The origins and history of the International System of Units, SI

Terry Quinn

The 24th General Conference on Weights and Measures (CGPM) *

Resolution 1

On the possible future revision of the International System of Units, the SI

The 24th CGPM,

Considering

- the international consensus on the importance, value, and potential benefits of a redefinition of a number of units of the International System of Units (SI),
- that the national metrology institutes (NMIs) as well as the International Bureau of Weights and Measures (BIPM) have rightfully expended significant effort during the last several decades to advance the International System of Units (SI) by extending the frontiers of metrology so that SI base units can be defined in terms of the invariants of nature − the fundamental physical constants or properties of atoms,
- that a prominent example of the success of such efforts is the current definition of the SI unit of length, the metre (17th CGPM, 1983, Resolution 1), which links it to an exact value of the speed of light in vacuum *c,* namely, 299 792 458 metre per second,

* October 2011

RAPPORT

FAIT À L'ACADÉMIE DES SCIENCES,

Sur le choix d'une unité de Mesures.

Par MM. BORDA, LAGRANGE, LAPLACE, MONGE & CONDORCET.

L'IDÉE de rapporter toutes les mesures à une unité de longueur prise dans la nature, s'est présentée aux mathématiciens dès l'instant où ils ont connu l'existence d'une telle unité & la possibilité de la déterminer. Ils ont vu que c'étoit le seul moyen d'exclure tout arbitraire du système des mesures, & d'être sûr de le conserver toujours le même, sans qu'aucun autre événement, qu'aucune révolution dans l'ordre du monde y jeter de l'incertitude; ils ont senti qu'un tel système n'appartenant exclusivement à aucune nation, on pouvoit se flatter de le voir adopter par toutes. *19 mars 1791.*

En effet, si on prenoit pour unité une mesure déjà usitée dans un pays, il seroit difficile d'offrir aux autres des motifs de préférence capables de balancer l'espèce de répugnance, sinon philosophique, du moins très-naturelle, qu'ont les peuples pour une imitation qui paroît toujours l'aveu d'une sorte d'infériorité : il y auroit donc au moins autant de mesures que de grandes nations. D'ailleurs, quand même presque toutes auroient adopté une de ces bases arbitraires, mille événemens faciles à prévoir, pourroient faire naître des incertitudes sur la véritable grandeur de cette base; & comme il n'existeroit point de moyen rigoureux de vérification, il s'établiroit à la longue des différences entre les mesures. La diversité qui existe

“The idea of referring all measurements to a unit of length taken from nature was seized upon by mathematicians as soon as the existence of such a unit and the possibility of determining it became known. They saw it as the only way to exclude all that was arbitrary from a system of measurement and to conserve it unchanged, so that no event or revolution in the world could cast uncertainty upon it.

They felt that with such a system, belonging exclusively to no one nation, one could hope that it would be adopted by all.”

aujourd'hui entre celles qui ſont en uſage dans les divers pays, à moins pour cauſe une diverſité originaire qui remonte à l'époque de leur établiſſement, que des altérations produites par le temps. Enfin, on gagneroit peu, même dans une ſeule nation, à conſerver une des unités de longueur qui y ſont uſitées; il n'en faudroit pas moins corriger les autres vices du ſyſtème des meſures, & l'opération entraîneroit une incommodité preſque égale pour le plus grand nombre.

On peut réduire à trois les unités qui paroiſſent les plus propres à ſervir de baſe; la longueur du pendule, un quart du cercle de l'équateur, enfin un quart du méridien terreſtre.

La longueur du pendule a paru en général mériter la préférence. Elle préſente l'avantage d'être plus facile à déterminer & par conſéquent à vérifier, ſi quelques accidens arrivés aux étalons en amenoient la néceſſité. De plus, ceux qui voudroient adopter cette meſure déjà établie chez un autre peuple, ou qui après l'avoir adoptée auroient beſoin de la vérifier, ne ſeroient pas obligés d'envoyer des obſervateurs à l'endroit où la première opération auroit été faite.

En effet, la loi des longueurs du pendule eſt aſſez certaine, aſſez confirmée par l'expérience pour être employée dans les opérations ſans avoir à craindre que des erreurs imperceptibles. Quand même d'ailleurs on ne voudroit pas avoir égard à cette loi, on ſent qu'une comparaiſon de la différence de longueur entre les pendules une fois exécutée, pourroit toujours être vérifiée, & qu'ainſi l'unité de meſure deviendroit invariable pour tous les lieux où cette comparaiſon auroit été faite; ainſi l'on y pourroit réparer immédiatement l'altération accidentelle des étalons, ou y déterminer la même unité de meſure à quelqu'époque que l'on prît la réſolution de l'adopter. Mais nous verrons dans la ſuite qu'on peut rendre ce dernier avantage commun à toutes les meſures naturelles, &

“One can reduce to three the units that seem most appropriate as the base;

the length of a pendulum, the quarter of the length of the equator and finally the length of a quarter of a meridian.

The length of a pendulum has the advantage of being the easiest to determine and, in consequence, the easiest to verify if some accident happens that renders it necessary.

Furthermore, those who wish to adopt this measure already adopted by another country, or having adopted it wish to verify it, would not obliged to send observers to the place where it was originally established.

In addition, the law of the length of a pendulum is well known, confirmed by experiment and can be used without fearing small errors.”

The Metre and Kilogram of the Archives

Photo TJQ

Label on the case containing the Metre of the Archives

In conformity with the law of the 18th Germinal an 3 (7 April 1795). Presented on 4th Messidor an 7 (22 June 1799)
(made by) F. P. Lenoir

