

THE REDEFINITION OF THE SI IN 2018 AND THE PRESENT STATUS FOR THE KILOGRAM

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Abstract – The 25th General Conference on Weights and Measures (CGPM) adopted its Resolution 1 "On the future revision of the SI" [1]. According to this Resolution, new definitions for the kilogram, the ampere, the kelvin and the mole will be based on fixed numerical values of selected constants. The Consultative Committee for Mass and Related Quantities (CCM) and the Consultative Committee for Units (CCU) established a joint roadmap in order to ensure that all necessary steps are completed in time for the 26th CGPM in 2018. The paper presents these steps and reviews the situation with the criteria proposed by the CCM in the light of the recent progress and published results.

Keywords: Redefinition, SI units, kilogram, CCM roadmap.

1. INTRODUCTION

Since 1889 the International Prototype of the Kilogram (IPK) has both defined the unit of mass, the kilogram, and served as the primary realization of the definition. The kilogram is today the only remaining base unit of the International System of Units (the SI) still defined by a materialized standard, or artefact. Its past stability with respect to physical constants is unknown to within a useful uncertainty because it is only relatively recently that accurate determinations of such constants could be made with traceability to the IPK. There is general agreement that redefining the kilogram through an absolute reference is now highly desirable.

According to Resolution 1 "On the future revision of the SI" adopted by the 25th CGPM in November 2014 new definitions for the kilogram, the ampere, the kelvin and the mole will be based on fixed numerical values of selected constants.

In summary, the Resolution 1 proposes that the kilogram, the ampere, the kelvin and the mole should be defined with respect to fixed numerical values of:

- the Planck constant h of exactly $6.626\ 06X \times 10^{-34}$ joule second,
- the elementary charge e of exactly $1.602\ 17X \times 10^{-19}$ coulomb,
- the Boltzmann constant k of exactly $1.3806X \times 10^{-23}$ joule per kelvin,
- the Avogadro constant N_A of exactly $6.022\ 14X \times 10^{23}$ reciprocal mole.

The SI second and metre are already defined in terms of physical constants and these definitions will not change. Note that in addition to h , e and k , the new definitions of the kilogram, ampere and kelvin also rely on the definitions of the second and/or the metre. In the given numerical values of h , e , k and N_A , the symbol X represents one or more digits to be added to each numerical value based on the Committee on Data for Science and Technology (CODATA) adjustment specially carried out prior to the redefinition.

A first review of the progress made since 2011 for the redefinition of the kilogram, the ampere, the kelvin and the mole was published in 2014 [2]. This paper is an update of this review focussed on the redefinition of the kilogram.

At its 14th meeting at the International Bureau of Weights and Measures (BIPM), the CCM approved CCM Recommendation G1 (2013) "On a new definition of the kilogram". Shortly after the 14th CCM meeting, the first CCM roadmap toward a redefinition was established. This roadmap contains in particular the timing for extraordinary calibrations using the IPK, for the establishment of a BIPM ensemble of reference mass standards, for a pilot study, for approving the *mise en pratique* of the (new) definition of the kilogram, for the publication of supporting work in a special edition of *Metrologia* and for publishing final data for the SI value of the Planck constant traceable to the IPK and the definitions of the metre and the second.

2. THE REDEFINITION OF THE KILOGRAM

2.1. The CCM Recommendation G1 (2013)

The CCM Recommendation G1 (2013) [3] 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 X-Ray Crystal Density (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."

2.2. The Joint CCM and CCU roadmap

In order to achieve this challenging objective by 2018, the CCM has 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 National Metrology Institutes (NMIs) and representatives of the States Parties to the Metre Convention. This roadmap includes 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 represent the milestones where the CCM conditions could be reached. The progresses with the major tasks of the roadmap will be presented in

Section 3. The details on the present status of the CCM conditions will be discussed in Section 4.

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 recently that experimental results to be used by the CODATA Task Group on Fundamental Constants in the evaluation of the fundamental constants leading to the fixed values for the defining constants of the new SI should be accepted for publication by 1 July 2017 [4].

The roadmap was refined after each important meeting and updated according to the discussions and decisions. The most recent version of the joint CCM and CCU roadmap is presented in Fig. 1.

