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REVIEW PAPER

Journey of Kilogram from Physical Constant to Universal Physical Constant (*h*) via Artefact: A Brief Review

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Abstract: The redefinition of mass adopted in November 2018 and implemented from 20 May 2019, i.e. World Metrology Day, eliminated the artefact-based approach dependent upon the International Prototype of the Kilogram (IPK), in favour of realizing the kilogram in terms of the Planck constant h by fixing its value as $6.62607015 \times 10^{-34}$ J s. In this paper, the authors present a general outline of the circumstances and related developments that paved the way for the new definition that replaced the IPK after a period of 130 years since it was formally sanctioned to define the kilogram in 1889. The new definition opens up fascinating developments in mass metrology which include different realization techniques, realizing the unit at values other than 1 kg, numerous sources for traceability can be envisaged etc.

Keywords: Redefinition of kilogram; Kibble balance; Metrology; Planck constant

1. Introduction

The implementation of the new definitions of SI base units on 20 May 2019 has been very significant for the fact that the unit of mass, the kilogram, the last of the seven base units which was hitherto represented by an artefact, has also been defined by a universal physical constant like the other six base units [1]. The redefinition of the kilogram in terms of the Planck constant h is the successful culmination of a series of effort spread over a period of many years. Indeed, the inadequacy of the artefact definition of the mass had become evident long ago and the need for replacing its definition was recognized by the International Committee for Weights and Measures (CIPM) way back in 1960 [2, 3]. The most worrisome aspect about artefact-based primary standard of mass was its stability. Over the years, occurrences of significant drift in values were found between the International Prototype of the Kilogram (IPK) and its official copies kept at the International Bureau of Weights and Measures (BIPM) and the National Prototype of the Kilogram (NPK), maintained at various National Metrology Institutes (NMIs) worldwide [4]. The main issue has been that it was very difficult to assign this drift either to the IPK and its official copies or to the NPKs, as there was no independent reference with respect to which the absolute drift could be determined. The only safe conclusion that could be drawn from this observation was that the primary standard of mass represented by the artefact was found to have drifted in value with the absolute value of this drift remaining unknown. Apart from that, due to safety concerns of the IPK, its use in measurements had been restricted to very rare occasions and as a consequence there had been the problem of assuring traceability of the mass calibrations at times [5, 6]. As is to be mentioned, the new definition helps to eliminate all the aforementioned concerns.

It is to be realized that the adoption of the new definition of the mass is the outcome of a very long process. As it was quite natural for the mass metrology community to have serious concerns on several points when initiating such a historic change as redefining the kilogram, it was necessary to prepare for resolving all the pertinent issues beforehand. It involved finding solutions to a lot of challenging tasks, both technical and operational [7]. In the first place, it was necessary to demonstrate the ability to develop measurement techniques that can realize the kilogram according to the new definition with the required accuracy. Apart from

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*Corresponding author, E-mail: singhnidhi@nplindia.org that, it was very much necessary to ensure that the implementation of the new definition would be able to accommodate all the measurement requirements the same or in a better way as they existed previously. These included ensuring the continuity of the unit of mass, its dissemination and traceability requirements, and validity of CIPM Mutual Recognition Arrangement (CIPM MRA) among others. All these requirements were met to the satisfaction of all concerned by 2018, resulting in the acceptance of the redefinition of the kilogram and three other SI base units for implementation by the General Conference on Weights and Measures (CGPM) in its 26th meeting. In this paper, the authors have tried to give a general picture of the important developments that drove the new definition of the kilogram into a practical reality by the collaborative work among a number of NMIs around the world and other metrology organizations. More detailed descriptions on specific topics discussed in this paper can be found in several individual publications, that deal with experiments carried out, methodology of data analysis for fixing the value of h and operational matters etc., a few of them are given in the references [8–12]. There are also some very recent publications which also explore the significance of the new SI definitions on metrology as a whole [13–18]. Even though the new SI definitions do not favour any particular methods to realize the units, a preference has been seen for the Kibble balance to realize the kilogram as several NMIs have already started operating or developing it in their laboratories [19–21]. Therefore, the basic principle and some of the developments that are going on concerning the Kibble balance have also been included in this paper.