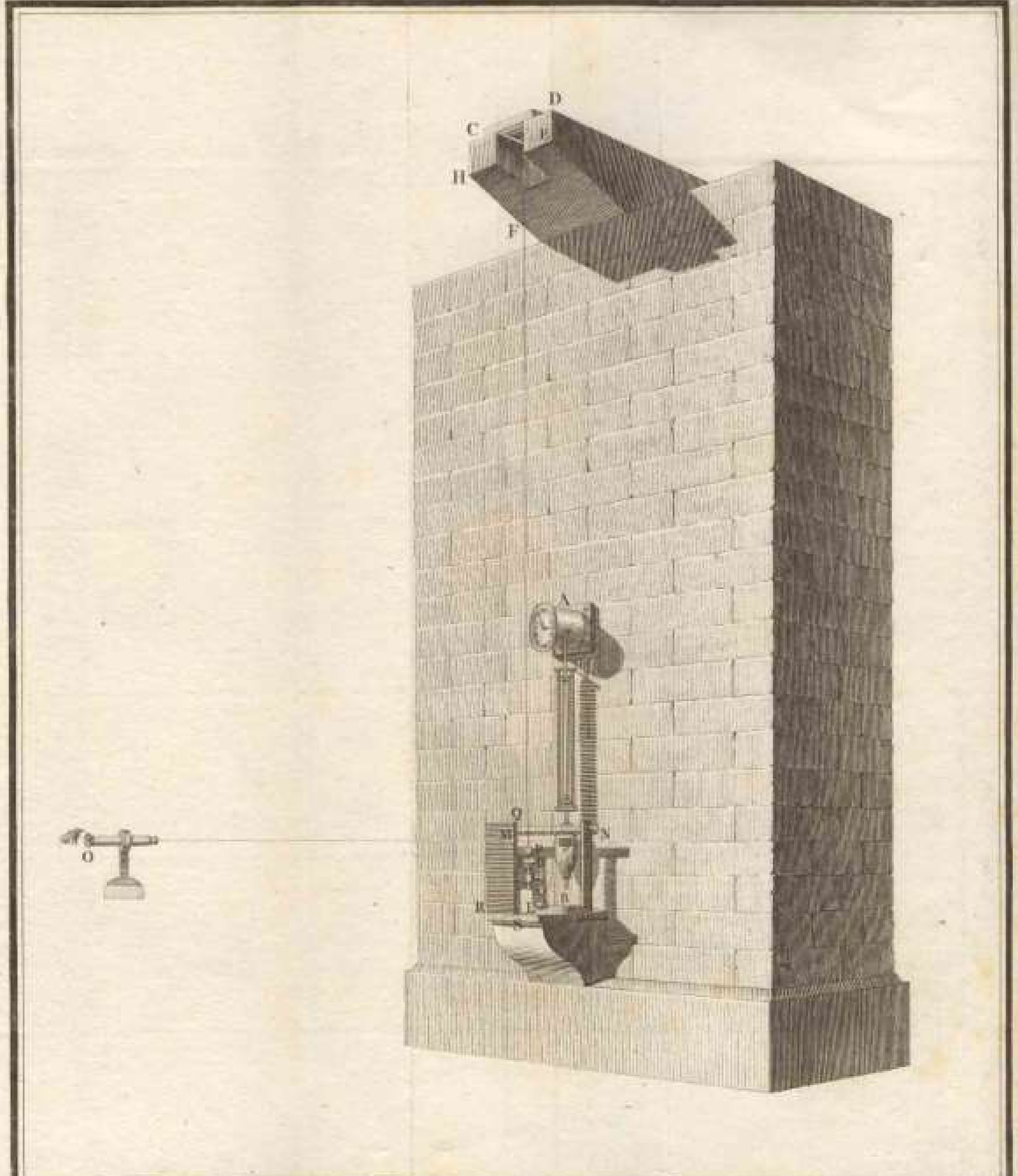
Photo TJQ

Label on the case containing the Kilogram of the Archives

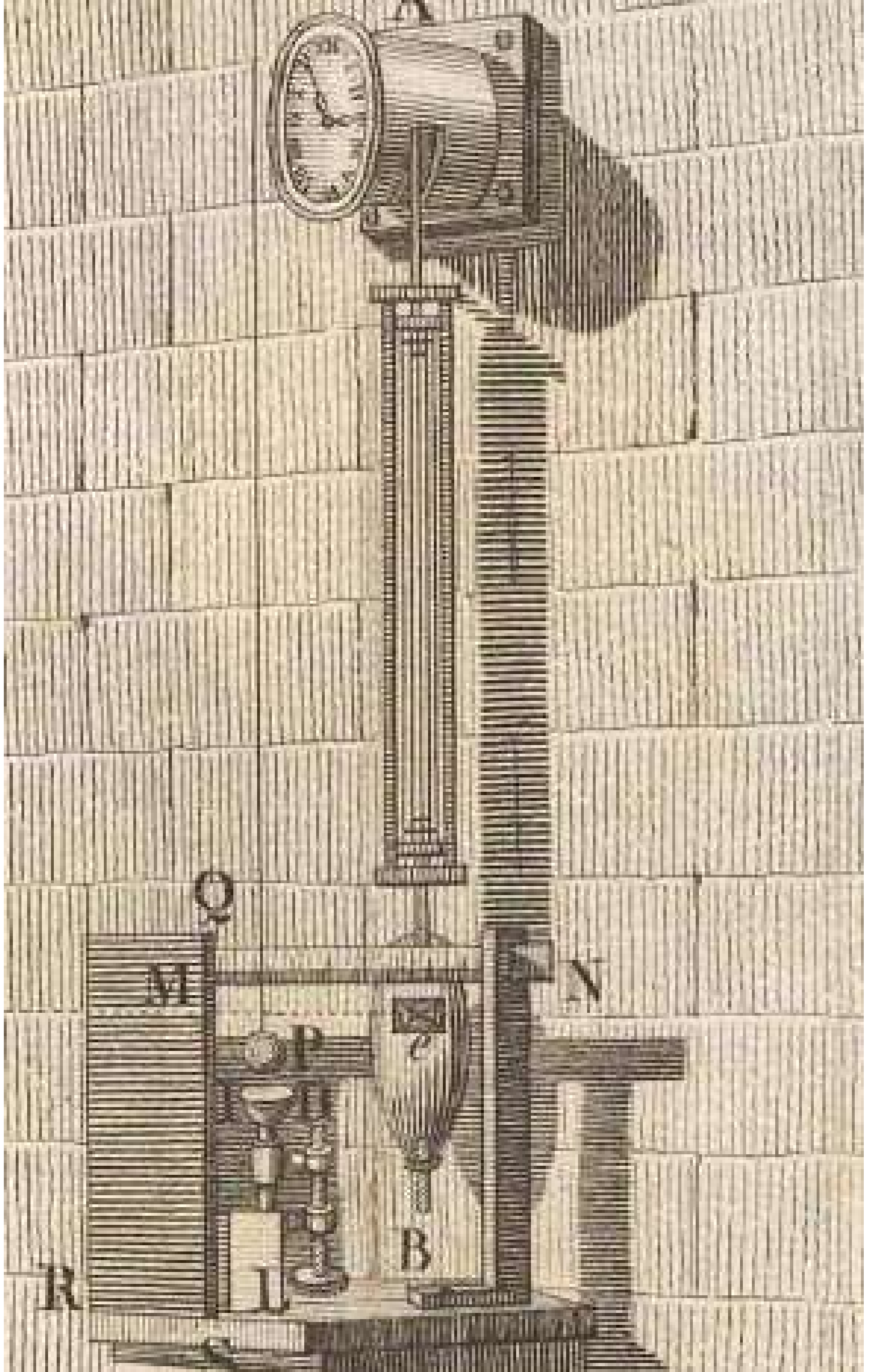
In conformity with the law of the 18th Germinal an 3 (7 April 1795). Presented on 4th Messidor an 7 (22 June 1799)
(made by) F. Fortin

Photo TJQ

Photo TJQ



Gravé par E. Collin, Quai des Augustins, N.° 5.



A
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M
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P
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B
R
L

Tableau des vingt expériences.

	Durée des comparaisons.	État des thermom.	Longueurs du pendule.	Différ. avec les résultats moyens.
	H. M.	D.	Parties.	Parties.
Première suite	4 53	16·1	50999·09	+ 0·49
	3 36	16·6	50999·45	— 0·15
	4 48	17·3	50999·78	+ 0·18
	3 33	18·0	50999·25	— 0·35
	4 53	16·4	50999·88	+ 0·28
	4 51	16·0	50999·67	+ 0·07
Seconde suite, la boule suspendue par un point diamétralement opposé au 1er.	4 49	17·5	50999·57	— 0·03
	4 46	18·6	50999·74	+ 0·14
	4 44	19·4	50999·79	+ 0·17
Troisième suite, la boule suspendue par un point placé à 90° des premières	4 48	18·0	50999·33	— 0·27
	4 56	18·2	50999·14	— 0·46
	4 48	20·0	50999·63	+ 0·03
	4 47	20·8	50999·81	+ 0·21
Quatrième suite, la boule suspendue par un point diamétralement opposé au précédent	4 49	20·6	50999·55	— 0·05
	4 46	21·0	50999·30	— 0·30
	4 48	21·0	50999·46	— 0·14
	4 46	21·6	50999·81	+ 0 21
Cinquième suite, le point de suspension étant le même que dans la troisième suite.	5 14	18·2	50999·53	— 0·07
	5 14	17·1	50999·29	— 0·31
	5 2	21·6	50999·90	+ 0·30
Résultat moyen			50999·60	

Relative standard deviation about the mean: 5 ppm!

Taken from *Base du Système métrique* by J-B Delambre

The Metre and Kilogram of the Archives

Photo TJQ

The Second International Conference for the Measurement of Degrees in Europe
Berlin October 1867 (the first having been in Berlin in 1864)

The Conference made 10 Recommendations:

1. On the need to compare standards of length and obtain new comparators
2. Set up a special commission to oversee this
3. Start research on the time variation of thermal expansion coefficients of standards
4. In everyone's interest to have a single system of weights and measures in Europe
5. Recommends the metric system
6. Recommends the metric system without change, opposes the metric foot
7. **Recommends the construction of a new European prototype of the metre to be based on the Metre of the Archives**
8. Construction to be entrusted to an international commission
9. **Recommends the creation of a European international bureau of weights and measures**
10. Recommends delegates to bring these Recommendations to the attention of their governments.

The metre is equal to one ten millionth part of the quarter of the terrestrial meridian

The kilogram is equal to the mass of a decimetre cube of water at the temperature of melting ice

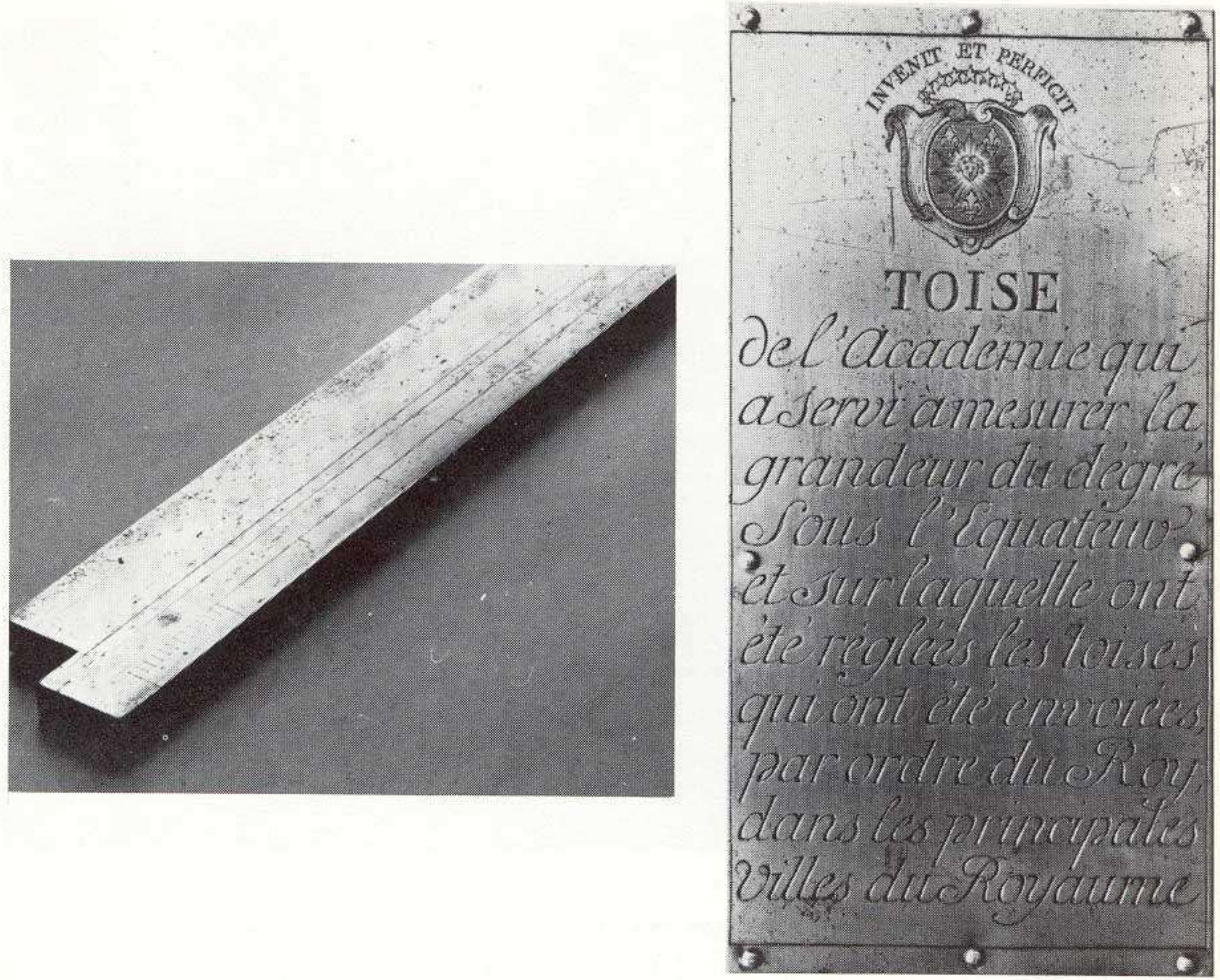
The quarter of the terrestrial meridian , deduced from the measurements of Pierre-Francois Méchain and Jean- Baptiste Delambre, was:

5 130 740 toise du Pérou, thus

1 mètre = 443,296 lignes of the toise du Pérou

What was the definition of the metre?

Photo TJQ



"Toise du Pérou" from the "Académie," conserved in the "Observatoire de Paris." On the right, the plate attached to the case.

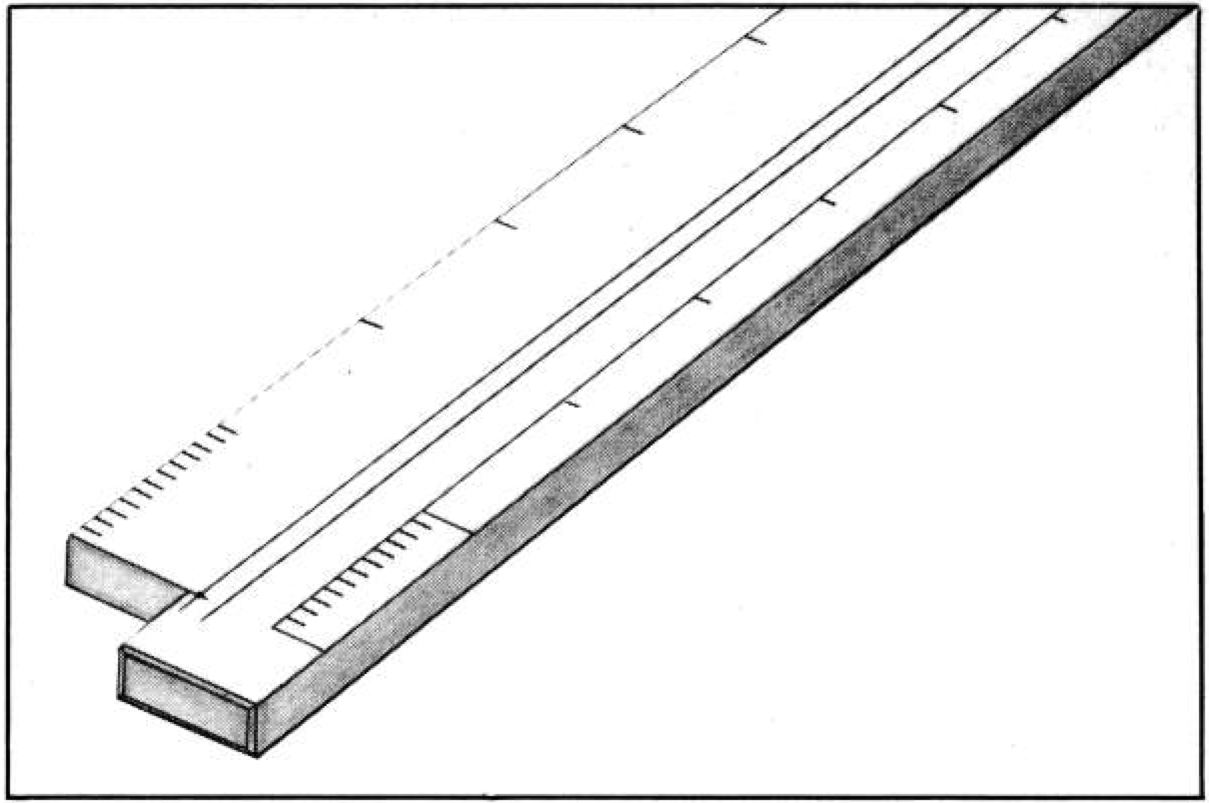


Fig. 1. — L'une des extrémités de la Toise du Pérou ou de l'Académie (1735).

