Kilogram: new definition, selected mises-en-pratique and direct link with SMD activities

"What about Instagram?"

Mieke Coenegrachts
WMD 2018
Outline

- Mass at the SMD - ENS
- Definition of the kilogram
  - Present
  - New
- Practical realization
  - Kibble balance
  - X-ray Crystal Density
- Traceability
Mass at SMD - ENS

- 2 Standard Pt-Ir prototypes kg: n° 28 en n° 37
- 2 Stainless steel standard kg
- Brussels: 1 mg – 20 kg
  - 1 mg to 1 kg with automatic comparators
- Haren: > 20 kg up to 5 ton
CMC’s: Calibration and Measurement Capability

<table>
<thead>
<tr>
<th>Range</th>
<th>CMC</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mg tot 100 mg</td>
<td>1 μg tot 2 μg</td>
<td>OIML klasse E1</td>
</tr>
<tr>
<td>0,1 g tot 1 g</td>
<td>2 μg tot 3 μg</td>
<td>OIML klasse E1</td>
</tr>
<tr>
<td>1 g tot 10 g</td>
<td>3 μg tot 7 μg</td>
<td>OIML klasse E1</td>
</tr>
<tr>
<td>10 g tot 100 g</td>
<td>7 μg tot 15 μg</td>
<td>OIML klasse E1</td>
</tr>
<tr>
<td>0,1 kg tot 1 kg</td>
<td>15 μg tot 150 μg</td>
<td>OIML klasse E1</td>
</tr>
<tr>
<td>1 kg tot 10 kg</td>
<td>0,15 mg tot 5 mg</td>
<td>OIML klasse E1 (1 kg) E2 (10 kg)</td>
</tr>
<tr>
<td>10 kg tot 20 kg</td>
<td>5 mg tot 10 mg</td>
<td>OIML klasse E2</td>
</tr>
<tr>
<td>Haren</td>
<td></td>
<td></td>
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<tr>
<td>20 kg tot 50 kg</td>
<td>100 mg tot 200 mg</td>
<td>OIML klasse F2</td>
</tr>
<tr>
<td>50 kg tot 100 kg</td>
<td>0,7 g tot 2 g</td>
<td>OIML klasse M1</td>
</tr>
<tr>
<td>100 kg tot 1000 kg</td>
<td>2 g tot 10 g</td>
<td>OIML klasse M1</td>
</tr>
<tr>
<td>1000 kg tot 5000 kg</td>
<td>10 g tot 50 g</td>
<td>OIML klasse M1</td>
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</tbody>
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http://economie.fgov.be
International comparison 2018

- EURAMET.M.M- K4.2015, comparison on mass standard 1 kg
- LNE, “comparaison interlaboratoires d’étalons de masse de 1 mg à 10 kg”
- EURAMET Project 1300, Comparison of 500 kg mass standard
Present definition:

- "The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram." (CGPM, 1901) ... immediately after cleaning and washing by a specified method (mise en pratique, CIPM 1989).
The kilogram is the unit of mass:

- represents the mass of 1 dm³ of H₂O at maximum density (4 °C)
- manufactured around 1880
- ratified in 1889
- alloy of 90% Pt and 10% Ir
- cylindrical shape, Ø = h ~ 39 mm
- kept at the BIPM in ambient air

The kilogram is the last SI base unit defined by a material artefact.
Cleaning + Ethanol + Ether + Steam = 1 kg
Calibration history

Official copies Nos. 43 and 47: first calibrated in 1946; all others in 1889.

IPK
Are the check standards getting heavier
or
Is the IPK losing ??

Cool j’ai maigri !
Cool I lost weight !!
Belgian Prototypes Pt Ir 28 en Pt Ir 37
Why change the present definition?

- **Advantages of the present definition**
  - Consistency of mass measurements worldwide
  - Simple
  - Very easy to understand

- **Disadvantages (= reasons to change)**
  - Calibration of the prototypes only every 40 - 50 years
  - Drift of prototypes between calibrations
  - IPK is not an absolute reference, the long-term drift of IPK is unknown
  - Artefact based: Risk (damage, loss)
  - Only accessible at one location, at one nominal value
  - Part of the definition of A, cd and mol
New definition

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 $\Delta v C_s$.