2. Important Phases in the Redefinition of the Kilogram: A Consolidated View

2.1. A Brief Historical Account of the Circumstances and Key Developments

Having realized the unit of mass in terms of a universal physical constant eventually, it is to be acknowledged that this was not the first time that the unit of mass was defined in terms of a physical constant. To be precise, in the year 1791 the unit of mass was in fact defined based on the density of water and a decree to this effect was passed by King Louis XVI. Since then a lot of development has taken place in the field of mass metrology. At the time of first CGPM in 1889, the mass of the IPK was sanctioned to define the unit of mass and the definitive wordings came in the third CGPM held in 1901. But soon, the drift in the mass values of IPK and NPKs was observed and by 1960 it had become almost clear that there would be a need to redefine kilogram in terms of a universal physical constant. The process for the redefinition was progressed step by step on timely resolutions made in successive CGPM meetings as well as on specific inputs received from the Consultative Committee for Mass and Related Quantities (CCM). Some of the most important developments relevant to mass metrology are presented in Table 1 in a chronological order from 1791 to the end of April 2020, indicating important steps that led to the developments before culminating into the redefinition in terms of the Planck constant h and its exact implementation.

2.2. Scientific Highlights

As can be understood from Table 1, in 1960 the need for redefining the kilogram was earnestly felt and a final decision for redefining the kilogram based on an atomic constant was taken in 1999 at the 21st CGPM meeting. The efforts since then that achieved the goal of redefining the kilogram can be identified broadly as belonging to those for choosing the defining constant, determining its most accurate value, establishing the realization experiments and refining them to the required accuracy. In order to redefine the kilogram, it was in 2011 that the CGPM decided to choose the Planck constant h. Before that both the h and the Avogadro number N_A were considered for the defining constant of mass, it was decided in favour of h mainly to benefit from the availability of quantum phenomena-based electrical measurements through Josephson and Quantum Hall effects. So, decision was taken in 2011 to redefine the mass by fixing the value of h as $6.62606X \times 10^{-34}$ with unit as kg m^2 s^{-1} [19, 32]. Here X represents more number of digits that would be made available by the CODATA to use in redefinition. The value of h can be determined either by XRCD experiment or watt balance; both methods can work complementary to each other. In fact, watt balance, which was developed by Dr. Bryan Peter Kibble in 1975 by equating electrical and mechanical forces on the mass, was one experiment that linked macroscopic mass with Planck constant for the first time [25]. The XRCD experiment involves counting number of atoms in a 1 kg sphere made up of Si^{28} atoms, and h is determined from a relationship involving the N_A and the Rydberg constant (R_∞) [10]. Determining the most accurate value of h needed intense scientific effort and the NMIs which took up this challenge working on watt balance (now renamed as Kibble balance in honour of its inventor, following his death in 2016) and XRCD experiments came up with consistent set of values for h with low measurement uncertainties. As the experiments improved greatly, the measured data of h were used as principal input to the CODATA fundamental constants adjustment and they can be found in the CODATA reports. Employing up-to-date experimental data, CODATA did

Table 1 Timeline focusing on some of the major developments and progress made over the years

