WhitePaper

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The redefinition of the unit „kilogram“ – what does it mean for weighing technology users?

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Abstract

On 20th of May 2019, a new definition of the unit "kilogram" comes into force – the closer we are reaching this date, the more respective articles are published in daily newspapers and magazines. This white paper aims to educate Sartorius' customers on the reasons for the redefinition and the foreseen consequences. Especially in highly regulated areas such as certified and/or accredited companies and laboratories where users may be faced with the task of assessing the impact of the redefinition on their work as part of a risk assessment or management review. For this purpose, this white paper should offer assistance.

Basically, for users of balances, weights and comparators, initially nothing will change in their daily work and processes do not have to be changed - in the development of the new definition, representatives of the industry were involved at an early stage to ensure just that. In particular, technology and staff of Sartorius has been involved from the beginning in the development of the redefinition of the kilogram. This white paper will therefore also give you a brief overview of how Sartorius was initially and remains involved in this innovation.

Introduction

Presumably, everybody has already heard the terms "original/prototype meter" and "original/prototype kilogram". While the "prototype meter", a platinum iridium rod of exactly one meter length, was superseded as the definition of the unit "meter" already in 1960, the "prototype kilogram" in the beginning of 2019 remains the definition of the unit "kilogram": One kilogram is simply defined as the mass of the "international prototype kilogram" (IPK), as it is formally called, which is a platinum iridium cylinder with a height and a diameter of 39 mm that is stored at the BIPM (Bureau International des Poids et Mesures) near Paris. On 16th of November 2018 it was decided by the responsible committee that from 20th of May 2019 on, this definition will be replaced by a new one based on the fundamental constant *h* (the Planck constant).

Also on the same date the units "ampere", "mole" and "kelvin" will have new definitions, meaning all seven SI base units (kilogram, meter, second, mole, ampere, kelvin, candela) will then be defined on the basis of fundamental constants. Actually, the fact that this did not happen before for the kilogram as one of the most important units for trade, economy and production is not due to lack of necessity, but rather due to the circumstance that a respective definition until now could not be realised with sufficient accuracy.

The definition of the kilogram coming into force on 20th of May 2019 appears rather unexciting on the first view [1]:

> "The kilogram is defined by taking the fixed numerical value of the Planck constant *h* to be 6.626 070 15 $\times 10^{-34}$ when expressed in the 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 $\Delta\nu_{Cs}$."

Admittedly, the intuitive intelligibility of this new definition is worse than the previous one ("as much as the IPK") – due to the linking with fundamental constants, it is however much more stable and future-proof than before. In fact, the IPK has lost approximately 50 µg over the last 100 years as can be seen by comparisons with further prototypes [2] – however, as the mass of the IPK is exactly 1 kg by definition, strictly speaking all other masses have gained 50 µg per kg over this time. While this may not seem like much, this is of course an intolerable condition in today's high technology world.

Thanks to the new definition, any experiment can be used for the realisation that links mass with one of the fundamental constants – it is then "only" necessary to ensure that there are no systematic errors in this experiment and that the measuring uncertainty is determined appropriately. At the moment, two different approaches exist for the linking of mass with the fundamental constant *h*: the so-called Avogadro experiment ("the silicon sphere") and the Kibble balance (also called Planck balance or Watt balance). These two approaches are often portrayed as competing with each other. However, it was rather one of the prerequisites of the redefinition that comparable results are obtained from two different approaches – both experiments were and are hence necessary.

The following two subchapters shall give the interested reader a very brief overview on these two realisations – much more comprehensive explanations and further details can be found in [3].

The Avogadro experiment

Centerpiece of the Avogadro experiment is a sphere made of isotopically pure ^{28}Si that often is considered mistakenly as a "new prototype kilogram". The truth is that such a sphere can be used to constitute the required connection between mass and the fundamental constant *h*:

If one multiplies the mass of a single ^{28}Si atom, m_{28Si}, by the number of atoms in an isotopically pure sphere of this material, n_{28Si}, one will obtain the mass of this sphere, m_{sphere}. Furthermore, the mass of a single atom can be obtained by dividing the mass of a mole of this substance, M_{28Si}, by the number of atoms in a mole, the Avogadro constant N_A, and the number of atoms in the sphere is the volume of the sphere, V_{sphere}, divided by the volume of a single atom, V_{28Si}.