La division comprend un premier intervalle de 1 pouce (27,07 mm*) subdivisé en 12 lignes (2,256* mm*) puis cinq intervalles de 1 pouce et ensuite des intervalles de 3 en 3 pouces jusqu'à l'autre extrémité. On voit aussi l'un des points de la «Toise à points».*

Le couvercle de la boîte de cet étalon porte l'inscription Toise de l'Académie qui a servi à mesurer la grandeur du dégré sous l'Equateur et sur laquelle ont été réglées les toises qui ont été envoiées, par ordre du Roy, dans les principales villes du Royaume, *précédée d'une gravure d'armoiries avec la devise* Invenit et Perficit.

Defined at 13^o Réaumur equal to 16.25 ^{o}C

The kilogram is the mass of one cubic decimetre of water at the temperature of melting ice.

The kilogram is the mass of the Kilogram of the Archives.

What was the definition of the kilogram?

Photo TJQ

The vault of the prototypes containing the International prototypes of the metre and the Kilogram plus their official copies. This was replaced by a modern safe in the 1990s

Photo BIPM

The International Prototype of the Kilogram K

No. III of a set of three made by Johnson-Matthey in London in 1879, chosen as the one closest in mass to that of the Kilogram of the Archives

Photo TJQ

The storage and carrying case of prototype metres

Photo BIPM

This subject is one in which we, as a scientific body, take a warm interest; and you are all aware of the vast amount of scientific work which has been expended, and profitably expended, in providing weights and measures for commercial and scientific purposes.

The earth has been measured as a basis for a permanent standard of length, and every property of metals has been investigated to guard against any alteration of the material standards when made. To weigh or measure any thing with modern accuracy, requires a course of experiment and calculation in which almost every branch of physics and mathematics is brought into requisition.

Yet, after all, the dimensions of our earth and its time of rotation, though, relatively to our present means of comparison, very permanent, are not so by any physical necessity. The earth might contract by cooling, or it might be enlarged by a layer of meteorites falling on it, or its rate of revolution might slowly slacken, and yet it would continue to be as much a planet as before.

But a molecule, say of hydrogen, if either its mass or its time of vibration were to be altered in the least, would no longer be a molecule of hydrogen.

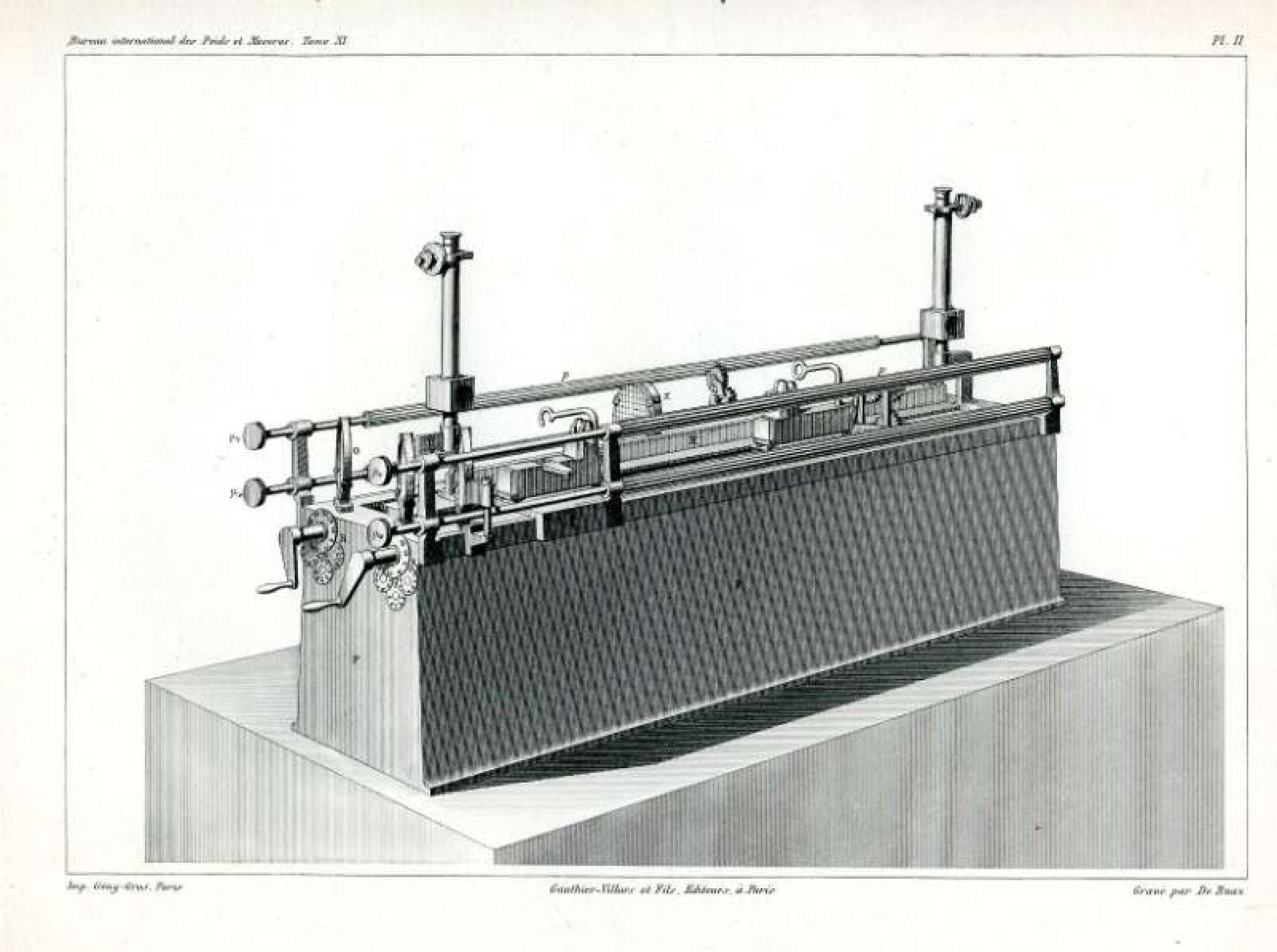
If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wave-length, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.

When we find that here, and in the starry heavens, there are innumerable multitudes of little bodies of exactly the same mass, so many, and no more, to the

James Clerk Maxwell,
British Association for the Advancement of Science, Liverpool, 1870

"From the very beginning of the International Committee it has been generally recognized to be of fundamental importance to determine the relation between the metric units and some basic fundamental constants that one can deduce from natural phenomena".

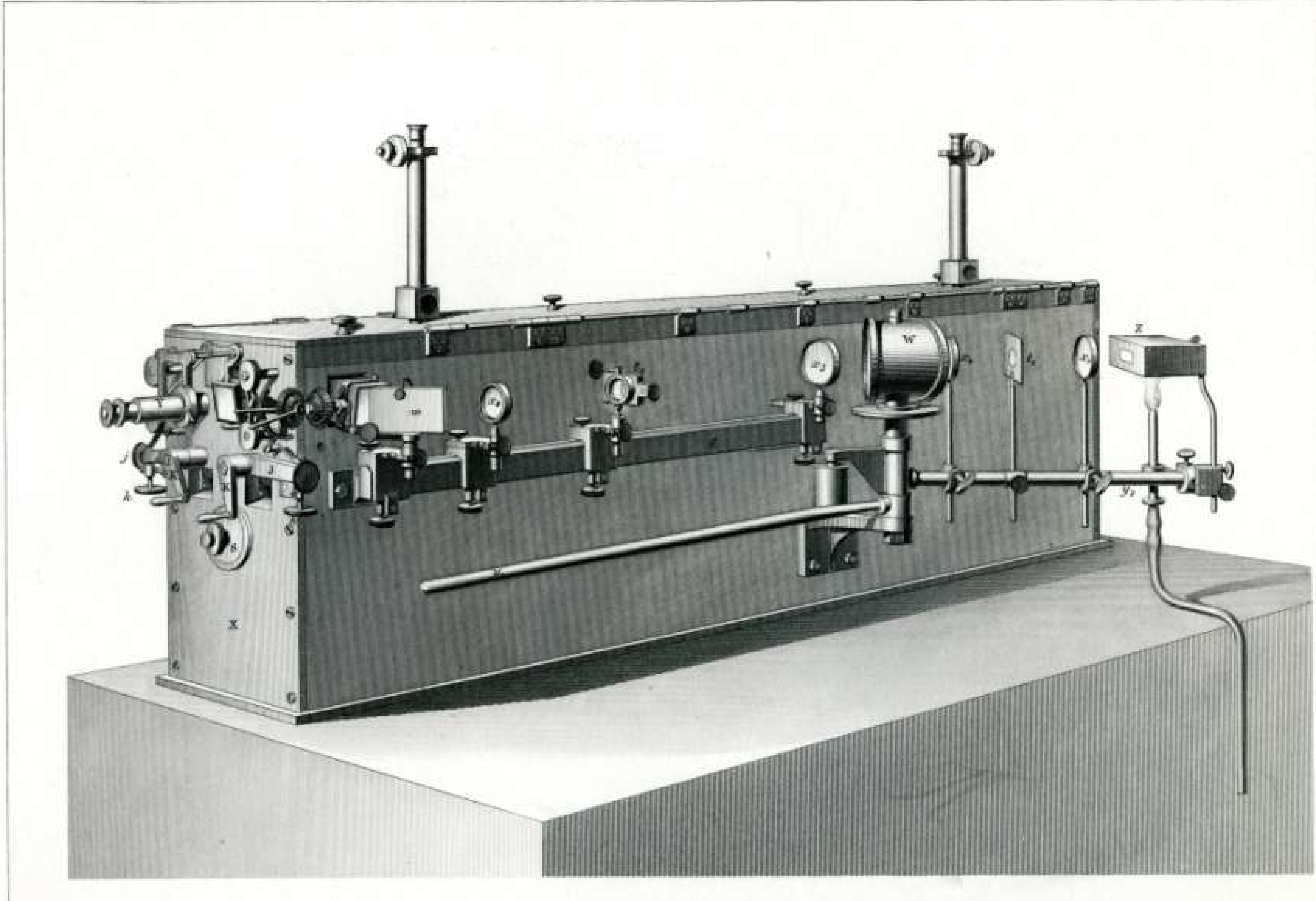
Extract from report of the 1891 meeting of the International Committee for Weights and Measures when it was decided to invite A.A. Michelson to come to the BIPM to measure the wavelength of the red light of cadmium in terms of the International prototype of the metre.