Year	Events	Major developments
1791		The idea to define kilogram based on the density of water, a physical constant, was conceived. A decree was passed by King Louis XVI on 30 March 1791 which emphasized on the definition and realization of measurement unit on the basis of a physical constant. Kilogram was initially defined as the mass of one litre (10^3 cm^3) of distilled water at 0 °C [22]
1795		Reference condition of water was changed from density at 0–4 °C which corresponds to the temperature of maximum density of water [22]
1799		The artefact of kilogram was realized by a cylinder made of platinum sponge referred to as the kilogram of archives, the KA. It became new unit of mass also called 'weight' at the time [22]
1872		A decision was taken that the kilogram would be redefined to be the mass of the IPK (made of an alloy consisting 90% Pt and 10% Ir) which would be first adjusted to be identical within experimental uncertainty to the mass of the KA. $m(\mathrm{KA}) = m(\mathrm{IPK})$ [22]
1875		BIPM was established
1889	1st CGPM	The mass of International Prototype of the Kilogram (IPK) was sanctioned to define the unit of mass
1901	3rd CGPM	Official definition of mass viz., "The kilogram is the unit of mass; it is equal to the mass of international prototype of the kilogram" was adopted
1939		During the preparation of second periodic verification of NPKs, IPK was compared with the KA and found $m(\mathrm{KA}) = m(\mathrm{IPK}) - 0.43$ mg [22]
1939–1946	The second periodic verification	During the second periodic verification carried out between IPK and its official copies, some of the official copies were found to have masses of several tens of micrograms higher than that of the IPK. This implied either increase in the mass of some of the official copies or that the mass of the IPK was decreasing [22]
By 1960		CIPM recognized that artefact-based definition of mass has to be replaced sooner or later
1960		Metre convention: the name SI (international system) was officially given to the system of units initially having six base units, viz., m, kg, s, A, K, cd [23]
1966	Formation of The Committee on Data for Science and Technology (CODATA)	The International Council of Science established CODATA for facilitating improved scientific and technical data management and use for addressing issues of scientific interest for the benefit of society. Since then it seeks to provide the best values of fundamental constants and conversion factors used in physics and chemistry to scientific and metrology communities [24]
1969	Formation of Task Group on Fundamental Physical Constants (TGFC)	CODATA established the TGFC in 1969 and the mandate of TGFC is "to periodically provide the scientific and technological communities with a self-consistent set of internationally recommended values of the basic constants and conversion factors of physics and chemistry based on all of the relevant data available at a given point in time" [24]
1975		Dr. Bryan Peter Kibble at NPL Teddington demonstrated the principle of watt balance, equating mechanical power to electrical power [25]
1988–1992	The third periodic verification	Confirmed the trend of mass change of prototypes of kilogram with respect to IPK which was also observed in second periodic verification. During verification, each NPK was calibrated against the IPK with the combined uncertainty of 2.3 μg [4]
1990		Availability of electrical measurements by Josephson Voltage Standard (JVS) and Quantum Hall Resistance (QHR) standard which are based on the quantum phenomena [26, 27] for determination of h using watt balance

Table 1 continued

Year	Events	Major developments
1995	20th CGPM	Reviewed the result of the third periodic verification of NPKs against IPK [5]
		Recommended laboratories to pursue their work with a view to monitoring the stability of IPK and in due course opening the way for the new definition of the unit of mass-based upon fundamental atomic constant
		Considered watt balance and X-ray Crystal Density (XRCD) (that counts the number of atoms in a silicon sphere) methods as candidates that could link mass with fundamental constant: watt Balance through Planck constant and XRCD through Avogadro constant. NIST USA, NPL UK, and NRLM Japan were working towards development of watt balance and PTB Germany was working to refine the Si sphere method [28]
1999	21st CGPM	Recommended in its resolution to redefine kg
		Recommended the NMIs to continue their efforts to refine watt balance and XRCD experiments with a view to future redefinition of kilogram [29]
2005		First publication to redefine kg and chose a “conventional value” of kg based on fundamental constant [30]
		Discrepancy of 1 part in 10^6 was found between watt balance experiment and XRCD method, which withheld the change in definition that time [29]
2007	23rd CGPM	Urged NMIs to “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 value of fundamental constants at time of the 24th CGPM 2011” [31]
2010	CCM 12th meeting	Definitive steps were taken to move forward for the redefinition. Towards this formulated number of essential conditions that should be met before the new definition could be adopted [5]. Accuracy and uncertainty limits to be achieved by targeted experiments were specified based on which CODATA to recommend values to be adopted for the fundamental constants
2011	24th CGPM	Decided to use Planck constant for the redefinition of mass with unit kg m^2 s^{-1}. Correlation factor between $\boldsymbol{h}$ and $\boldsymbol{N}_{\mathbf{A}}$ should be $-$ 0.999
		CGPM asked TGFC “to carry out a special least-squares adjustment (LSA) of the values of the fundamental physical constants to provide values for defining constants to form the foundation for the revised SI” [32]
2012	CCM workshop	Workshop held by CCM held a rigorous discussion and debate on the draft of mise en pratique (French for ‘practical realization’) [29]
2013	CCM 2013	Four main conditions that had to be met before the redefinition were slightly modified. The four resolutions were to fulfil Consistency, Uncertainty, Traceability and Validation of the new definition
		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 X-Ray Crystal Density (XRCD) 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’ [29]
2014	The extraordinary calibration	IPK was used to check the consistency of experiments realizing mass. On the request of CCM, a pilot study was conducted between five participating NMIs and BIPM. Five NMI participated in the pilot study, three of them (LNE, NIST and NRC) with Kibble balance and two with Si Sphere (NMIJ and PTB). It tested continuity of mass unit across the redefinition by comparing mass calibration based on Kibble balance and XRCD experiment [11]
2014	25th CGPM	Urged strongly to complete all works on time to enable the adoption of new SI definitions in the 26th CGPM meeting [33]