As there furthermore is a well-known relationship between the Avogadro constant and several other fundamental constants:

$$N_A = \frac{M_u \cdot c \cdot \alpha^2 \cdot A_r^e}{2 \cdot R_\infty \cdot h} \qquad (1)$$

M_u: molar mass constant;
c: speed of light;
α: fine structure constant;
A_r^e: relative atomic mass of the electron;
R: Rydberg constant,

the following relationship between the mass of the sphere, m_{sphere}, and the Planck constant *h* can be derived:

$$m_{Kugel} = m_{28Si} \cdot n_{28Si} = \frac{M_{28Si} \cdot V_{Kugel}}{N_A \cdot V_{28Si}} = \frac{M_{28Si} \cdot V_{Kugel} \cdot 2 \cdot R_\infty \cdot h}{V_{28Si} \cdot M_u \cdot c \cdot \alpha^2 \cdot A_r^e} \qquad (2)$$

The practical aspect about this equation is that on its right side there are only very well-known quantities, except the volume of the sphere, V_{sphere}. Hence, if one determines this volume with extreme precision - and that is exactly where the determination linked to a spherical shape comes from, since for a sphere the volume can be determined most exactly - one can calculate the mass of the sphere absolutely. This may not sound very exciting at first, but is in fact a groundbreaking novelty, since so far masses could only ever be determined relative to another, while now an absolute determination is possible.

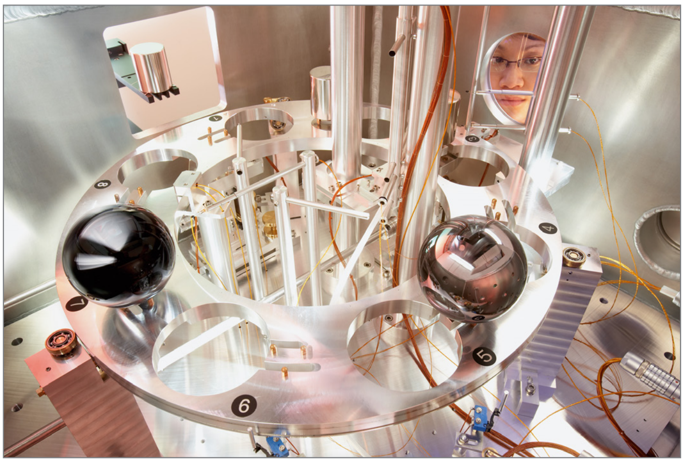

Figure 1: Two copies of a silicon sphere in a specially designed mass comparator from Sartorius.

The Kibble balance

The so-called Kibble balance (often also referred to as Planck balance or Watt balance) represents another realisation of the mass based on the Planck constant, the principle of which is quite similar to that of many modern electronic balances that work with a so-called electromagnetic force compensation principle. Firstly, the current *I* through a coil with a length *L* is measured, which is necessary to compensate for the weight of the mass to be determined by the electromagnetic force on the coil in a magnetic field *B*:

$$m \cdot g = I \cdot B \cdot L \qquad (3)$$

In a second step, the same coil is moved through the magnetic field at the speed v and the voltage U induced thereby is measured. Since for the voltage then applies:

$$U = v \cdot B \cdot L \qquad (4)$$

equations (3) and (4) can be solved to $B \cdot L$ and equated, so that these two quantities B and L, which are difficult to determine exactly, disappear from the equation:

$$m \cdot g \cdot v = U \cdot I = \frac{U^2}{R} \qquad (5)$$

The voltage U can be measured as the n-fold of a so-called Josephson voltage $U_J = f_J \cdot h/2e$ where f_J is a microwave frequency that can be set very precisely, e is the elementary charge of an electron and h again is the Planck constant. The resistance R in equation (5) can further be represented as an integer fraction of the Klitzing constant $R_K = h/e^2$ and thus also dependent on the natural constants e and h. Hence, equation (5) can be transformed to:

$$m = \frac{p \cdot n^2}{4 \cdot g \cdot v} \cdot f_J^2 \cdot h \qquad (6)$$

Therefore in the same way as the silicon sphere establishes a relationship to the Avogadro constant, the Kibble balance establishes a relation between mass and the Planck constant h, which allows for an absolute determination of the mass.