3. PROGRESS WITH THE JOINT ROADMAP

3.1. Progress with the determination of the Planck constant

After the CODATA 2010 least square adjustment six different new results for the Planck constant (or Avogadro constant) were published. Four results were published from watt balance experiments. The Federal Institute of Metrology (METAS) [5] published its first value of the Planck constant with the first version of the experiment in 2011. The second version of the experiment [6] will be ready to take initial measurements in 2015. The Laboratoire National de Métrologie et d'Essais (LNE) published its first value of the Planck constant recently [7].

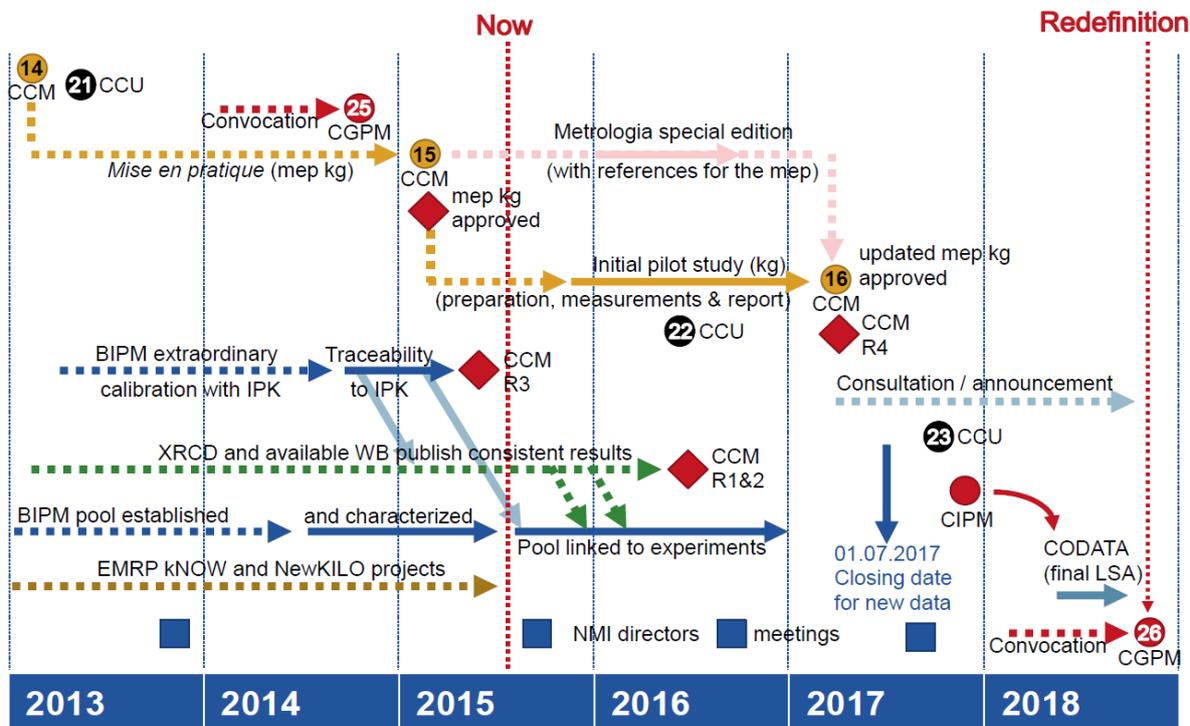


Fig. 1. Joint CCM and CCU roadmap 2018. The red diamonds represents the milestones related to the CCM conditions.

The National Institute of Standards and Technology (NIST) published in 2015 a summary of the Planck constant measured with their third watt balance set up [8]. The National Research Council of Canada (NRC) published in 2014 the very first value of the Planck constant determined with a relative uncertainty below 2 parts on 10^8 by means of a watt balance [9, 10].

Two other results were published from the International Avogadro Coordination (IAC) based on the XRCD method. The more recent values of the Planck constant (and Avogadro constant) were published in 2011 [11] and were further improved in 2015 [12].

The recent experimental values for the Planck constant are presented at Fig. 2. Previous data could be found in the CODATA 2010 [13] evaluation. In Fig. 2, all experimental data presented are corrected according to a recent recalibration of the national prototypes (see also 3.3) with the only exception of METAS for which the correction was negligible.

Additional results are expected both for watt balances and XRCD experiments before the closing date of July 2017. It is hoped that they will improve both the redundancy and the consistency of the set of data.