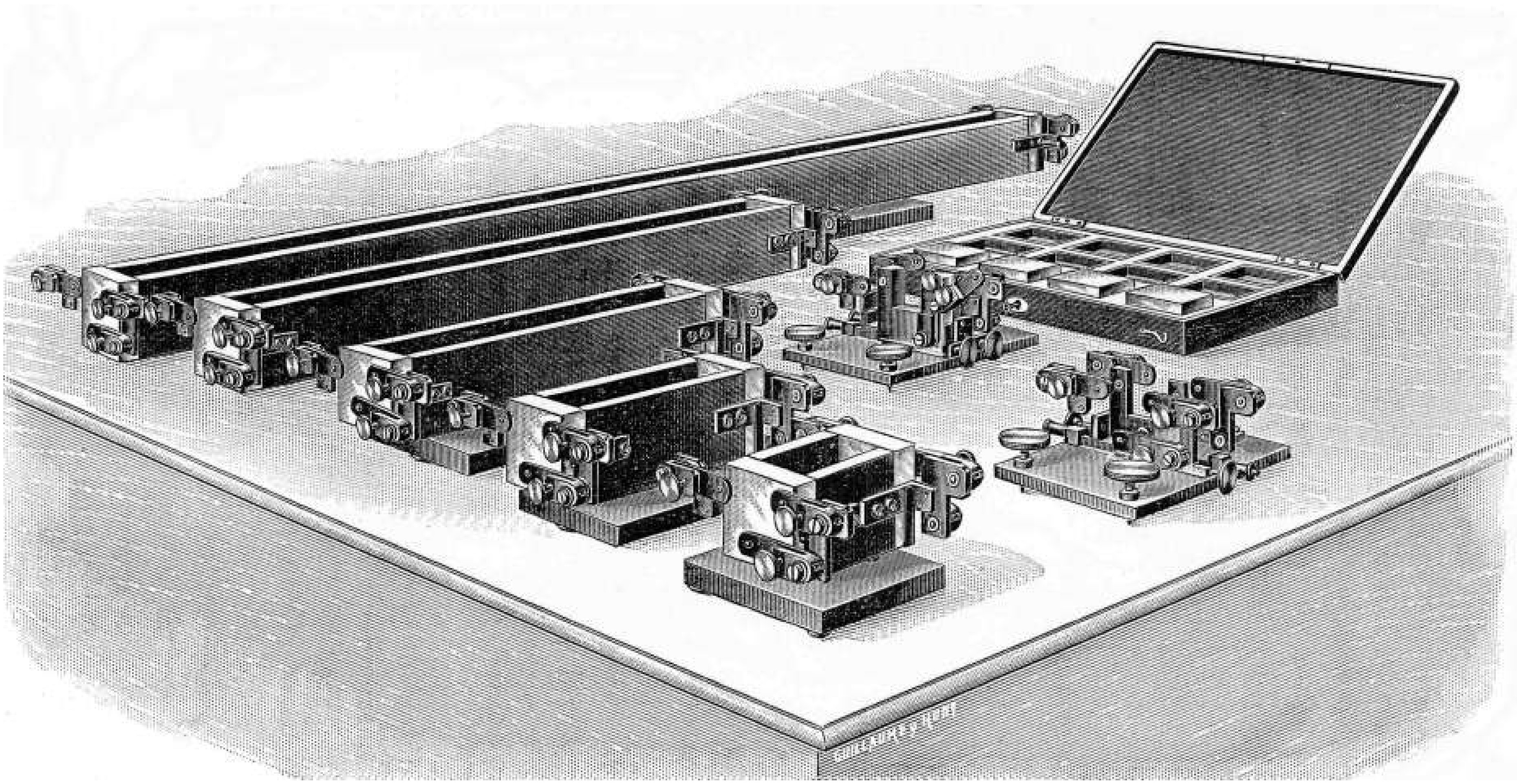
Interferometer built and used at the BIPM in 1892 by A. A. Michelson for the measurement of the metre in terms of the wavelength of the red radiation of cadmium

1 metre = 1 553 164.13 λ_R

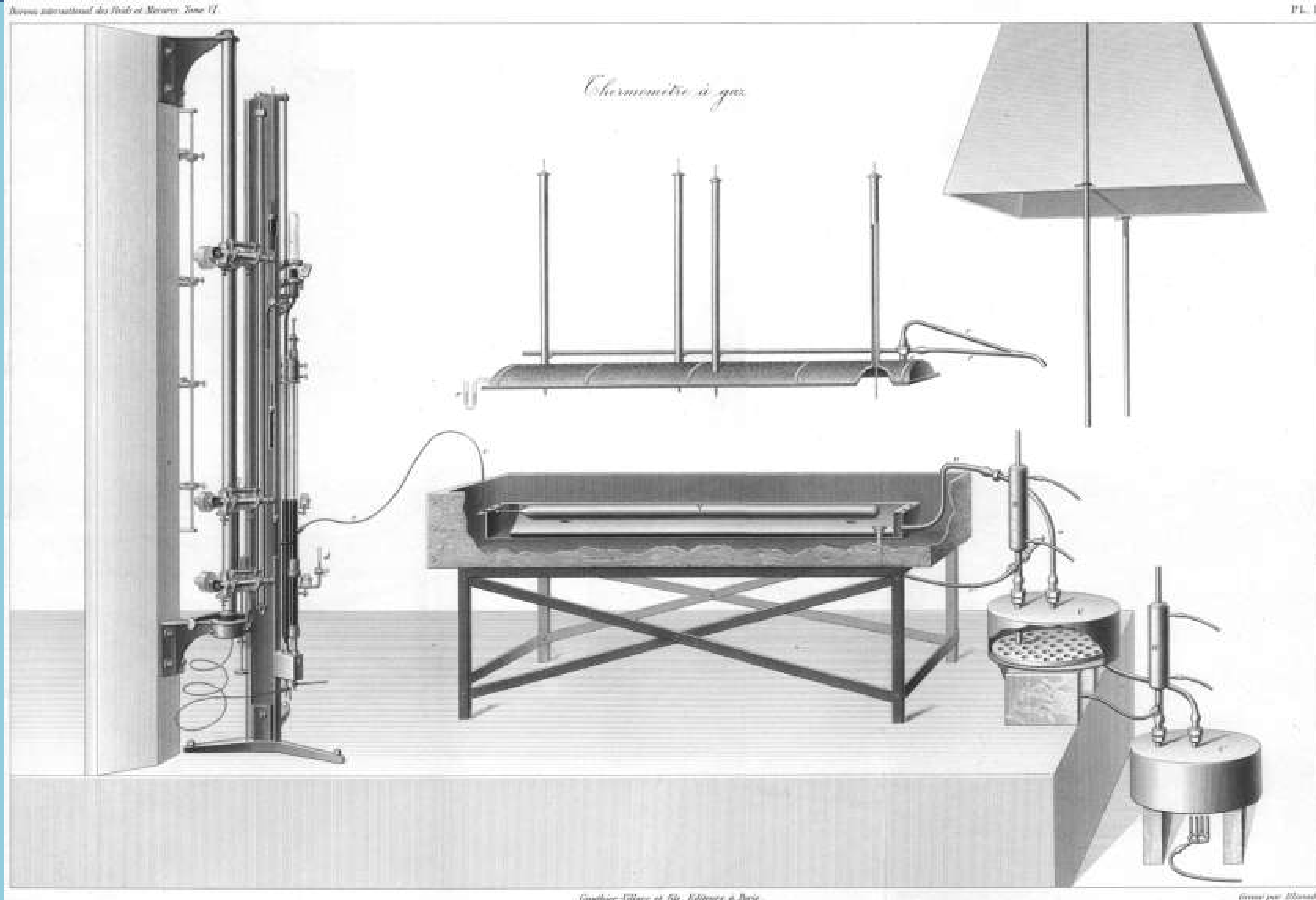
Image BIPM



Imp. Geny-Gros, Paris
Gauthier-Villars et Fils, Editeurs, à Paris
Gravé par De Ruaz.



Etalons used by Benoît, Fabry and Perot in their wavelength determinations.



The constant volume gas thermometer used at the BIPM to establish the normal hydrogen scale between -25 ^{o}C and + 100 ^{o}C adopted by the International Committee in 1887. This was the first internationally agreed thermodynamic temperature scale. This was followed in 1927 by the first international practical scale, the ITS-27.

Image BIPM

As for electrical units, the story is well known

International agreement began with the 1881 Paris Congress of Electricians which led up to the 1908 London Conference which adopted the international practical units.

The main activity of the Consultative Committee for electricity created in 1927 and meeting many times in the 1930s, was the move from practical to absolute electrical units working in collaboration with the SUN commission of IUPAP.

As to which should be the base unit for electrical quantities, the ampere or the ohm, this was finally settled at the 10th General Conference in 1954 in favour of the ampere.

The new system, which is the one we have now, came into force on 1 January 1948 with the ampere being defined so as to fix the value of the magnetic constant, μ_0 at $4\pi \times 10^{-7}$ N A^{-2}

In 1948 at the 9th General Conference the first moves were made, at the suggestion of IUPAP, to define formally an International system of Units.

This finally came to fruition in 1960 with the adoption of the SI by the 10th General Conference.

At this same Conference the metre was finally re-defined in terms of the wavelength of light and twenty three years later was again redefined in terms of a fixed numerical value for the speed of light.

The unit of time, the second had been defined until 1954 as simply 1/86 400 of the mean solar day. When this was shown in the 1930s and 1940s not to be sufficiently stable it was redefined in 1954 as a fraction of the tropical year 1900, very much an astronomers definition!

It resulted in the problems we now have with the leap second.

The atomic definition we have today was adopted in 1967 by the 13th General Conference.

