current situation is that after the kilogram is redefined, traceability to the definition of the kilogram will, in principle, be available from more than one source. The international recognition of mass measurement traceability to a particular realization experiment will be based on successful participation of that realization in international measurement comparisons.

Section 2 of this paper describes in some detail the consequences of the transition from a system with a unique source of traceability to a system with multiple independent realizations. Section 3 presents the plans for comparisons to ensure the worldwide uniformity of mass calibrations. Section 4 describes the future role of a stable ensemble of reference masses established at the BIPM. Sections 5 and 6 describe how traceability to the definition of the kilogram may be obtained in the future.

2. From an artefact-based definition to a universal definition of the kilogram

The Consultative Committee for Mass and Related Quantities (CCM) is responsible for agreeing the *mise en pratique* of the definition of the kilogram [8], which describes the available primary methods for the practical realization of the kilogram. A primary method is a method having the highest metrological properties, whose operation can be completely described and understood, for which a complete uncertainty statement can be written down in terms of SI units and which does not require a reference standard of the same quantity. A mass standard calibrated by a primary method will become a primary mass standard. After the kilogram has been defined in terms of the Planck constant, any method capable of deriving a mass value traceable to the Planck constant will have the potential to become a primary method. The *mise en pratique* can be extended in the future, when new practical realization methods become available.

At the time of writing it has been demonstrated that two primary methods have the capability of realizing the kilogram according to its future definition with the required uncertainty; the Kibble\(^5\) balance [9] and the x-ray crystal density (XRCD) method [10]. It should be noted that the use of the XRCD method is made possible by the fact that the relative uncertainties of the Rydberg constant \(u(R_{\infty}) = 5.9 \times 10^{-12}\) and the fine structure constant \(u(\alpha) = 2.3 \times 10^{-10}\) are well below those of the XRCD measurements themselves [11].

The new definition opens the possibility to realize a primary mass standard of any mass value directly. This may be of particular benefit for masses much smaller than 1 kg. For masses in the milligram range, present uncertainties are relatively large also because they are calibrated via a long chain of sub-division from 1 kg standards. The new definition will facilitate the direct determination of such masses [12]. It will also become possible to determine an atomic mass \(m_a\) from the measurement of the recoil velocity of the atom after absorption of a photon, which is directly related to the ratio of \(h/m_a\) [13].

Although the new definition will, in principle, allow any NMI to develop its own primary method to realize the kilogram, the present-generation experiments are complex and require significant resources. This is likely to limit the number of NMIs that will develop and maintain such experiments after the redefinition. Only five NMIs were capable of participating in the Pilot Study of future realizations of mass standards in 2016 (section 3.1). Three NMIs participated with their Kibble balances, and two with isotopically enriched \(^28\)Si-spheres from the International Avogadro Coordination, following the XRCD method. A number of additional Kibble balances are under development, but it is not yet known how many of these will be transformed from research projects to facilities for realizing the kilogram.

Currently, the best Kibble balances achieve relative standard uncertainties of \(1\text{--}2 \times 10^{-8}\), corresponding to 10 \(\mu\)g to 20 \(\mu\)g at 1 kg [14–16]. This is larger than the uncertainty of current mass measurements directly traceable to the IPK. However, a standard uncertainty of 20 \(\mu\)g at 1 kg is sufficient for the most demanding weighing applications [17]. This was chosen as the target set by CCM Recommendation G1 (2013) for realizing and disseminating the kilogram after redefinition [18].

In contrast, a high quality mass comparator allows the comparison of similar mass standards of 1 kg to better than 1 \(\mu\)g. Based on past experience, the mass of 1 kg reference standards can be assumed as stable or at least predictable over several years, if precautions are taken to avoid excessive use and contamination. For this reason even those NMIs that maintain a Kibble balance might not use it regularly for practical calibration work. The most likely approach is that the Kibble balance will be used to calibrate a set of reference mass standards, which will then be used to maintain the kilogram for that NMI. Such a local ensemble would be recalibrated periodically against the Kibble balance, while the mass scale would be realized separately using conventional ‘build-down’ and ‘build-up’ methods. Hence the primary realization may

\(^5\) We refer to watt balances as ‘Kibble balances’ *in homage* to Dr Bryan Kibble, who originally conceived the idea of this experiment.
only be used infrequently, raising questions about the need for frequent use of fully-functional realization experiments.