3.2. Progress with the "mise en pratique"

In order to redefine the kilogram one must select a constant (since 2011 the CGPM made the choice of the Planck constant) 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 does not tell how to realize the

kilogram, the *mise en pratique* is a recipe which describe how the kilogram could be realized experimentally by means of physical experiments like the XRCD method or the watt balance.

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

The latest version [14] of the *mise en pratique* 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 3.4) and is planned to be adopted by the CCM at its 16th meeting in May 2017.

3.3. Progress with the traceability to IPK

In order to ensure continuity of the kilogram derived from its present definition to its future definition, the CCM has recommended (already in 2010) that the traceability to the IPK should be established by a new calibration campaign (see 2.1, condition No 3).

The first conclusion of this campaign [15] which took place from January 2014 to January 2015 was that the IPK and its six official copies (always stored with IPK) have behaved as a consistent set of reference standards since their last use more than 23 years ago. A continuation of the well known divergence in their masses observed between the time of the 2nd and 3rd Periodic Verification (PV) has not been observed.

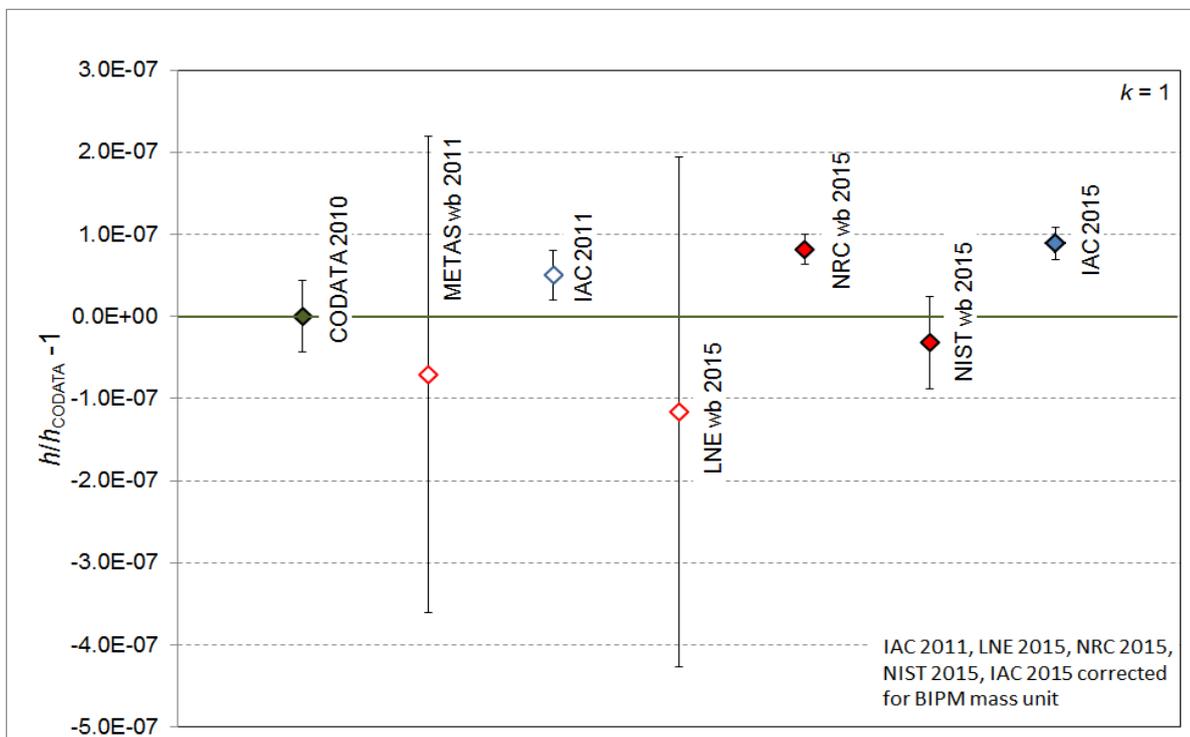


Fig. 2. Recent Planck constant determinations expressed with respect to the 2010 CODATA value. The error bars indicate standard uncertainties ($k = 1$).

However, comparison of the IPK versus the 10 Pt-Ir BIPM working standards shows that they have lost mass since the 3rd PV.