Table 1 continued

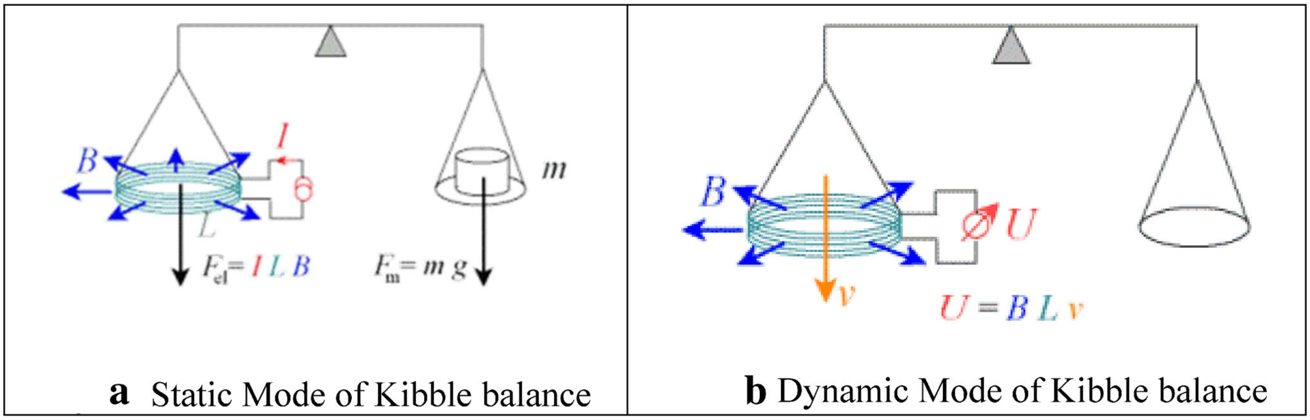
Year	Events	Major developments
2015		CIPM recommended publication of new experimental results by 1 July 2017 to enable CODATA to arrive at final values of the fundamental constant for redefinition of SI units on time [29]
2017		CODATA provides exact values of fundamental constant for redefinition of SI units based on up-to-date experimental data [8]
2018	26th CGPM	Mass was redefined (along with three other base units)
		“The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be 6.62607015 × 10^{-34} when expressed in unit J s, which is equal to kg m^2 s^{-1},where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$” [1]
2019		On 20 May 2019, the new definition was implemented globally

vigorous statistical and scientific analysis to find the most accurate value of Planck constant with the minimum uncertainty that fulfilled CCM requirements [34]. Table 2 shows the subset of eight input data that has been used to find the adjusted value of h by CODATA 2017 [8]. First four inputs (value of h) are from Kibble balance, and later four inputs (value of N_A) are from XRCD experiments. In 2017, CODATA finally gave the most accurate value for h as 6.62607015 × 10^{-34} J s with relative uncertainty of 1.0 × 10^{-8}.