Recent publications show that the development of Kibble balances continues. Targets for these new Kibble balance designs could be to make them easier to build and operate [19, 20], to achieve lower uncertainties or to use them directly and routinely for mass calibration over a range of mass values. Some of these new Kibble balance designs might even be sufficiently straightforward to use that they would eliminate the need for sets of calibrated mass standards and instead provide calibration directly traceable to the SI through electrical standards at accuracies of parts in 10^6 or 10^7.

The situation is somewhat different for the XRCD method, the application of which gives rise to a carefully characterized primary mass standard, an isotopically enriched 28Si sphere [10]. Such a sphere could be used directly in a mass comparator under vacuum. However, the high value and the amount of work necessary to obtain such standards make it impractical to expose them to the risks of regular use. As for the Kibble balance, the most likely approach is that such spheres would be used to calibrate a local ensemble of working standards directly after their characterization, which would then be used for dissemination. Further developments can also be expected on the XRCD method, in particular improvements of the different experiments needed to carry out this method.

In order to reach the smallest uncertainties, both the Kibble balances and the XRCD experiments operate under vacuum, and thus the mass of the primary mass standards used with them will be known under vacuum. Since mass metrology below the highest metrological level will continue to rely on mass standards maintained and used in air, carefully optimized methods for the transfer of mass standards from vacuum to air will be needed. The uncertainty of the change in mass of a Pt–Ir prototype going from vacuum to air is at the level of a few micrograms. However, it has been observed that the mass of a standard that is repeatedly transferred from vacuum to air can increase significantly during the first few air to vacuum cycles [21, 22].

3. Comparisons of realizations of the kilogram

3.1. The CCM Pilot Study, a comparison of realizations of the kilogram before the redefinition

An essential requirement for the effective implementation of the new definition of the kilogram is that different experiments to realize the kilogram should give consistent results. In order to show that this is possible, the CCM decided in 2013 that a comparison of the available realizations of the kilogram with primary methods should be performed as a Pilot Study before the redefinition took place [18]. This Pilot Study is one of the activities required on the joint CCM and CCU roadmap towards the redefinition and is also referred to in the draft mise en pratique for the definition of the kilogram [8]. In addition to its main purpose of demonstrating the consistency, it will also test the continuity between the present and the future definitions of the kilogram.

As part of the Extraordinary Calibrations in 2014, 1 kg Pt–Ir mass standards of NMIs involved in the determination of the Planck constant were calibrated at the BIPM with respect to the IPK with a standard uncertainty of 3.5 μg. The input data from these experiments for the CODATA adjustment of fundamental constants in 2014 [11] were therefore traceable to the IPK with a very small uncertainty and, as a consequence, the adjusted value for the Planck constant is also traceable to the IPK. This should, in principle, ensure that the future kilogram, traceable to the Planck constant, will be consistent (within the associated uncertainties) with the present kilogram. The Pilot Study tested this assumption in practice. The experience gained from the Pilot Study will also allow the technical protocol for future comparisons of realizations of the kilogram to be optimized.

All NMIs that would be able to realize the kilogram with a relative uncertainty of less than 2 parts in 10^7 (equivalent to 200 μg at 1 kg), were invited to take part in the Pilot Study. Five confirmed their participation: the LNE (France), the NIST (USA), the NRC (Canada), the NMIJ (Japan) and the PTB (Germany). The LNE, NIST and NRC used Kibble balances. The NMIJ and the PTB used the 23Si-spheres AVO28-S5c and AVO28-S8c from the International Avogadro Coordination [10] as the basis for their calibrations.

The Pilot Study was carried out using two sets of 1 kg travelling standards, provided by each of the participants. The standards of Set 1 (one Pt–Ir standard and one optional standard of the participant’s choice) were calibrated under vacuum as directly as possible with respect to the realization experiment. The standards of Set 2 (two stainless steel standards) had to be calibrated in air, traceable to the realization experiment. This required transferring mass standards, calibrated under vacuum, into air by making a correction for surface sorption and applying any necessary buoyancy correction. The aim of this was to assess the equivalence of the mass scale when disseminated from individual realization experiments.