The results obtained for the set of BIPM working standards indicate that the “as-maintained BIPM mass unit” (traceable to the IPK at the 3 Periodic Verification (3d PV) 1988-1992) had drifted away from the IPK over 22 years by 35 µg. Further studies (to be published) identified the biggest effect between (attributed to wear) in the time period from 2003 to 2010.

The results of the calibration campaign were discussed at the meeting of the CCM in February 2015. The CCM reviewed the situation and made a recommendation [16] to NMIs on how to manage the consequences of the corrections to the BIPM as-maintained mass unit.

At the beginning of 2015, NMIs measuring the Planck constant received a new calibration of their national prototypes in order to fulfil the CCM Recommendation on the traceability to IPK. This will allow them a direct link between the IPK and the experimental determination of the Planck constant.

Other NMIs possessing a national prototype received corrected calibration certificates taking into account the consequences of the corrections to the BIPM as-maintained mass unit.

3.4. Progress with the pilot study

In order to validate the *mise en pratique* the CCM recommended carrying out a Pilot Study prior to the redefinition. This Pilot Study will be performed according to the principles of the CIPM MRA and will be the starting point of an on-going key comparison of the future the realization of the kilogram.

The Pilot Study should compare realizations of the unit of mass at the level of 1 kilogram obtained with the primary realization experiments which are capable of producing results at an appropriate level of uncertainty (a relative standard uncertainty of less than 2 parts in 10^7) at the time of the Pilot Study.

The outcome of the Pilot Study may also result in an update of the *mise en pratique* (see 3.2). The protocol has been designed so that primary realizations based on the different primary realisation methods may be compared as directly as possible.

The Pilot Study will be carried out by using two independent sets of travelling standards (provided by each participant) to be calibrated as follows:

- Set 1: one Pt-Ir standard and optionally 1 standard of the participant’s choice (e.g. Si-sphere, tungsten cylinder), to be calibrated as directly as possible with the primary realization experiment (in general under vacuum);
- Set 2: two stainless steel standards, calibrated in air, traceable to the primary realization experiment.

The measurement at the NMIs are planned to be performed between January and October 2016. The final report should be available by March 2017 in order to be ready for the 16th CCM meeting in May 2017.

3.5. Progress with the BIPM ensemble of mass standards

The BIPM is establishing an Ensemble of Reference Mass Standards (ERMS) in order “to facilitate the dissemination of the unit of mass when redefined” (CGPM Resolution 1 of 2011). A linking of the ERMS to the primary realization experiments will provide a first calibration in terms of the new primary realizations.

The BIPM ERMS is configured with three different materials placed in four different environments. The materials are Pt-Ir and stainless steel cylinders and silicon spheres. The environment are nitrogen, vacuum and laboratory air (as for IPK). All standards have the nominal value of one kilogram. At the time of the 15th CCM, the Pt-Ir and stainless steel cylinders had been produced and are being monitored in air for mass stability. The silicon spheres have been manufactured, etched and a thermal oxide have been grown on three of them.

For the study of surface and sorption effects, stacks (sorption artefact having relatively large geometrical surfaces) of all three different materials are also manufactured. For further surface studies, specific small surface samples of Pt-Ir, stainless steel and silicon have been manufactured. The small surface samples will be periodically sent to collaborating NMIs for chemical surface analysis.

Preparatory measurements are under way; the metal kilograms have already been compared with the IPK. The standards of the ERMS will be put into the final storage containers during 2015. Finally, mass comparisons and surface analysis will take place regularly until 2018.

Another objective of the Pilot Study (see 3.4) is to link the BIPM ensemble of reference mass standards to primary realizations (for future dissemination and bilateral comparison with new primary experiments).

3.6. Progress with the special issue of Metrologia

A special issue of *Metrologia* is planned for 2016. The main subjects will be closely related to the *mise en pratique* of the definition of the kilogram. This special issue is intended to contain basic supporting documents which may then be directly cited in the final version of the *mise en pratique*.