Sartorius' role in the redefinition

Of course, Sartorius as an important stakeholder in the topic "mass" was involved in the redefinition of the unit "kilogram" right from the beginning:

Firstly, Sartorius has been involved in important discussions and developments regarding the redefinition since the outset by holding important roles in relevant committees - for example, Sartorius holds the presidentship of the Legal Metrology Group of the European Scale Manufacturers Association CECIP. The responsible committee for the redefinition (BIPM's General Conference on Weights and Measures) has ensured from the outset of the process that industrial stakeholders are involved through such manufacturers' associations to ensure that the redefinition does not harm the industry and its customers.

On the other hand, also Sartorius' technologies were significantly involved in the redefinition process: before the redefinition of the unit "kilogram" based on the Planck constant h could take place, the Planck constant had to be determined very precisely by using the equations (2) and (6) the other way round. If one solves the two equations to h, one can then determine the Planck constant very accurately with the two methods mentioned, if the respective mass is known very well. This exact process was carried out over several years at various metrology institutes to finally determine a reference value for h from the independent measurements at different locations and with both methods. In several institutes, e.g. the BIPM and the PTB, a Sartorius CCL1007 mass comparator was used for this purpose, designed and optimised for mass determination of weights and silicon spheres with the highest possible accuracy.

Additionally in the second way of realising the new definition, the Kibble balance (or Planck/Watt/Joule balance), Sartorius' products are used on the highest metrology level – several setups of such Kibble balances at National Metrology Institutes comprise Sartorius load cells, for example the Joule balance at NIM (China) or the Watt balance at BIPM.

What does that mean for Sartorius' customers of....

...mass comparators

Even if, as described above, the new definition of the kilogram makes it possible to determine masses in absolute terms, instead of comparing them as hitherto, mass comparators will still be required for various metrological tasks in the future: On the one hand, for a "transfer" of the new primary realisations to conventional weight pieces and on the other hand, calibrated weights will continue to be used as reference standards, working standards and test equipment, which will have to be calibrated with mass comparators.

The mass comparator CCL1007 mentioned above was developed by Sartorius in cooperation with the BIPM / France at the beginning of the 2000s, with the aim to determine the mass of 1 kg silicon spheres with the highest possible accuracy through mass comparison. In the first step, the Avogadro constant should be re-determined as part of the Avogadro experiment (see above). For this experiment the mass comparator CCL1007 was and is also used at the PTB (Physikalisch-Technische Bundesanstalt) in Braunschweig, Germany.

Following the introduction of the new definition of the SI unit kilogram, it will be possible for national metrology institutes worldwide, such as the PTB in Germany, to use this mass comparator irrespective of the International Prototype Kilogram (IPK) in Paris / Sèvres as a traceable mass scale for the respective nation. Because everything is based on the kg, the mass determination from milligrams to the tonne can thus be realised in the future using SI spheres.

It speaks for itself that even at the very highest metrological level Sartorius' know-how and technology are trusted.

Figure 2:
Mass comparator
Sartorius CCL1007.

...balances

All balances manufactured by Sartorius are adjusted during production, tested several times and, if applicable (for verified balances) conformity assessed. All these processes are conducted with weights that are regularly calibrated by the in-house calibration laboratory for mass which is accredited by the DAkkS (German Accreditation Body) and that are thus traceable to the national standard. Through the "seamless" (i. e. without a noticeable shift in the values) transition in the redefinition of the kilogram, there will be no change here. At some point after May 20th 2019, if the first reference standard of the calibration laboratory for mass has to be recalibrated, this recalibration will be done at PTB with a formal traceability to a standard according to the new definition; and then, the next time a production weight is recalibrated, this too will be formally traceable to the new definition.

