Redefinition of the kilogram standard and consensus value setting

Redefiniowanie wzorca kilograma i wartości konsensu

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The Mass Laboratory of the Central Office of Measures (GUM) is responsible for transferring the mass unit, conducting research for metrological control, and calibrating mass measurement standards. GUM possesses the national prototype of the mass unit – the kilogram prototype No. 51. The new definition of the SI mass unit – the kilogram – based on the Planck constant, came into effect on May 20, 2019, paving the way for future independent realizations of this unit by National Metrology Institutes (NMI). To ensure global uniformity during the transition from a material standard to the new realization method, the Consultative Committee for Mass and Related Quantities (CCM) introduced the concept of consensus value. The consensus value acts as a bridge, enabling a safe and smooth transition during the redefinition. This article discusses the stages of transferring the mass unit after the redefinition, the process of determining the consensus value, and the impact of these changes on national mass values. It also presents prospects for the future development of techniques to realise and disseminating the kilogram unit according to the new definition.
KEYWORDS: kilogram, redefinition, SI units, consensus value, metrology

Laboratorium Masy Głównego Urzędu Miar (GUM) zajmuje się przekazywaniem jednostki miary masy, prowadzeniem badań na potrzeby kontroli metrologicznej oraz wzorcowaniem wzorców pomiarowych masy. GUM posiada państwowy wzorzec jednostki miary masy – prototyp kilograma nr 51. Nowa definicja jednostki masy układu SI – kilograma – oparta na stałej Plancka, weszła w życie 20 maja 2019 r., otwierając drogę do przyszłych niezależnych realizacji tej jednostki przez Krajowe Instytuty Metrologiczne (NMI). Aby zapewnić globalną jednolitość podczas przejścia z materialnego wzorca do nowego sposobu realizacji, Komitet Konsultacyjny ds. Masy i Wielkości Pochodnych (CCM) Międzynarodowego Biura Miar w Sevres (BIPM) wprowadził koncepcję wartości konsensusu. Wartość konsensusu działa jako pomost umożliwiający bezpieczne i bezkolizyjne przeprowadzenie redefinicji. Artykuł omawia etapy przekazywania jednostki masy po redefinicji, proces wyznaczania wartości konsensusu oraz wpływ tych zmian na przekazywanie jednostki miary masy w poszczególnych krajach. Przedstawiono także perspektywy przyszłego rozwoju technik realizacji i rozpowszechniania jednostki kilograma zgodnie z nową definicją.
SŁOWA KLUCZOWE: kilogram, redefinicja, jednostki SI, wartość konsensusu, metrologia

Introduction

Since 1889, the unit of mass kilogram has been defined as the mass of the International Prototype of the Kilogram (IPK), stored in the Bureau International des Poids et Mesures (BIPM) in France. This physical artefact, made of an alloy of platinum and iridium, served as a mass standard for over a century. However, due to limitations related to the physical standard, such as mass changes due to adsorption and desorption of gases, the decision was made to redefine the kilogram [1–3].

On May 20, 2019, a new definition of the SI unit of mass – the kilogram – came into force, based on the Planck constant. This change meant a transition from a physical standard to a definition based on fundamental physical constants, allowing for a more stable and precise determination of the mass unit. The new definition enables National Metrology Institutes (NMIs) around the world to realize the kilogram independently, using advanced techniques such as the Kibble balance and the X-ray crystal density (XRCD) method [4, 5].

However, the transition from a material standard to a new definition required global uniformity of measurements. To achieve this, the Consultative Committee for Mass and Related Quantities (CCM). CCM introduced the concept of consensus values. The consensus value is determined on the basis of the results of key comparisons of the kilogram realization by different NMIs and acts as a bridge, allowing the redefinition to be carried out safely and without collisions [6].

The purpose of this article is to discuss the steps for transferring a unit of mass after redefinition, the process of determining consensus values, and the impact of these changes on national mass values. In addition, the prospects for the future development of techniques for the implementation and dissemination of the kilogram unit according to the new definition have been presented.

Methods of kilogram realization

The Kibble balance

Currently, there are two main methods of the realization of the kilogram. The Kibble balance (or the Watt

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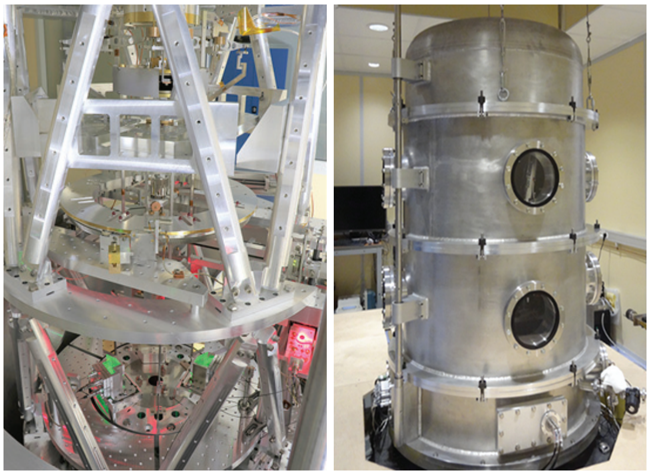

Fig 1. The Kibble balance in BIPM [5]

balance) uses an electromagnetic force balanced by the force of gravity on a mass by equationing electrical and mechanical energy using electrical-mechanical balances. It is an electromechanical device that combines mass with electrical measurements, allowing tracking to the Planck constant. Electric current, voltage, and other parameters are measured using physical constants such as the Joseph constant (KJ) and the von Klitzing constant (RK), which are known with very high accuracy. Currents and voltages are expressed in units based on these physical constants. This makes it possible to determine the mass of the sample in units of kilogram (see Fig. 1) [5].