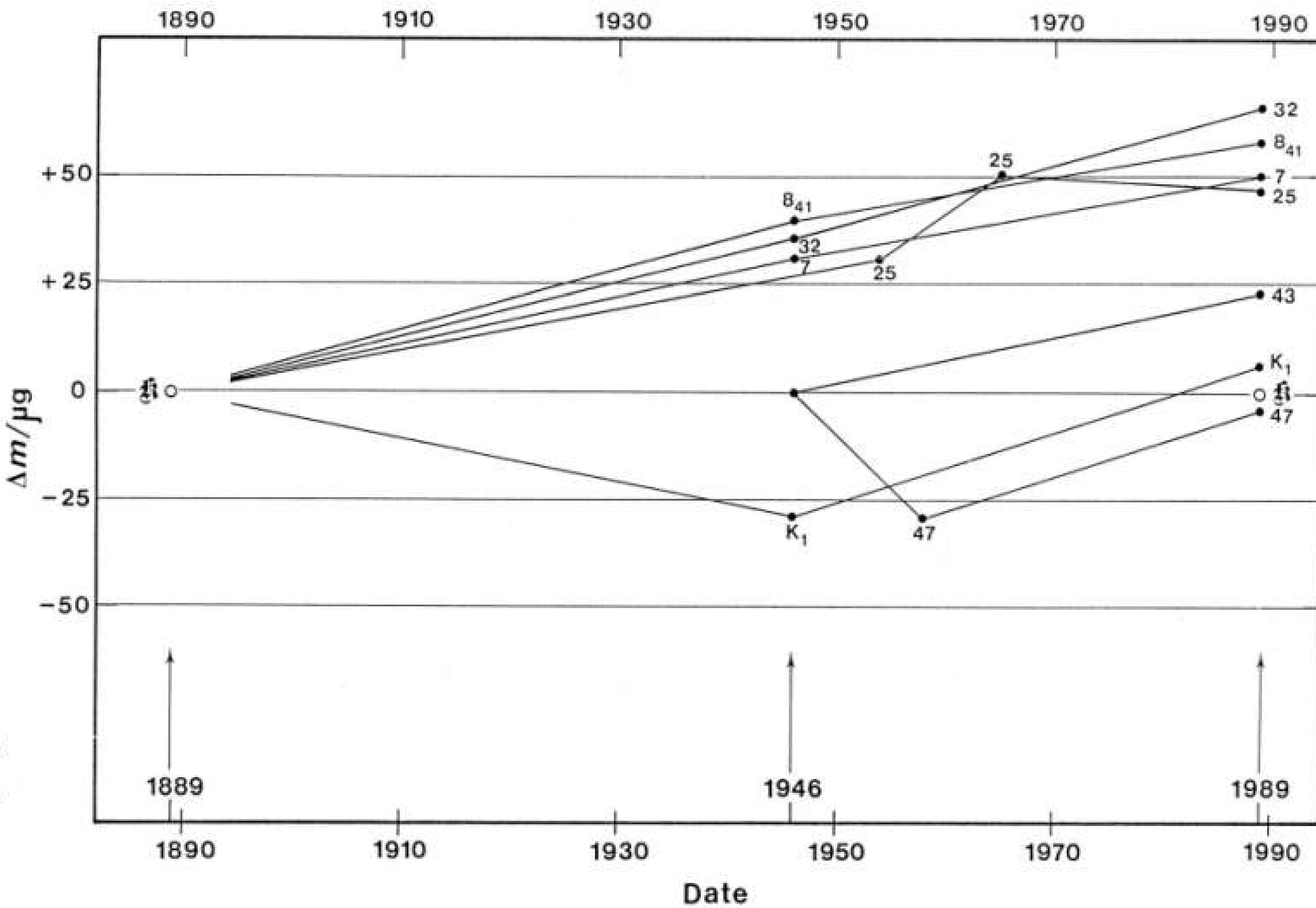
In 1971, when introducing the definition of the mole to the
14th CGPM, Jan de Boer said:

Naturally, one might ask also in the case of the mole would it not be preferable to replace the definition of the mole given here by a molecular one; but as in the cases of the unit of mass and of electric current this would require determinations such as the absolute counting of molecules or the measurement of the mass of molecules that are not possible with the required precision.

and about electrical units:

Here again one could imagine the elementary charge of the proton as the natural and fundamental electrical unit to serve as the base of a universal system of units; but in this case as well it is the requirements of metrology that render such a proposition impracticable for the high precision measurement of electrical quantities, and he added:

As far as the unit of mass is concerned, the choice of an atomic definition, for example the mass or a proton or the unified atomic mass unit would seem natural; but such a proposal seems to me still a far cry from practical because of the necessity of determining to high precision the mass of the proton,



1890
1910
1930
1950
1970
1990
+50
+25
0
−25
−50
Δm/μg
32
8₄₁
25
7
25
8₄₁
32
7
25
43
K₁
47
K₁
47
1889
1946
1989
Date

Fig. 5

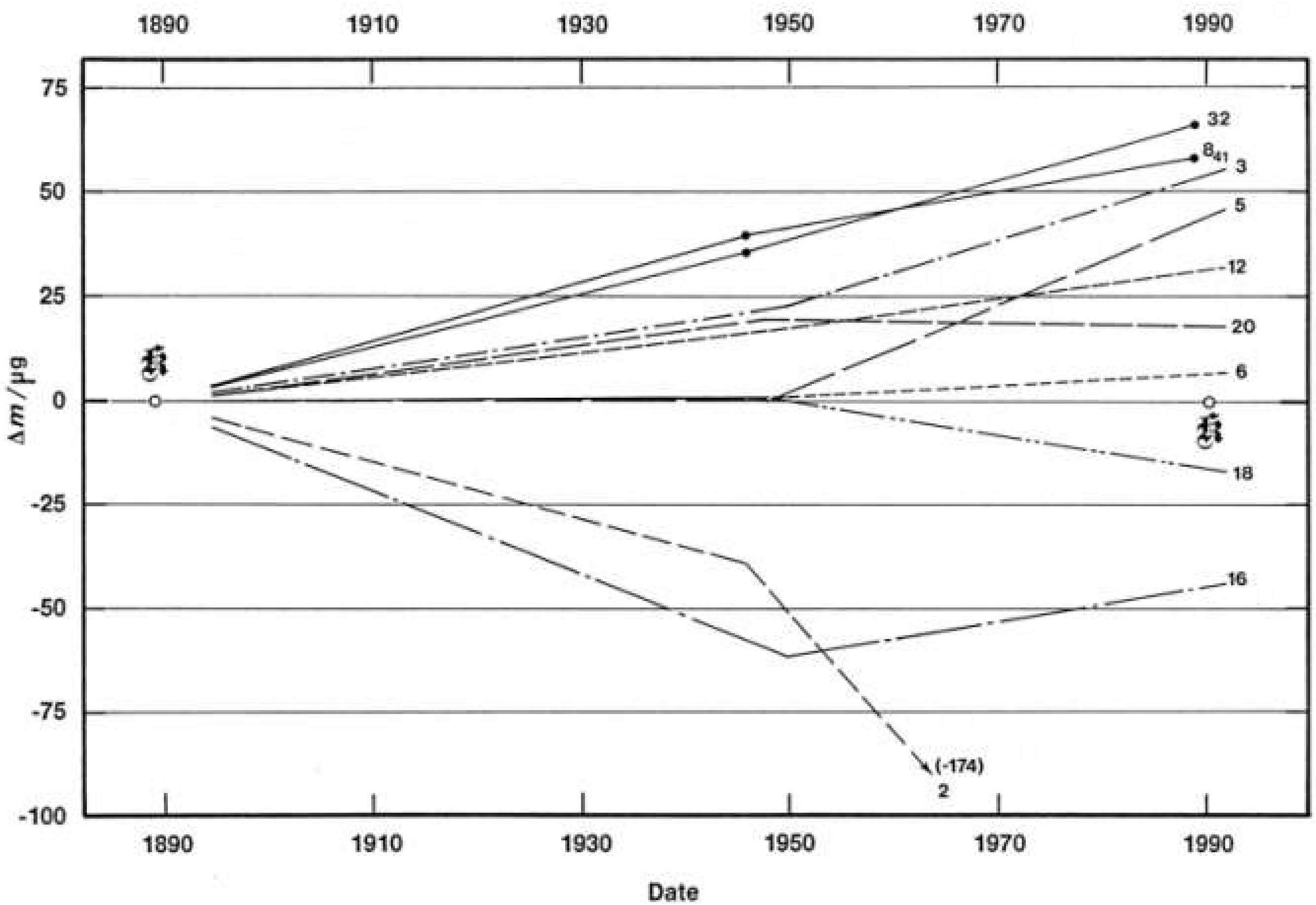

1890
1910
1930
1950
1970
1990
75
50
25
0
-25
-50
-75
-100
Δm / μg
32
8
41
3
5
12
20
6
18
16
(-174)
2
Date

Fig. 6

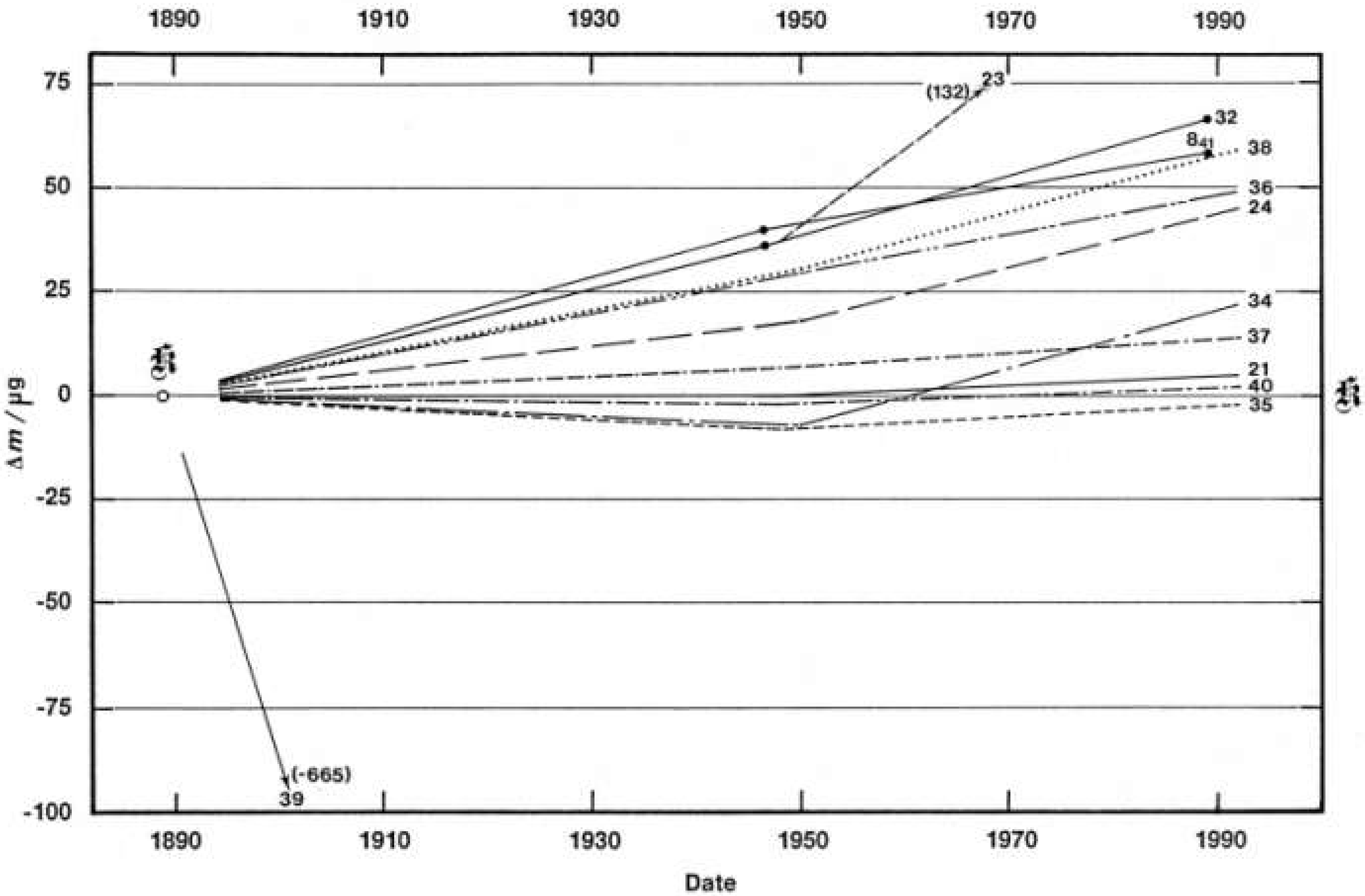

1890
1910
1930
1950
1970
1990
75
50
25
0
-25
-50
-75
-100
Δm / μg
(132)
23
32
8
41
38
36
24
34
37
21
40
35
(-665)
39
Date