Meeting the tight constraints laid down by CCM catalysed the activities for ensuring continuity of the unit after the redefinition, i.e. the unit kg represents exactly the same quantity before and after the redefinition. This needed

Table 2 Measurement data from Kibble balance and XRCD experiments used by CODATA 2017 to calculate the value of *h*

Data source	Parameter	Value	Relative uncertainty
NIST-15 (NIST USA)	h	6.62606936(38) × 10^{-34} J s	5.7 × 10^{-8}
NRC-17 (NRC, Canada)	h	6.626070133(60) × 10^{-34} J s	9.1 × 10^{-9}
NIST-17 (NIST USA)	h	6.626069934(88) × 10^{-34} J s	1.3 × 10^{-8}
LNE-17 (LNE, France)	h	6.62607040(38) × 10^{-34} J s	5.7 × 10^{-8}
IAC-11 (International Avogadro Coordination)	N_A	6.02214095(18) × 10^{23} mol^{-1}	3.0 × 10^{-8}
IAC-15 (International Avogadro Coordination)	N_A	6.02214070(12) × 10^{23} mol^{-1}	2.0 × 10^{-8}
IAC-17(International Avogadro Coordination)	N_A	6.022140526(70) × 10^{23} mol^{-1}	1.2 × 10^{-8}
NMIJ-17 (NMI Japan)	N_A	6.02214078(15) × 10^{23} mol^{-1}	2.4 × 10^{-8}



a Static Mode of Kibble balance

b Dynamic Mode of Kibble balance

Fig. 1 Schematic diagram showing the basic principle of Kibble balance. (Adapted from https://www.bipm.org/en/bipm/mass/watt-balance/wb_principle.html) determining the value of h fully consistent with IPK. To ensure this, special efforts were made through the extraordinary calibration campaign so that the value of h was determined traceable directly to the IPK when the IPK's assigned mass was exactly 1 kg [11]. The value of h given above is an outcome of that exercise. To carry out this activity, all the NMIs which were involved in the determination of h had got their mass standards calibrated against IPK with a standard uncertainty of 3.5 µg. The redefinition of kg was done by taking the value of h provided by CODATA without the uncertainty. So, the kilogram is now equal to $\frac{h}{6.62607015 \times 10^{-34}}$ m^{-2} s. With this, the IPK lost its status as the mass standard. On the basis of the new definition, the IPK was deemed to have an uncertainty of 10 µg at the time of the redefinition, corresponding to the relative uncertainty of 1.0×10^{-8} that h had before it was assigned the exact numerical value. Continuity of the unit is ensured by taking into account this uncertainty in all measurements that derive their traceability from IPK [12].

2.3. Mechanism for Dissemination of Kilogram After the Redefinition

The other essential task that needed to be accomplished was regarding the mechanism for ensuring dissemination of the unit after its redefinition. One of the important features of the new definition is that it does not prescribe any unique realization experiment for kg. The definition also provides the possibility of realizing the mass unit at values other than 1 kg. Any NMI who operates the Kibble balance or XRCD experiment can, in principle, consider disseminating the unit. For NMIs who do not have their own realization method, in future traceability can be obtained from BIPM or other NMIs having the realization capability. Presently, because of inconsistency in the values among the participating laboratories, it was decided to provide dissemination phase wise till the time the experiments are matured to the extent that the differences in their values become sufficiently small. For ensuring traceability till that time, a procedure based on using a consensus value (CV) to be obtained from key comparison exercise has been worked out for disseminating the unit of mass [35]. The operation of this scheme envisages four phases which are explained below.