All participants had sent their travelling standards to the BIPM, which acted as the pilot laboratory. During the period from May to July 2016 the mass standards were compared at the BIPM with each other and with BIPM working standards. The results of the participants were found to be in good agreement for both sets of standards. The standard-uncertainty bars of four participants overlap, the standard-uncertainty bar of the fifth participant overlaps with the others when expanded by a factor of two. The standard uncertainty of the weighted mean of the participants’ results is 0.010 mg for both sets. The weighted mean agrees with the value based on the IPK within the uncertainty. The results meet the conditions for the redefinition to go ahead set by the CCM in 2013 [18]. The details and the results of the Pilot Study will be published in a separate publication.

Results published since the completion of the Pilot Study are less consistent. The consequences of these results are discussed in section 6.

The mass standards that have been brought together at the BIPM for the Pilot Study were also used to calibrate the mass of the artefacts of the BIPM ensemble of reference mass
standards (ERMS, section 4) and the Pt–Ir working standards for current use. The mass of these standards is therefore known traceable to the realization experiments in addition to their traceability to the IPK. As stated above, both sets of mass values agree within the uncertainties.

3.2. Key comparisons of realization experiments after the redefinition

After the redefinition of the kilogram, traceability for mass measurements may, in principle, be obtained from any valid realization of the kilogram. For calibrations based on a particular Kibble balance or Avogadro sphere to be recognized internationally, their equivalence with calibrations from other primary methods will need to be demonstrated. The international framework for the mutual recognition of calibration capabilities is the CIPM mutual recognition arrangement (MRA) [23] and its technical basis is measurement comparisons. It will be necessary for the CCM to organize periodic key comparisons of primary mass standards to quantify the equivalence of independent realizations by providing evidence that the claimed uncertainty of each participating NMI is consistent with the key comparison reference value (KCRV).

The general approach for future CCM comparisons is described in the draft mise en pratique for the definition of the kilogram [8]. The BIPM will organize an ongoing key comparison in which NMIs with an operational realization experiment are expected to participate; the periodicity of participation being decided by the CCM. During the first years after the redefinition a shorter repetition interval might be chosen and increased later when more experience with realization experiments has been gained. The present CCM Strategy [24] foresees that a first key comparison is organized directly after the redefinition, the second at the latest 5 years later. The period between comparisons may be extended to as much as 10 years, if the results of the previous comparisons are acceptable, according to the criteria laid down in CCM recommendation G1 (2013) [18]. The KCRV of each key comparison will be maintained on the BIPM working standards and the ensemble of BIPM reference mass standards.

In between these key comparisons, the BIPM would propose bilateral comparisons to validate new primary realizations, which would become available. In such a comparison the primary mass standards of the NMI will be compared to the BIPM working standards, which maintain the KCRV of the last key comparison. In this way, the results of a new participant can be compared with those of the previous participants and the KCRV can be updated.

If the organization of a key comparison of all operational realization experiments would be impractical, perhaps because experiments would not be available at the same time, the equivalence could be established through ongoing bilateral comparisons with the BIPM. In this case the calculation of the KCRV would be more complex, because the results of the participants would not be available at the same time, but would come in one after the other, potentially over several years. A grouped comparison, following the approach chosen for the Pilot Study, appears to be preferable for its greater transparency.

In addition to these comparisons at the highest metrological level, there will be a continued need for comparisons at the level of dissemination, for example using stainless steel standards in air and also at mass values different from 1 kg. These comparisons will test other key techniques of mass metrology such as buoyancy corrections and vacuum-to-air transfers (if the participant has a realization experiment). They will also be important for NMIs without realization experiments who need supporting evidence for their CMCs (Calibration and Measurement Capabilities).

4. Need for stable mass standards at the BIPM after the redefinition

At the present stage continued access to realization experiments cannot be guaranteed. It is therefore important to set up sets of stable reference mass standards, with which traceability to realization experiments can be maintained over some time.

Since the adoption of the IPK in 1889 as the reference for the kilogram, the BIPM has used a set of 1 kg Pt–Ir working standards to maintain the kilogram and for calibrations of national prototypes. Increased requirements for 1 kg calibrations from the BIPM have necessitated that the size of that set should increase over the years. In 1889 it was composed of three standards, and today it is composed of 12 standards, which still include the three original ones. On the rare occasions when the IPK has been available for measurements, it was used to calibrate these working standards. The kilogram was maintained by the working standards and it was this ‘as-maintained BIPM mass unit’ which served for the calibrations of national Pt–Ir and stainless steel standards of the NMIs. Between the uses of the IPK, comparisons of the masses of the individual working standards were the only means to detect mass changes and to ‘steer’ the mass values [1]. This set of Pt–Ir working standards has worked efficiently, however a limitation of this approach is that mass changes common to all of the working standards cannot easily be detected.