Fig. 7

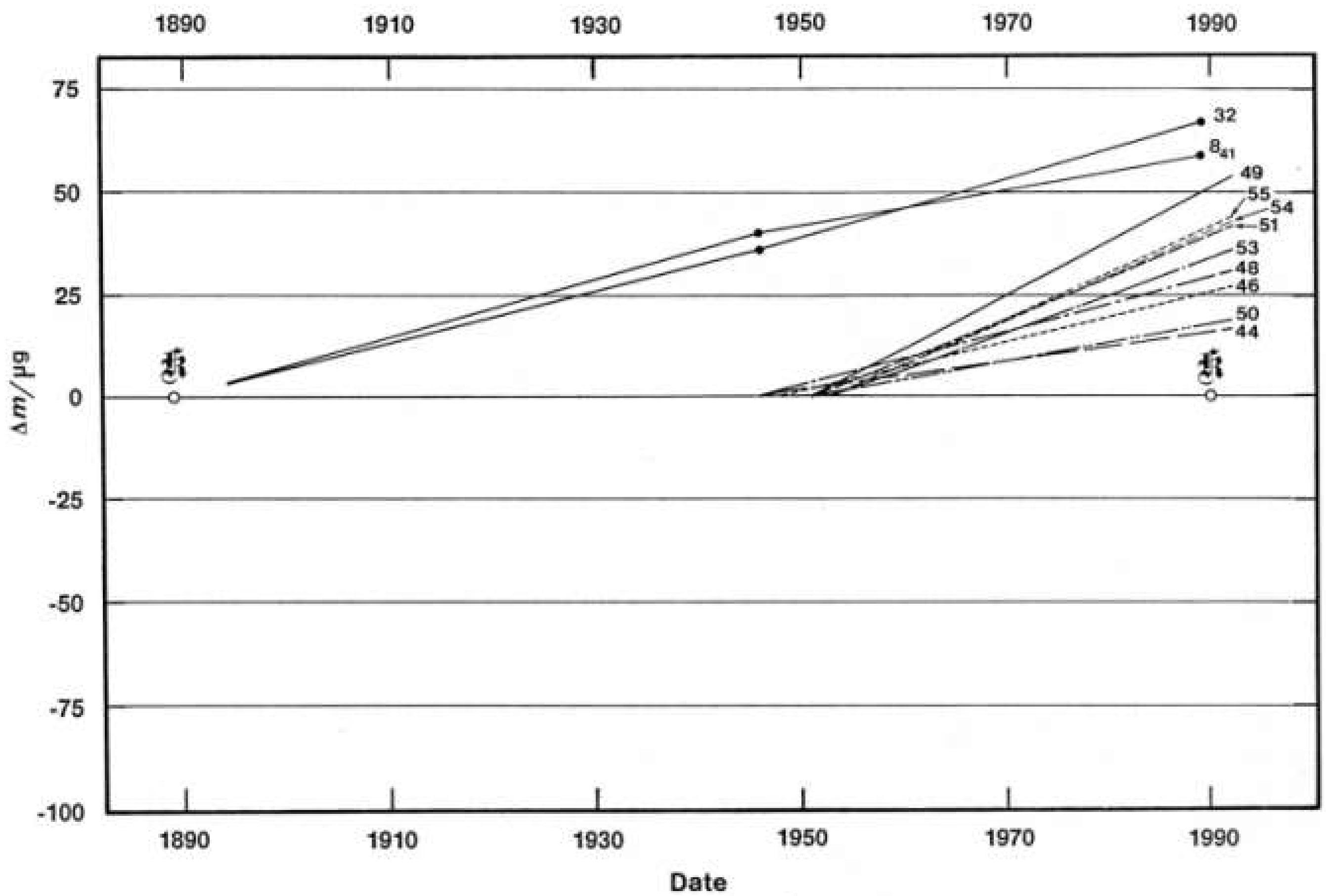

1890
1910
1930
1950
1970
1990
75
50
25
0
-25
-50
-75
-100
Δm/μg
32
8
41
49
55
54
51
53
48
46
50
44
Date

Fig. 8

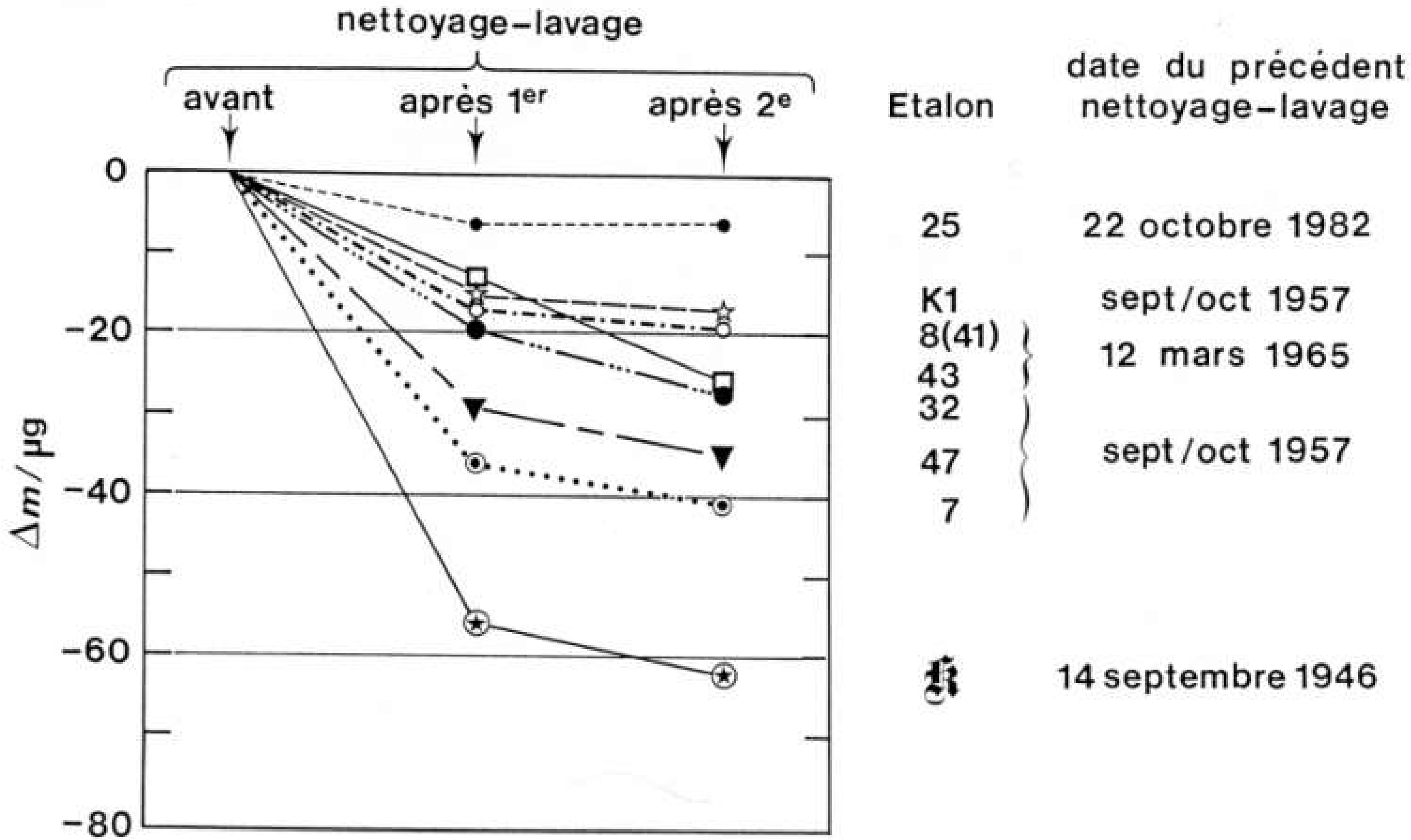

nettoyage–lavage
avant
après 1er
après 2e
0
–20
–40
–60
–80
Δm / μg
Etalon
date du précédent nettoyage–lavage
25
22 octobre 1982
K1
sept/oct 1957
8(41)
43
12 mars 1965
32
47
7
sept/oct 1957
14 septembre 1946

Fig. 2

Change in mass of Pt-Ir kilograms immediately after washing and cleaning using the BIPM procedure