Phase 0 This phase belonged to pre-redefinition era, i.e. until 20 May 2019 when the traceability was drawn from IPK having zero uncertainty. During this period, effort was made by NMI's to measure the value of h. Further, dissemination by NMIs was through NPK which was in turn traceable to IPK.

Phase 1 The duration of Phase 1 is from the date of implementation of the new definition of kilogram, viz., 20 May 2019 till CCM approval of consensus value from the first key comparison. The key comparison is to be held among the NMIs operating the Kibble balance or the XRCD. During this period, IPK will have the uncertainty of 10 µg. Till the CV is achieved, this approach for the mode of dissemination would continue. At the time of writing this paper, we fall in this phase of dissemination.

Phase 2 This phase comprises the duration having post-approval of CV by CCM obtained from key comparison and ends when the realization technique refined itself to the extent that CV will no longer be needed. In this regime, traceability will be taken from h and dissemination from CV. Work to refine each realization experiment would be pursued by the participating NMIs.

Phase 3 This phase would start with the completion of each realization experiment in the best achievable refined manner to the extent that we no longer need CV. After this, traceability would be from h and dissemination from individual realizations.

3. Kibble Balance and Its Principle

Kibble balance (watt balance) holds an important position in the redefinition and realization of the kilogram in terms of h occupying a pivotal position in mass metrology in the new SI. It was developed in 1975 by Dr. Bryan Peter Kibble originally for realizing the ampere from its definition in terms of mechanical units by balancing virtual mechanical power and virtual electrical power. Bringing in quantum phenomena-based measurements for the voltage and current into the system through the Josephson and Quantum Hall effects led to the determination of h in terms of macroscopic mass using the Kibble balance. The availability of the Kibble balance as a proven technique that could relate macroscopic mass to h was the main reason behind choosing h as the defining constant for redefining the kilogram. It is also for the same reason that the Kibble balance has now been developed as a method of realizing the kilogram according to its new definition.

The basic principle of the working of the Kibble balance is depicted schematically in Fig. 1. It is basically an electromechanical balance which provides the measurement of mass in terms of a magnetic force. The magnetic force to balance the gravitational force on the mass is produced by the movement of the current-carrying coil situated in the magnetic field of a very strong magnet [20, 36, 37].

In the actual Kibble balance, the mass measurement is completed in two modes, viz., the static mode and the dynamic mode.

In the static mode, the mechanical force due to mass is balanced by the magnetic force generated by a current-carrying coil in a well-aligned magnetic field.

$$mg = \mathrm{BL}\,I \tag{1}$$

where m is the mass, g is the acceleration due to gravity, BL is the geometric factor and I is the current.

In the dynamic mode, the coil is moved in the vertical direction in the same magnetic field with some velocity and there is induced voltage in the coil, expressed as,

$$U = \mathrm{BL}\,v \tag{2}$$

where U is the induced voltage and v is the velocity of coil. Presuming that BL remains constant in both the measurement modes, combining both the equations results,

$$mgv = UI \tag{3}$$

Basically by using the dynamic mode, we eliminate the need for measuring BL. So the primary quantities of measurement will be the voltage and current. It can be measured with the highest precision and accuracy using quantum standards of voltage and resistance, viz., the Josephson voltage standard (JVS) and Quantum Hall resistance (QHR) standard. On using JVS and QHR in the measurement, the mass measurement result can be realized in terms of the Planck constant h through the Josephson constant $\boldsymbol{K}_{\mathbf{j}}$ and von-Klitzing constant $\boldsymbol{R}_{\mathbf{K}}$. Without going into the details, using the primary standard for voltage and resistance in the measurement, we can get

$$h = \frac{4mgv}{(K_J^2 R_K)UI}$$

In principle, this was the method by which the Kibble balance could measure the most accurate value of h. As discussed earlier, the Kibble balance measurements allowed CODATA to fix the exact numerical value of h and formed the basis for achieving the new definition of the kilogram.