The last period of access to the IPK was during the Extraordinary Calibrations in 2014 [5]. During this calibration campaign the BIPM working standards were recalibrated with respect to the IPK. The newly attributed mass values were 35 μg lower than those attributed directly before the recalibration. The latter were based on the previous calibration campaign using the IPK (1988–1992) and subsequent adjustments derived from mass comparisons within the set of working standards. This overestimation of the mass of the working standards is most likely due to an undetected wear effect which affected all standards, although not at the same level [25]. To avoid the occurrence of such a problem in the future, a hierarchy has been established among the BIPM working standards (figure 1). Six working standards are used for the ongoing calibration work. They are compared once a year with three standards for limited use, which are not used for other purposes. The latter being compared once every 5 years with three standards labelled for exceptional use.
It had always been a concern that all Pt–Ir standards of a set could be subject to a common undetected drift. Observations of unexplained instabilities of mass standards were presented and discussed at a workshop on the *mise en pratique* of the definition of the kilogram at the BIPM in November 2012. These two concerns led to the conclusion that a new set of standards of different types and with improved characteristics needed to be developed. Two aspects were identified as offering the potential for improvement: the storage conditions and the materials of the standards composing the set. Regarding the storage conditions, little was known about the influence of the storage environment (air, inert gases, vacuum) on long-term mass stability, since NMI’s had just begun to investigate storing mass standards in gas and under vacuum [26–28]. On the materials side, the experience gained by the International Avogadro Coordination using the XRCD method with silicon spheres [10] (e.g. mass stability and ease of cleaning) indicated that natural silicon spheres should be included in the new BIPM set of standards. Stainless steel also stood out as a key material, due to its wide use in legal metrology and industry. Experience shows that good mass stability can be achieved by the best stainless steel alloys.

Taking all this into account the BIPM started a project to assemble an ‘ensemble of reference mass standards’ (ERMS) [29], to complement its existing set of twelve Pt–Ir working standards. The ensemble was to be composed of four newly fabricated Pt–Ir 1 kg standards, four new stainless steel standards and four new natural silicon spheres. Four different storage environments were to be used: ambient air (as used in the past for storing the Pt–Ir working standards), vacuum (at the mPa level), low flow (about 0.4 l min$^{-1}$) argon gas and low flow nitrogen gas. A mass standard of each material was to be kept permanently in each environment. The different combinations of materials and storage environments were intended to elucidate mass changes related to any particular material or storage condition.

These initial plans have recently been modified as a consequence of reports that storage under vacuum might lead to a mass increase of the standards, due to the removal of the protective water layer on the surface [27]. Two of the four sets of standards (Pt–Ir, stainless steel, Si-sphere) are now stored in air, in addition to the two sets stored under nitrogen and argon. A fifth set of four new stainless steel standards is stored under vacuum, to gain experience with vacuum storage.

The BIPM has been manufacturing and assembling the ensemble and the storage system since 2011. Storage under nitrogen and argon and in air is now fully operational with all the standards installed in the storage containers. The gas flowing through the storage containers is analyzed on a daily basis for oxygen, humidity and hydrocarbons. The system for vacuum storage is close to completion. In 2014, during the Extraordinary Calibrations, all the elements of the ERMS and those of the existing set of Pt–Ir working standards were calibrated with respect to the BIPM working standards (traceable to the IPK). During the CCM Pilot Study (section 3.1), the standards stored in air, nitrogen and argon were calibrated in their respective gas environments—without exposure to air—with reference to the travelling standards, traceable to five different realization experiments.