$$h = 6,626\,070\,15 \times 10^{-34} \, kg \, m^2 \, s^{-1}$$

Fixed from nature

Numerical value: determined by Codata

m and s already defined in the SI

To define the kg
How can we realize the new kg definition

- X-ray Crystal Density Method
- Watt or Kibble balance
X-ray Crystal Density (XRCD)

- Used for the determination of the Avogadro constant
  - counting the number of atoms in a $^{28}\text{Si}$-enriched crystal
  - reduction of uncertainty in the values of $N_A$ and $h$ to 2 parts in $10^8$

Method can be used reversely:

- Determination of the mass of a 1 kg sphere prepared from the crystal.

\[ m_{\text{sphere}} = \frac{8 \, M_{\text{Si}} \, V_{\text{sphere}}}{a_0^3 \, N_A} \]
XRCRD

- **Before redefinition** (stable parameters)
  - Molar mass (isotopic composition) \( M \)
  - Crystal perfection (impurity content)
  - Lattice parameter \( a \)

  Measured only once

- **After redefinition** (changing parameters)
  - Surface layer characterization
  - Volume \( V \)

  Measured for each primary realization

\[
m_{\text{sphere}} = \frac{8 M_Si \ V_{\text{sphere}}}{a^3_0 \ N_A}
\]
Volume V

- Calculated from the measured mean diameter
- Silicon crystals are covered with thin oxide layers
- Evaluation volume without the surface layers

\[
\text{difference between the maximum and minimum diameters: } \quad = 39 \text{ nm}
\]
Manufacturing of the sphere

$^{28}\text{Si single crystal}$:
Kibble balance route

- Determine the numerical value of $h$ in the present SI

  Other Si base units $s$ and $m$

  Present definition of the kilogram

  Planck constant, $h$

- Redefine the kilogram by fixing this numerical value

  Fixed value for Planck constant

  New definition of the kilogram

- Use the fixed Planck constant to realize the kilogram
KB Principle: static phase / weighing mode

Weight of a unknown mass is compared with the force on a coil in a magnetic field

\[ mg = -I \frac{d\Phi}{dz} \]

In a radial magnetic field, this can be simplified to

\[ mg = I B L \]

\[ F_{el} = I B L \]

\[ F_m = m g \]
KB Principle: dynamic phase / velocity mode

Coil is moved through the magnetic field and a voltage is induced.

\[ U = -v \frac{d\Phi}{dz} \]

In a radial magnetic field, this can be simplified to

\[ U = B L v \]

- \( U \): Induced voltage
- \( B \): Magnetic flux density
- \( L \): Wire length
- \( v \): Velocity
Watt balance equations:

- **Static phase**
  \[ mg = I B L \]

- **Dynamic phase**:
  \[ U = B L \nu \]

- If B, L constant:
  \[ U I = m g \nu \]

\[ P_{el} = P_{mech} \]
Link between the kg and the Planck constant

\[ P_{el} = UI = \frac{U_1 U_2}{R} \]

**Josephson effect**

\[ U = u' f_j \frac{h}{2 e} = u' \frac{f_j}{K_j} \]

**Quantum Hall effect**

\[ R = r' \frac{h}{e^2} = r' R_K \]

\[ UI = \frac{U_1 U_2}{R} = C_{elf_1f_2} h = m g v \]

Before redefinition

\[ h = \frac{m g v}{C_{elf_1f_2}} \]

After redefinition

\[ m = \frac{C_{elf_1f_2}}{g v} h \]
The projects around the world

NRC - Canada

NIM - China

METAS - Swiss

MSL - New Zealand

KRISS - Korea

http://economie.fgov.be
LNE/CNAM - France

BIPM

UME - Turkey

NPL - GB
Traceability

International Prototype Kilogram
U = 0 µg

Mass comparison
Nat. Primary standard (Pt/Ir)
u = 4 µg

Mass comparison + air buoyancy
NMI secondary standard (SS)
u = 12 µg

Mass comparison
End user reference standard (SS)
u = 15 µg

Kibble balance/XRCD in vacuum
Target u = 10 µg

Vacuum/ vacuum transfer
Vacuum / air transfer
Vacuum / inert gas transfer
u = 10 µg

Air/vacuum transfer
Nat. standard
u = 15 µg

Mass comparison + air buoyancy
NMI secondary standard (SS)
u = 20 µg

Mass comparison
End user reference standard (SS)
u = 25 µg

Vacuum/ air transfer
Local set of reference standards
u = 15 µg

Temporary use of a consensus value for h!

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Thank you for your attention.