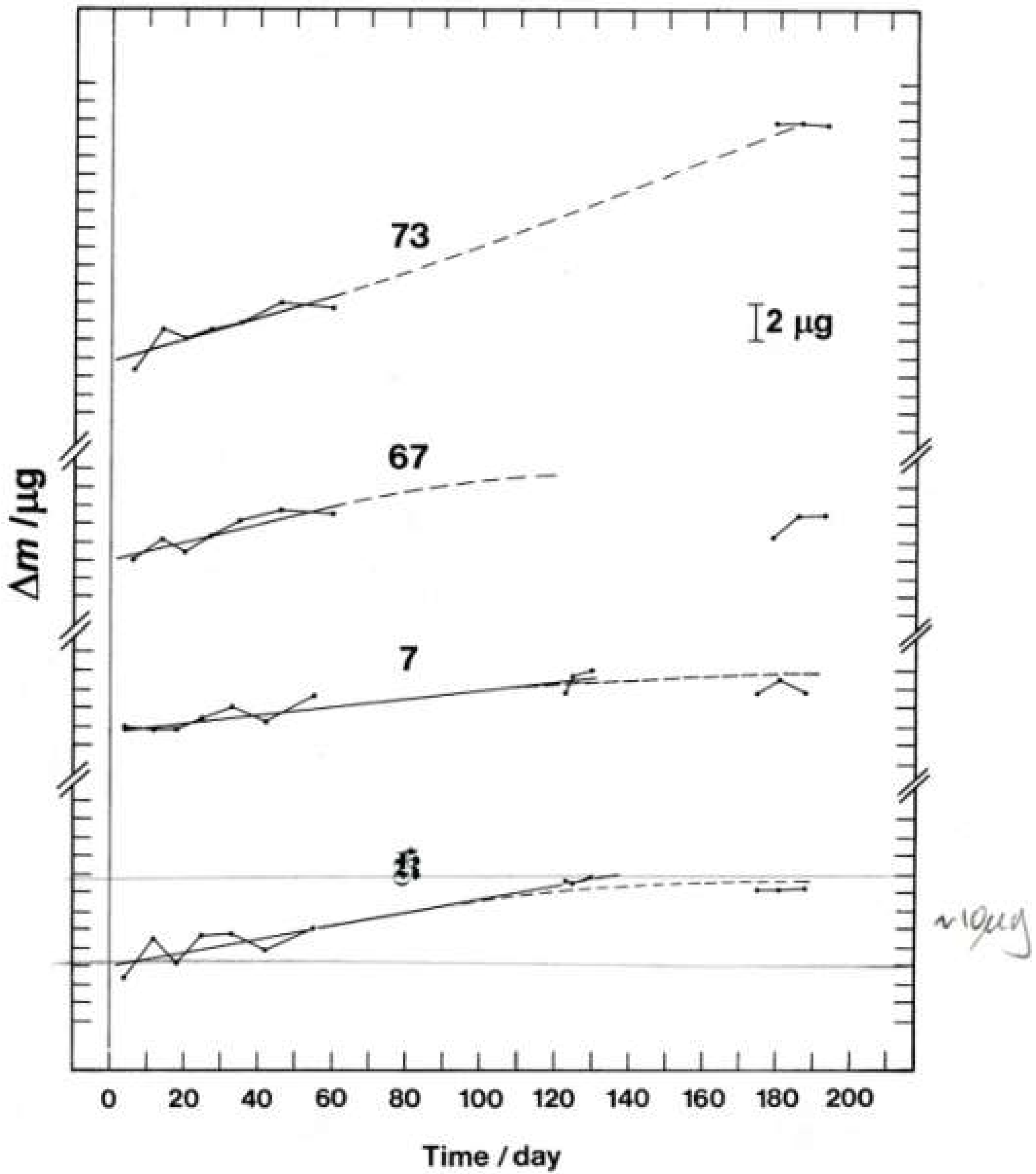
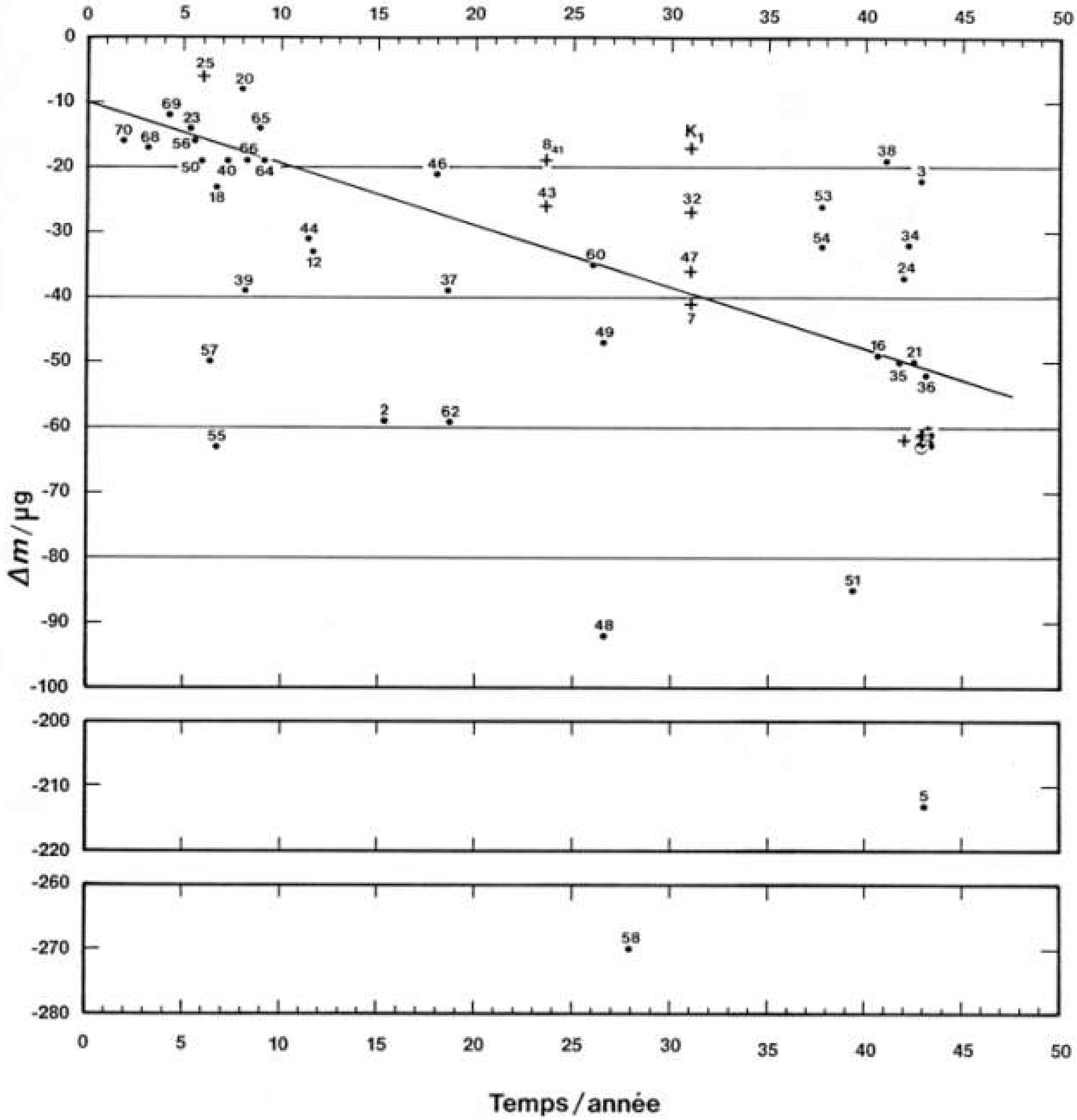
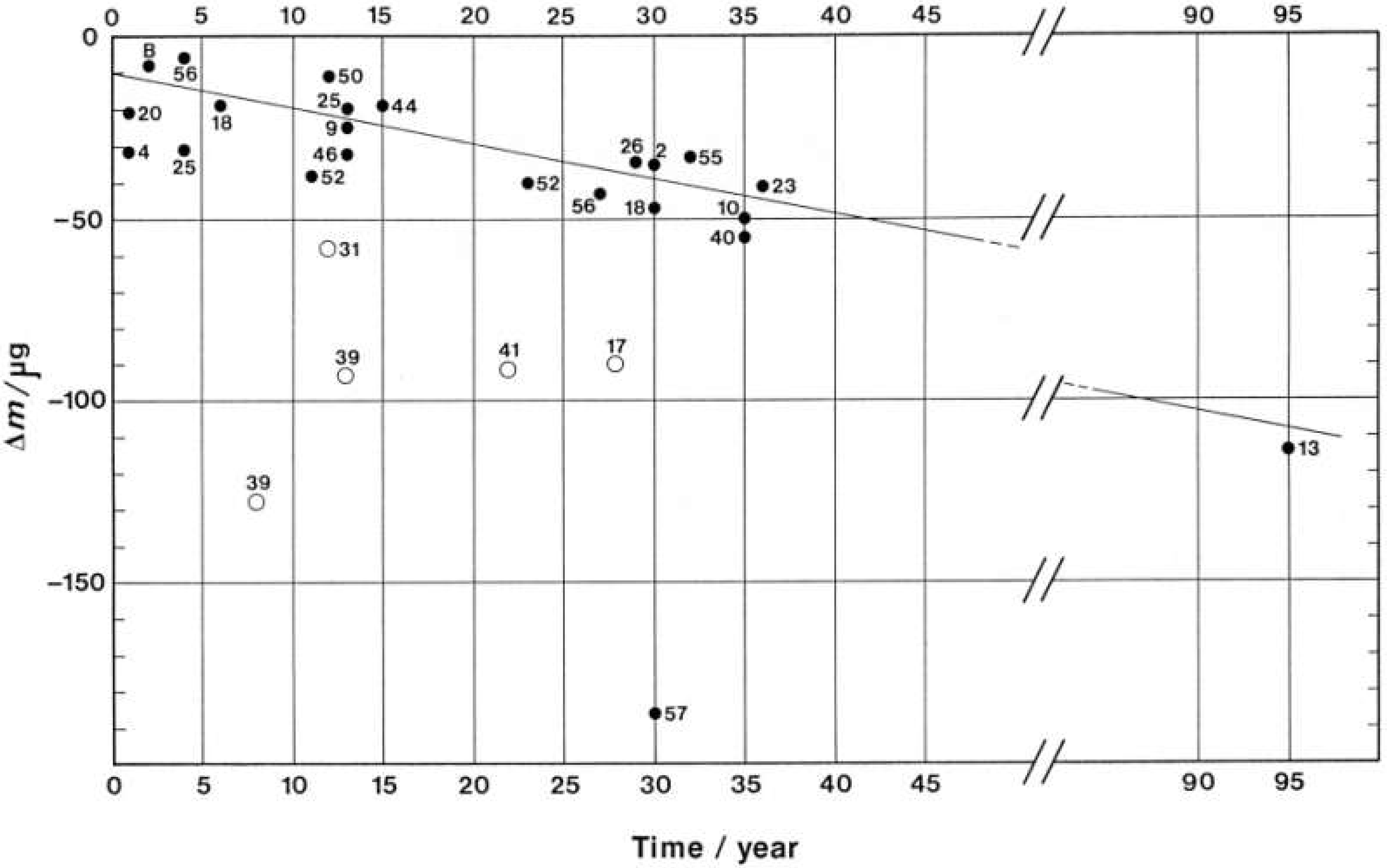


Fig. 4. — Increase in mass Δm during the first six months after cleaning and washing. Shown are the international prototype 𝕶, an official copy (No. 7) and two prototypes made (polished and adjusted) by diamond turning.