As described above, a hierarchy has been set up amongst the Pt–Ir working standards to reduce the risk of undetected mass change. The ERMS will be used to provide additional information on the mass stability of the Pt–Ir prototypes: the three Pt–Ir prototypes for limited use will be compared once a year with the masses of the ensemble stored under nitrogen and argon and one of the sets stored in air. The three Pt–Ir prototypes for exceptional use will be compared once every 5 years with the second set of standards of the ensemble kept in

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**Figure 1.** Hierarchy of BIPM Pt–Ir working standards, established after the Extraordinary Calibration campaign in 2014. The standards for current use serve to calibrate national prototypes during two calibration campaigns per year. Their stability is verified once per year by comparison with the standards for limited use. The latter are compared every 5 years with the prototypes for exceptional use. The IPK and the official copies will lose their special status after the redefinition.
air. It is expected that the hierarchical use of the Pt–Ir standards and the additional information provided by the ensemble, combining different mass materials and storage environments, will eliminate the risk of undetected mass change of the Pt–Ir working standards. The ensemble will thus support the continuing activity of the BIPM in providing mass calibrations (section 5) and the ongoing comparison of primary mass standards (section 3.2).

In addition, the ERMS is a mass metrology experiment which is capable of providing useful information regarding the effects on the mass of the standards of the long term storage under different environments and of the material from which each mass is made. It is expected to achieve a mass stability and mass predictability that is better than the present state of the art and hence to enable research on mass metrology by allowing more subtle mass changes to be detected.

Further technical details of the ERMS and its operation will be the subject of a separate publication.

**5. Dissemination of the kilogram at the highest level**

The dissemination route for the current unit of mass from the IPK via platinum–iridium national prototypes of the kilogram and stainless steel national standards is relatively straightforward and takes place entirely in air. The demonstration of the equivalence of national mass scales is also straightforward and is achieved through comparisons of stainless steel standards in air such as CCM.M-K4 [2].

After the redefinition, the realization of the kilogram may be undertaken by any NMI with a realization apparatus (a Kibble balance or XRCD experiment). In practice the equivalence of these experiments will need to be demonstrated by comparisons as discussed in section 3. Subsequently NMIs without realization experiments may take traceability from an NMI operating a Kibble balance or XRCD experiment which has demonstrated equivalence within its stated level of uncertainty. In practice, due to the complex nature of these experiments, traceability will normally be to the primary artefact mass standards of those NMIs with realization experiments (that is, to the NMI’s local ensemble of mass standards).

NMIs may also choose to continue to take traceability from the BIPM as described in section 4. The BIPM ERMS and the set of Pt–Ir working standards will provide a reference against which to compare any new realization experiments and to provide a means of maintaining and disseminating the kilogram, as described in section 4 and [29].

The maintenance of the kilogram in this way will be necessary since ongoing continuous access to realization experiments cannot be guaranteed at the present stage. The ERMS and the Pt–Ir working standards will be directly traceable to the available realization experiments. An additional point to note is that, while the dissemination route from the realization experiments has not yet been fixed in detail, it will in any case

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**Figure 2.** Current traceability route to the IPK and indicative future traceability route to primary methods after the redefinition. All uncertainties are given at the $k = 1$ level. They have not been rigorously evaluated due to the variation in or lack of data but are meant to give an idea of the potential increase in uncertainty after redefinition. (Pt–Ir: platinum–iridium, SS: stainless steel, Si: silicon.)
involve vacuum to air transfer of mass standards. Figure 2 shows the current and possible future traceability routes for the kilogram from the IPK and from future realization experiments respectively, including typical uncertainties. An uncertainty of 1 part in $10^8$ in the new realization experiments has been assumed but even at this level the uncertainty achievable for end user calibrations by NMIs (equivalent to their CMC listed in the BIPM Key Comparison Database) will be larger than at present.

Figure 3 illustrates in more detail possible dissemination routes for the kilogram from the realization experiments (Kibble balance (KB) and XRCD) after 2018 with indicative uncertainties at each level of the dissemination and showing the comparisons necessary for dissemination. Dissemination can be achieved through standards of platinum–iridium (Pt–Ir), silicon (Si), or other materials such as tungsten (W) [30]. It is likely that secondary standards of NMIs and end user reference standards will continue to be stainless steel (SS). The dissemination route for NMIs with realization experiments is straightforward and essentially just includes the addition of a vacuum to air stage to achieve traceability to the Kibble balance or XRCD experiment. NMIs without a realization experiment can take traceability from an NMI operating such an experiment (and having demonstrated equivalence through a comparison). Such a calibration could be done directly using its primary realization but in practice traceability will probably be via national primary mass standards (NMI local ensembles) since the calibration process will be simpler and the uncertainties are not significantly greater. The BIPM ERMS and the Pt–Ir working standards will be traceable to the realization experiments and will offer an alternative traceability route for those NMIs without realization experiments. The IPK will lose its role of defining the kilogram, but will be kept at the BIPM after the redefinition. This offers the possibility to investigate the long-term stability of its mass, should the CCM wish to do so. This would then become a question of scientific interest, but without any consequence on the new kilogram definition.