When buying a new balance, it is therefore irrelevant whether the balance is produced (or adjusted / tested / conformity assessed) before or after the 20.05.2019, as a complete and continuous traceability of the weights used is given and the "correctness" of a weight or a scale is not changed by the redefinition. In particular, it is not necessary to wait with the purchase of a balance, "so that it is already compliant with the new definition of the kilogram".
Also with existing balances, the redefinition will not change anything. Regardless of the fact that we recommend to our customers regular calibrations by our service, there is no need for an additional calibration in view of the redefinition of the kilogram.

...weights
Also with calibration of weights, the redefinition of the kilogram will not change anything directly. Neither will an existing calibration certificate of a weight become "invalid" by the new definition, nor the weight itself - to prevent any misconception here: for the end user calibrated weights will remain in the future to be cylinder or knob shaped and not spherical.
Existing weights can therefore continue to be used for testing and quality assurance purposes; regardless of whether they are calibrated or not – although we always recommend the use of calibrated weights for such purposes.
And similarly to the balances, there is no necessity to postpone an intended purchase of a weight to after 20.05.2019.

Figure 3: Class E2 knob weights from the "ProofLine" series from Sartorius.

...mass calibrations
Sartorius operates mass calibration laboratories in several countries with accreditations from the respective national accreditation bodies. In these calibration laboratories, customer weights are compared against reference standards using Sartorius mass comparators. These reference standards are regularly recalibrated at national metrology institutes by comparison with their working standards, and these in turn by the respective metrology institute (possibly over several intermediate steps) with the respective national standard. With weights, the principle of the "traceability chain" can as such be demonstrated very nicely. The national standards generally are also "only" kilogram weights, which so far were compared over reasonably long intervals with the "original kilogram" (the IPK).
After redefining the kilogram, the metrology institutes will gradually either build or purchase primary realisations of the kilogram definition (namely, a kibble balance or a silicon sphere) and calibrate their national standard with it, or will have their national standard calibrated at another national metrology institute. Subsequently, the formal passing of the new definition along the traceability chain is reversed to the order described above: From the national standard, the kilogram (with intermediate steps, if applicable) is passed to working standards, then subsequently from those to reference standards of calibration laboratories and finally from those to customer weights. The requirements set in advance of the redefinition ensure that neither the values nor the uncertainties change systematically as a result of the new definition. Ultimately, the end customer will not even notice whether his weight has been attributed to the original kilogram or already to a primary realisation of the new definition.
As already written above, it is therefore not necessary after 20.05.2019 to send all weights for an unscheduled recalibration, nor does it make sense to wait with a purchase of a new calibrated weight.

...balance calibrations
Sartorius further operates accredited calibration laboratories for balances in several countries. To calibrate balances, usually weights are used that were previously calibrated in a Sartorius calibration laboratory for mass. Thus, the same applies here as in the previous section - since for balances another intermediate step is added in the traceability chain, it will only take a little longer for balances until the end customer gets a balance calibration for the first time, which is formally traceable to a primary realisation according to the new definition. However, also for balances, the customer will not even notice that.

Conclusion

Even if the redefinition of the kilogram on the basis of the Planck constant represents a real paradigm shift and can be considered a milestone in the quest for future-proof, stable and permanently valid definitions of the units, this will definitely not result in any change for the end user. Furthermore, unscheduled new purchases and/or recalibrations of balances or weights due to the new definition are just as unnecessary as a postponement of a new acquisition of a weight or a balance.
Due to careful consideration prior to the redefinition, including the involvement of Sartorius experts, it is ensured that the redefinition does not result in an "offset" of e.g. weighing values, nor will uncertainties increase as a result.
The fact that Sartorius' know-how and technology played a major role in the process of redefinition at several points shows that Sartorius' competence in metrological and technical matters is in demand and recognised at the highest level.

References

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