4. The International Status of Existing Kibble Balance Experiments

- NPL, UK: The work on Kibble balance started in 1976 in NPL, UK by Dr. Bryan Peter Kibble. Till date NPL, UK has developed two Kibble balances, i.e. Mark I and Mark II. Presently NPL, UK is working on single-mode two-measurement phase Kibble balance. The new technique uses mass raised and mass lowered as two independent Kibble balances and does not require precise coil alignment [19].
- NIST, USA: NIST has developed four Kibble balances, and the first results were published in 1989. NIST-4, the latest developed Kibble balance uses wheel with knife edge and permanent magnet with yoke configuration. It operates in vacuum, and the latest relative uncertainty reported by NIST is 1.3×10^{-8} [38].
- NRC, Canada: NRC started working on Kibble balance in 2009 when Mark II of NPL, UK was shipped to NRC Canada. Systematic error related to the effect of weight of the test mass on the structure of apparatus was properly analysed and rectified by NRC [19]. Modifications were done to the mass lift and coil support system. Latest relative uncertainty reported by NRC Canada was found to be 9.1×10^{-9} which is smallest in the world [39].
- BIPM, France: BIPM started working on Kibble balance in 2003. It works on single-mode one-measurement phase Kibble balance. In this, static and dynamic phases are carried out simultaneously. As the current flows continuously, the change in magnetic field due to the current will not affect the measurement. In 2013, Type A uncertainty was of the order of a few parts in 10^7 and Type B uncertainty was in the order of a few parts in 10^5 [40].
- KRISS, Korea: KRISS started working on Kibble balance in 2012. It includes a closed type cylindrical permanent magnet, a motion guiding stage and a coil position measurement system [41].
- LNE, France: LNE started developing Kibble balance in 2002, and the first results were obtained in 2014 and 2016 with relative uncertainty of 3.1×10^{-7} and 1.4×10^{-7}. It uses large flexure-bearing balance which is indigenously designed and built. In 2017, the balance was operated in air and h was calculated with an uncertainty of 5.7×10^{-8} [42].
- METAS, Switzerland: METAS has developed two Kibble balances, and the latest one is called MARK II. In MARK II, a weighing cell with the coil attached is moved by an external mechanism. MARK II is built for 100 grams and is the first one to introduce thermal compensation for their magnet system [36].
- MSL, New Zealand: MSL uses twin-pressure balance for both static mode and dynamic mode. The cylinder of the pressure balance provides guidance for the coil in dynamic mode [43].

Because number of NMIs are working on different designs of the Kibble balance, it is going to be the most important device for the realization of the kilogram in the revised SI. A state-of-the-art Kibble balance for 1 kg is a highly complex system. However, the future may see the development of much more simple systems.

5. Conclusions

In this paper, authors have tried to give a brief outline of the story behind the evolution of the mass standard starting from the one based on density of water, then the artefact IPK and finally through fundamental physical constant by assigning an exact numerical to the Planck constant. Our attempt has been to give a consolidated view of the key developments that opened up the way for the redefinition of the kilogram. The redefinition of kilogram has been possible due to the combined effort of several leading NMIs of the world and other metrological organizations. The outlook for the future of mass metrology appears very fascinating. Now the traceability path for the mass calibrations is not restricted to BIPM alone; any NMI which operates a realization experiment can be a source of traceability [5]. Presently, the Kibble balance and the XRCD are the two realization methods that are available and they need very large investments and very high level of expertise to build them. In view of this fact, not many NMIs are developing either the Kibble balance or the XRCD on their own. But the new definition doesn't forbid development for any new methods for realizing the kg in terms of ***h***, and it may be that some more simple methods that are easier to build and operate would emerge in the near future. Further, compared to developing a state-of-the-art 1 kg Kibble balance which needs huge investment and high level of expertise. Options are available to build Kibble balance for lower nominal values which can provide a comfortable choice for many NMIs those who want to establish in-house traceability for their mass standards with less effort and investment. In this regard, CSIR-NPL has developed a 1 g demonstrational model of Kibble balance [44].

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