It is important to note that the redefinition will only require development of new instrumentation and techniques for NMIs that wish to realize the SI definition of the kilogram and for the BIPM. There will be no impact on all other NMIs except that they can in future obtain traceability not only from the BIPM, but from a number of NMIs.

6. Temporary use of a consensus value for the maintenance and dissemination of the mass unit

After the completion of the Pilot Study, in early 2017, new results for the Planck constant were published to provide data for the CODATA special fundamental constants adjustment, which will determine the numerical values of the constants used to define the revised SI. The agreement within this new data set is less good than the agreement observed during the Pilot Study and the individual results are not in agreement at the level of their respective standard uncertainties. By inference this means that, after redefinition, realizations of the kilogram made by the various experiments would not be in
agreement, meaning non-equivalence of global mass measurements based on these realizations. Rather than delay the redefinition of the kilogram until such time that the discrepancies in the realization experiments can be resolved, the CCM has recommended at its 16th meeting, in 2017, that NMIs with realization experiments shall disseminate a consensus value for the redefined kilogram, instead of their own local realization [31]. This arrangement would remain in place until the dispersion in values becomes compatible with the individual realization uncertainties.

It is proposed that such a consensus value for the kilogram be realized from a key comparison of all realization experiments. The consensus value would be broadly equivalent to the key comparison reference value (KCRV) and could be maintained and disseminated in the short term as described in section 4. The uncertainty of the consensus value would reflect the NMIs’ uncertainty estimates and the spread in the results. The recently-completed Pilot Study of realization experiments provides a model for how such a key comparison might be implemented and could provide a first instance of the consensus value (notwithstanding the fact that new results for the Planck constant have been published since the comparison was completed). Having participated in the key comparison, NMIs would disseminate the consensus value by applying a correction to their locally realized value. As results from new realization experiments become available, and indeed as the results of existing experiments are improved, they would be linked to the KCRV through bilateral comparisons with the BIPM and adjustment of the consensus value (and its uncertainty) would take place. Thus, a value for the kilogram would be maintained and global equivalence would be preserved. It is expected that the accuracy of the values from the realization experiments will improve and the values will become consistent at a level that will allow the CCM to decide that dissemination via a consensus value is no longer necessary. At such a time, and after the experimental results have been validated by a key comparison, it should be possible for values from independent realizations of the kilogram to be used, whilst maintaining the equivalence of measurements worldwide.

7. Conclusions

The redefinition of the kilogram will, in principle, enable any National Metrology Institute (NMI) to realize the kilogram. This is a fundamentally new situation because at present all mass standards are ultimately traceable to the International Prototype of the Kilogram, kept at the BIPM. To ensure that the independent realizations in the revised SI will be consistent, and to provide international recognition within the framework of the CIPM/MRA, key comparisons at the highest metrological level will be needed. A trial comparison (also referred to as a Pilot Study) between five realization experiments was conducted in 2016. The CCM has recommended that initially NMIs with realization experiments shall disseminate a consensus value, until the time when the dispersion in values becomes compatible with the individual realization uncertainties.

Currently, the number of operational realization experiments in the years following the redefinition of the kilogram is unknown, but is expected to be limited because of their complexity and maintenance costs. Consequently, an ensemble of 1 kg reference mass standards is being set up at the BIPM to complement the existing set of BIPM Pt–Ir working standards that will be traceable to the available realization experiments and which will maintain the kilogram over time. It will be used as a reference for future comparisons and for mass dissemination from the BIPM. A first calibration of the new ensemble and the existing Pt–Ir working standards with respect to realization experiments was carried out during the CCM Pilot Study in 2016.

National Metrology Institutes that decide not to develop realization experiments can obtain traceability to the revised SI from calibrations of mass standards at NMIs that do realize the kilogram or, as at present, from the BIPM. Since the uncertainties of the realization experiments currently in operation are larger than those for calibrations in terms of the IPK, the uncertainties for some end users may—at least initially—be somewhat higher than at present, but will be adequate for the even the most demanding applications.

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