Δm / μg
Temps / année
0
5
10
15
20
25
30
35
40
45
50
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-200
-210
-220
-260
-270
-280
25
20
69
65
23
70
68
56
66
50
40
64
18
K_1
8_{41}
46
38
3
43
32
53
44
12
54
34
60
47
24
39
37
7
49
57
16
21
35
36
2
62
55
51
48
5
58



0
5
10
15
20
25
30
35
40
45
90
95
0
−50
−100
−150
Δm / μg
Time / year
B
56
50
20
18
25
44
9
4
25
46
52
26
2
55
52
23
56
18
10
40
31
39
41
17
13
39
57

Resolution 1
The 24th General Conference on Weights and Measures (CGPM),
Considering

• the international consensus on the importance, value, and potential benefits of a redefinition of a number of units of the International System of Units (SI),
• that the national metrology institutes (NMIs) as well as the International Bureau of Weights and Measures (BIPM) have rightfully expended significant effort during the last several decades to advance the International System of Units (SI) by extending the frontiers of metrology so that SI base units can be defined in terms of the invariants of nature – the fundamental physical constants or properties of atoms,
• that a prominent example of the success of such efforts is the current definition of the SI unit of length, the metre (17th CGPM, 1983, Resolution 1), which links it to an exact value of the speed of light
in vacuum *c, namely, 299 792 458 metre per second,*

•that of the seven base units of the SI, only the kilogram is still defined in terms of a material artefact, namely, the international prototype of the kilogram (1st CGPM, 1889, 3rd CGPM, 1901), and that the definitions of the ampere, mole and candela depend on the kilogram,

• that although the international prototype has served science and technology well since it was sanctioned by the 1st CGPM in 1889, it has a number of important limitations, one of the most significant being that its mass is not explicitly linked to an invariant of nature and in consequence its long-term stability is not assured,

• that the 21st CGPM in 1999 adopted Resolution 7 in which it recommended that "national laboratories continue their efforts to refine experiments that link the unit of mass to fundamental or atomic constants with a view to a future redefinition of the kilogram",

• that many advances have been made in recent years in relating the mass of the international prototype to the Planck constant *h*, by methods which include watt balances and measurements of the mass of a silicon atom,

- that the uncertainties of all SI electrical units realized directly or indirectly by means of the Josephson and quantum Hall effects together with the SI values of the Josephson and von Klitzing constants K_J and R_K could be significantly reduced if the kilogram were redefined so as to be linked to an exact numerical value of *h,* and if the ampere were to be redefined so as to be linked to an exact numerical value of the elementary charge *e,*

- that the kelvin is currently defined in terms of an intrinsic property of water that, while being an invariant of nature, in practice depends on the purity and isotopic composition of the water used,

- that it is possible to redefine the kelvin so that it is linked to an exact numerical value of the Boltzmann constant *k,*

- that it is also possible to redefine the mole so that it is linked to an exact numerical value of the Avogadro constant N_A, and is thus no longer dependent on the definition of the kilogram even when the kilogram is defined so that it is linked to an exact numerical value of *h,* thereby emphasizing the distinction between amount of substance and mass,

•that the uncertainties of the values of many other important fundamental constants and energy conversion factors would be eliminated or greatly reduced if *h, e, k and* N_A had exact numerical values when expressed in SI units,

• that the 23rd General Conference, in 2007, adopted resolution 12 in which it outlined the work that should be carried out by the NMIs, the BIPM and the International Committee for Weights and Measures (CIPM) together with its Consultative Committees (CCs) so that new definitions of the kilogram, ampere, kelvin, and mole in terms of fundamental constants could be adopted,

• that, although this work has progressed well, not all the requirements set out in Resolution 12 adopted by the 23rd General Conference in 2007 have been satisfied and so the International Committee for Weights and Measures is not yet ready to make a final proposal,

• that, nevertheless, a clear and detailed explanation of what is likely to be proposed can now be presented,

takes note of the intention of the International Committee for Weights and Measures to propose a revision of the SI as follows:

The International System of Units, the SI, will be the system of units in which:

- the ground state hyperfine splitting frequency of the caesium 133 atom $\Delta v(^{133}Cs)_{hfs}$ *is exactly 9 192 631 770* hertz,
- the speed of light in vacuum *c is exactly 299 792 458* metre per second,
- the Planck constant *h is exactly* $6.626\ 06X \times 10^{-34}$ joule second,
- the elementary charge *e is exactly* $1.602\ 17X \times 10^{-19}$ coulomb,
- the Boltzmann constant *k is exactly* $1.380\ 6X \times 10^{-23}$ joule per kelvin,
- the Avogadro constant *NA is exactly* $6.022\ 14X \times 10^{23}$ reciprocal mole,
- the luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} Hz is exactly 683 lumen per watt,

where
(i) the hertz, joule, coulomb, lumen, and watt, with unit symbols Hz, J, C, lm, and W, respectively, are related to the units second, metre, kilogram, ampere, kelvin, mole, and candela, with unit symbols s, m, kg, A, K, mol, and cd, respectively, according to $Hz = s^{-1}$, $J = m^2\ kg\ s^{-2}$, $C = s\ A$, $lm = cd\ m^2\ m^{-2} = cd\ sr$, and $W = m^2\ kg\ s^{-3}$,
(ii) the symbol X in this Draft Resolution represents one or more additional digits to be added to the numerical values of *h, e, k, and* N_A, using values based on the most recent CODATA adjustment,

What does it mean to fix the numerical value of a constant?
Let us take the velocity of light, c.

$$c = 299\,792\,458 \ \text{m/s}$$

$$(c = 983\,571\,056.4 \ \text{ft/s})$$

value of *c* = numerical value × unit

The value of *c* is a constant of nature.

1. If we define the units independently, then we must determine the numerical value of *c* by experiment, and it will have an uncertainty. That was the situation before 1983, when both the metre and the second were independently defined.

2. If the second is independently defined in terms of the frequency of the caesium transition, and we choose to fix the numerical value of *c*, then the effect is to define the metre *. This is the current definition of the metre, since the change in 1983. The numerical value now has zero uncertainty.

*or the foot or any other unit of length we might choose

$$h = 6.626\,0693 \times 10^{-34}\ \mathrm{m^2\,kg\,s^{-1}}$$

$$\text{value of } h = \text{numerical value} \times \text{unit}$$

The value of *h* is a constant of nature.

1. If we define the unit $m^2\ kg\ s^{-1}$ independently, then we must determine the numerical value of *h* by experiment, and it will have an uncertainty. That is the present situation.

2. If the metre and the second are already independently defined, and we choose to fix the numerical value of *h*, then the effect is to define the kilogram. This is the proposed new definition of the kilogram. The numerical value will have zero uncertainty.

Note: $J\ s = m^2\ kg\ s^{-1}$

from which it follows that the SI will continue to have the present set of seven base units, in particular

• the kilogram will continue to be the unit of mass, but its magnitude will be set by fixing the numerical value of the Planck constant to be equal to exactly 6.626 06X $\times 10^{-34}$ when it is expressed in the SI unit m2 kg s⁻1, which is equal to J s,

• the ampere will continue to be the unit of electric current, but its magnitude will be set by fixing the numerical value of the elementary charge to be equal to exactly 1.602 17X $\times 10^{-19}$ when it is expressed in the SI unit s A, which is equal to C,

• the kelvin will continue to be the unit of thermodynamic temperature, but its magnitude will be set by fixing the numerical value of the Boltzmann constant to be equal to exactly 1.380 6X $\times 10^{-23}$ when it is expressed in the SI unit m^2 kg s^{-2} K^{-1}, which is equal to J K^{-1},

• the mole will continue to be the unit of amount of substance of a specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles, but its magnitude will be set by fixing the numerical value of the Avogadro constant to be equal to exactly 6.022 14X $\times 10^{23}$ when it is expressed in the SI unit mol^{-1}.

further notes that since

• the new definitions of the kilogram, ampere, kelvin and mole are intended to be of the explicit-constant type, that is, a definition in which the unit is defined indirectly by specifying explicitly an exact value for a well recognized fundamental constant,

the existing definition of the metre is linked to an exact value of the speed of light in vacuum, which is also a well-recognized fundamental constant,

• the existing definition of the second is linked to an exact value of a well defined property of the caesium atom, which is also an invariant of nature,

• although the existing definition of the candela is not linked to a fundamental constant, it may be viewed as being linked to an exact value of an invariant of nature,

• it would enhance the understandability of the International System if all of its base units were of similar wording,

the International Committee for Weights and Measures will also propose the reformulation of the existing definitions of the second, metre and candela in completely equivalent forms, which might be the following:

•the second, symbol s, is the unit of time; its magnitude is set by fixing the numerical value of the ground state hyperfine splitting frequency of the caesium 133 atom, at rest and at a temperature of 0 K, to be equal to exactly 9 192 631 770 when it is expressed in the SI unit s^{-1}, which is equal to Hz,

• the metre, symbol m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299 792 458 when it is expressed in the SI unit m s^{-1},

• the candela, symbol cd, is the unit of luminous intensity in a given direction; its magnitude is set by fixing the numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz to be equal to exactly 683 when it is expressed in the SI unit m^{-2} kg^{-1} s^{3} cd sr, or cd sr W^{-1}, which is equal to lm W^{-1}.

In this way, the definitions of all seven base units will be seen to follow naturally from the set of seven constants given above.

In consequence, on the date chosen for the implementation of the revision of the SI:

• the definition of the kilogram in force since 1889 based upon the mass of the international prototype of the kilogram (1st CGPM, 1889, 1889, 3rd CGPM, 1901) will be abrogated,

etc, etc

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further notes that on the same date

• the mass of the international prototype of the kilogram *m(*K*)* will be 1 kg but with a relative uncertainty equal to that of the recommended value of *h* just before redefinition and that subsequently its value will be determined experimentally,

• that the magnetic constant (permeability of vacuum) μ_0 will be $4\pi \times 10^{-7}$ H m^{-1} but with a relative uncertainty equal to that of the recommended value of the fine-structure constant α and that subsequently its value will be determined experimentally,

• that the thermodynamic temperature of the triple point of water *TTPW* will be 273.16 K but with a relative uncertainty equal to that of the recommended value of *k* just before redefinition and that subsequently its value will be determined experimentally,

•that the molar mass of carbon 12 $M(^{12}C)$ will be 0.012 kg mol^{-1} but with a relative uncertainty equal to that of the recommended value of $N_A h$ *just* before redefinition and that subsequently its value will be determined experimentally.

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encourages

- researchers in national metrology institutes, the BIPM and academic institutions to continue their efforts and make known to the scientific community in general and to CODATA in particular, the outcome of their work relevant to the determination of the constants *h, e, k, and* N_A, *and*
- the BIPM to continue its work on relating the traceability of the prototypes it maintains to the international prototype of the kilogram, and in developing a pool of reference standards to facilitate the dissemination of the unit of mass when redefined,

invites

- CODATA to continue to provide adjusted values of the fundamental physical constants based on all relevant information available and to make the results known to the International Committee through its Consultative Committee for Units since these CODATA values and uncertainties will be those used for the revised SI,
- the CIPM to make a proposal for the revision of the SI as soon as the recommendations of Resolution 12 of the 23rd General Conference are fulfilled, in particular the preparation of *mises en pratique* for the new definitions of the kilogram, ampere, kelvin and mole,
- the CIPM to continue its work towards improved formulations for the definitions of the SI base units in terms of fundamental constants, having as far as possible a more easily understandable description for users in general, consistent with scientific rigour and clarity,
- the CIPM, the Consultative Committees, the BIPM, the OIML and National Metrology Institutes significantly to increase their efforts to initiate awareness campaigns aimed at alerting user communities and the general public to the intention to redefine various units of the SI and to encourage consideration of the practical, technical, and legislative implications of such redefinitions, so that comments and contributions can be solicited from the wider scientific and user communities.


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