The following content (working titles) and main authors were outlined at the time of the 15th CCM meeting:

- P. Richard: "Foundation for the redefinition of the kilogram";
- G. Mana: "A system of units based on fundamental constants of physics";
- I. Robinson: "The watt balance: a technique for implementing the new SI definition of the mass unit";
- K. Fujii: "Realization of the kilogram by the XRCD method";
- Zhang Zhonghua: "A new generation joule balance with electromagnet at the NIM";
- K. Marti: "Surface science for mass artefacts";
- S. Davidson: "Air-vacuum transfer; establishing traceability to the new kilogram";
- S. Guelatti-Khélifa: "Precise determination of the ratio h/m: a way to link Avogadro project to watt balance";

- L. Nielsen: "Dissemination, mass scale and CMCs after the redefinition of the kilogram";
- E. de Mirandés: "The BIPM ensemble of reference mass standards";
- R. Davis: "Pilot Study for an on-going BIPM Key Comparison";
- M. Stock: "Redefinition of the kilogram: ensuring continuity between the definitions based on the International Prototype of the Kilogram and on the Planck constant".

The deadline for paper submission will be early 2016.

4. PRESENT STATUS WITH THE CCM CONDITIONS

4.1. Consistency

The first CCM condition is related to consistency of the Planck constant obtained experimentally from two independent methods. The CCM wants a sufficiently high redundancy and requires in its first condition that "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 ".

According to the section 3.1 and Fig. 2, data published recently include three independent experimental results with relative uncertainties $< 50 \mu\text{g}/\text{kg}$. Depending on the method used to check for consistency, the total set of data is still not entirely consistent. Further experimental results from potentially three or four experiments are expected until the closing date of July 1st 2017. It is expected that this condition on consistency will be fully achieved by July 2017. Finally the CCM has to decide about consistency. Nevertheless, according to a discussion at the 15th CCM meeting, the majority of CCM members would be reassured by an observed chi-square well within the high-density region of the probability density function.

4.2. Uncertainty

The second CCM condition is related to the uncertainty of measurement of the best determination of the Planck constant. The CCM wants a sufficiently low uncertainty of measurement for the best determination of the Planck constant and requires in its second condition that: "at least one of these results should have a relative standard uncertainty not larger than 2 parts in 10^8 ".

Data published recently include two independent experimental results with relative uncertainty $< 20 \mu\text{g}/\text{kg}$. Thus both watt balance and XRCD method have now achieved the target relative standard uncertainty of 2.0×10^{-8} necessary for the realization of the definition of the kilogram. The expected additional experimental results until July 2017 could only confirm and improve this already excellent result (assuming they agree with the present results).

4.3. Traceability to the IPK

The third CCM condition is related to the re-establishment of the traceability to the IPK prior to the

redefinition. The CCM wants the closest and best possible link to the IPK for the determination of the Planck constant and requires thus in its third condition that: "the BIPM prototypes, the BIPM ensemble of reference mass standards, and the mass standards used in the watt balance and XRCD experiments have been compared as directly as possible with the international prototype of the kilogram".

According to section 3.3, the traceability to IPK was re-established for all NMIs with a primary realization experiment. The third CCM condition is already fully achieved.

4.4. Validation of the *mise en pratique*

Finally, the fourth and last CCM condition is related to the validation of the *mise en pratique* of the definition of the kilogram with a successful key comparison prior to the redefinition. The CCM wants to demonstrate the ability of the *mise en pratique* in practice to realize and disseminate the kilogram and requires in its last condition that: "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".

The validation will take place as a pilot study which will become a key comparison of the primary realizations of the new definition according to the *mise en pratique*. The final protocol of the pilot study will be approved by the participants in the second half of 2015. It is planned that the CCM condition number 4 be achieved at the 16th CCM in May 2017.

5. CONCLUSIONS

The CCM roadmap and the CCM conditions were described in detail. The present status of the CCM conditions was discussed.

All activities related to the redefinition of the kilogram requested by the CCM conditions are fully on schedule according to the joint CCM and CCU roadmap.

The four CCM conditions are on track to be fulfilled according to the time schedule agreed in the joint CCM and CCU roadmap.

Deslattes wrote already in 1974: "It would thus appear that a value of N_A is obtainable with an uncertainty of the order of 0.01 ppm. Should this be achieved, one might wish to assert that the artifact kilogram is redundant and that masses can be obtained via an algorithm of realization from the atomic mass unit." [17].

After more than 40 years of efforts with XRCD and watt balance experiments (June 2015 saw the 40th anniversary since the principle of the watt balance was first proposed at the National Physical Laboratory (NPL) by Dr Bryan Kibble [18, 19]) the road towards the redefinition of the kilogram in 2018 is now quite clear. All actors are pretty optimistic that the four CCM condition will be met on time for the convocation to the 26th CGPM in 2018.

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