X-ray Crystal Density (XRCD) Method

This method involves measuring the density of a high-purity silicon crystal using X-rays and using this measurement to determine the mass of a single 28Si silicon atom. By counting the number of atoms in the crystal and knowing Avogadro's constant, it is possible to precisely determine the mass (see Fig. 2) [6].

The importance of the consensus value

The new situation in mass metrology requires international coordination to ensure global uniformity of measurements. The consensus value is calculated and updated based on the results of comparisons of different kilogram realizations. This is essential because the Kibble and XRCD methods can produce different results. Adopting the consensus value helps reduce these differences, enabling consistency of measurement at the international level.

The consensus value for the kilogram, or international average value of the kilogram, is calculated as the arithmetic mean of the last three "cores" for the kilogram unit mass value. This value is relative to the weight of the International Kilogram Prototype (IPK) and is currently entirely based on the results of realization experiments. This process ensures that mass measurements remain consistent and precise around the world, even though different institutes may determine the value of the kilogram mass error and estimate the measurement uncertainty using different implementation methods [6, 7].

Fig. 2. Vacuum Comparator in PTB and Silicon Sphere [4]

Consensus value and its importance

The Consultative Committee for Mass and Related Quantities (CCM) recommended that the consensus value should be calculated based on the results of key comparisons of kilogram realization, carried out every two years. To avoid significant abrupt changes, this value is the arithmetic mean of the key reference values of the last three comparisons. The first key comparison (CCM.M-K8.2019) made it possible to determine the first consensus value, adopted on February 1, 2021. The conclusion of the second key comparison (CCM.M-K8.2021) on January 17, 2023 resulted in a redetermination of the consensus value.

The Consensus Value for 2023 for the SI unit of mass, the kilogram, has been defined as: 1 kg – 7 μg with a standard uncertainty of 20 μg with respect to the International Kilogram Prototype (IPK) mass value, which is equal to the unit of mass held by the BIPM. This means that the mass of the IPK, based on the consensus value, is 1 kg – 7 μg. (The consensus value for 2023 is 5 μg lower than the consensus value for 2021) (see Table I) [6, 7].

TABLE I. The consensus value in different years

Implementation	Consensus value	Uncertainty
May 20, 2019	*m*(IPK) = 1 kg	10 μg
Febr. 1, 2021	Consensus value 2021 *m*(IPK) = 1 kg – 2 μg	20 μg
March 1, 2023	Consensus value 2021 *m*(IPK) = 1 kg – 7 μg	20 μg

The SI Unit Mass tracking will be based on the 2023 kilogram consensus value, starting on March 1, 2023. The consensus value will be reviewed after each Key Comparison of realization that are currently planned every two years.

Steps for transferring the unit of mass

The CCM recommended that until a satisfactory agreement is achieved between independent realizations, key comparisons should be made every two years between the realizations of the kilogram using Kibble balances and XRCD experiments. The first phase began with the implementation of the new definition on May 20, 2019 and ended with the adoption of the first consensus value on February 1, 2021.

The second phase lasted from the adoption of the first consensus value to the adoption of the second consensus value on March 1, 2023, and the next, and the last, is ongoing and will continue until the CCM considers that a sufficient number of independent implementation experiments have reached adequate compliance. Implementation experiments are tests and measurements that are aimed at practical implementation and confirmation of the new definition of the unit of mass measurement in accordance with established metrological standards. In this phase, certain criteria must be met, such as the consistency of the results of key comparisons and the stability of the results [5, 6].

TABLE II. Stages of transferring the unit of mass

Stage	Period	Description
1st stage	20.05.2019 – 01.02.2021	Implementation of the new definition
2nd stage	01.02.2021 – 01.03.2023	Independent implementations, consensus value, conformity assessment
3rd stage (future)	01.03.2023 – once the criteria have been met	Global dissemination

Consensus value for kilogram

Consensus value in the first stage has been calculated as the arithmetic mean of the last three "results" for the value of the kilogram mass unit. The consensus value is relative to the weight of the International Kilogram Prototype (IPK). The uncertainty of the consensus value was set at 20 μg ($k = 1$). In 2021, it was not necessary to make a weight adjustment, but it was necessary to increase the CMC to account for the uncertainty [8].

In the second stage, the consensus value is entirely based on the results of realization experiments. The 2023 consensus value differs significantly from the IPK value. A correction of the mass values (-7 μg with respect to the IPK) was required, however, there was no need for further correction of the CMC.

Summary and conclusions

As kilogram realization techniques evolve, the Kibble balance and XRCD method will continue to play a key role. The technology is planned to be available to end users, allowing them to perform measurements with direct traceability down to the SI unit of mass. Further research and improvement of the implementation experiments are necessary to achieve full agreement between the different realizations of the kilogram.

The new definition of the kilogram based on the Planck constant provides a more stable and precise determination of the unit of mass. The process of transition from a material standard to a definition based on fundamental physical constants required global coordination and the introduction of consensus values to ensure uniformity of measurements.

The consensus value, which is the arithmetic mean of the results from different executions of the kilogram, allows for consistent measurements around the world. The value of consensus is the foundation of global uniformity of units of measurement and is determined every two years. With regular key comparisons and updates to this value, mass metrology can provide consistent and reliable measurements around the world. Future developments in kilogram realization techniques will bring even greater precision and accessibility, with significant implications for science, technology and industry.

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