The Metre Convention, the BIPM and the development of measurement standards from 1791 to the New SI in 2018

Part 1
The Metre Convention and the creation of the BIPM

Terry Quinn

Emeritus Director *Bureau International des Poids et Mesures* (BIPM)

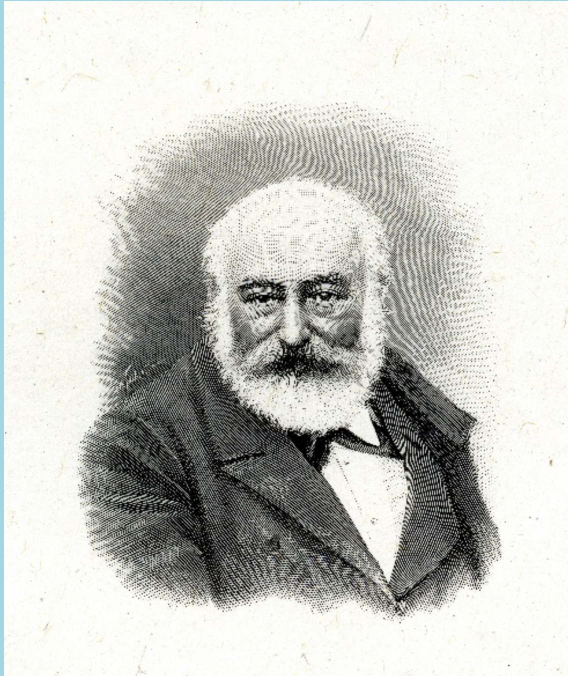
The Second International Conference for the Measurement of Degrees in Europe
Berlin October 1867 (the first having been in Berlin in 1864)

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

Who initiated all this:
Otto Struve from Saint Petersburg and Adolph Hirsch from Neuchatel who formulated the Recommendations

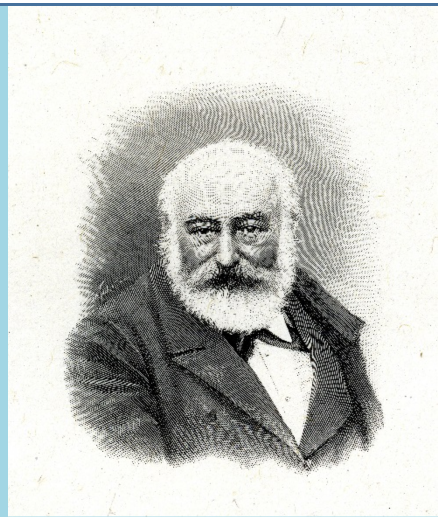
Otto Wilhelm von Struve 1819 – 1905 Director of the Pulkovo Observatory between 1862 and 1889 and was a leading member of the Russian Academy of Sciences.



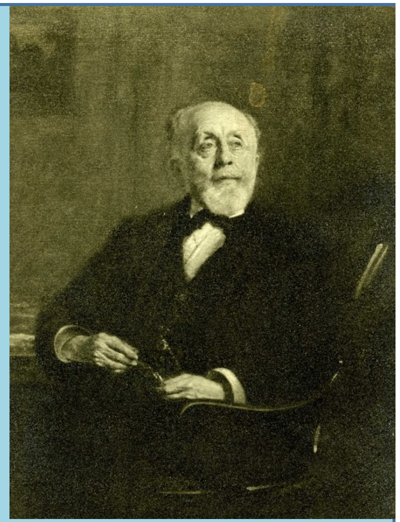
Adolph Hirsch, 1830 – 1901, Director of the Neuchatel Observatory was the first Secretary of the International Committee for Weights and Measures from 1875 to 1901

Claude-Louis Mathieu
1783-1875

Jean-Baptiste Dumas
1800-1884



Adolph Hirsch
1830-1901



Wilhelm Foerster
1832-1921

Arthur Morin
1797-1880

Henri Tresca
1814-1885

Henri Saint-Claire Deville
1818-1881

Reactions in Paris from:

1. The Bureau des Longitudes
2. The Académie des sciences
3. The French Government

Also, a question from the Academy of Science of Saint Petersburg: What is the definition of the metre?

Creation of the International Metre Commission by the French Government in 1869.............meetings in Paris in August 1870 and in October 1872.

Diplomatic Conference of the Metre held in Paris from 1 March to 20 May 1875. Metre Convention signed 20 May 1875

After 1795 what were the real definitions of the metre and kilogram?

The metre is one ten millionth of the quarter of the terrestrial meridian which, 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
or was it
the length of the Metre of the Archives

The kilogram is the mass of one cubic decimetre of water at the temperature of melting ice
or was it
the mass of the Kilogram of the Archives.

Photo TJQ

La Convention du Metre
Convention

*SA MAJESTÉ L'EMPEREUR D'ALLEMAGNE, SA MAJESTÉ L'EMPEREUR
D'AUTRICHE-HONGRIE, SA MAJESTÉ LE ROI DES BELGES, SA MAJESTÉ
L'EMPEREUR DU BRÉSIL, SON EXCELLENCE LE PRÉSIDENT DE LA CONFÉDÉRATION
ARGENTINE, SA MAJESTÉ LE ROI DE DANEMARK, SA MAJESTÉ LE
ROI D'ESPAGNE, SON EXCELLENCE LE PRÉSIDENT DES ÉTATS-UNIS D'AMÉRIQUE,
SON EXCELLENCE LE PRÉSIDENT DE LA RÉPUBLIQUE FRANÇAISE,
SA MAJESTÉ LE ROI D´ITALIE, SON EXCELLENCE LE PRÉSIDENT DE LA RÉPUBLIQUE
DU PÉROU, SA MAJESTÉ LE ROI DE PORTUGAL ET DES ALGARVES,
SA MAJESTÉ L'EMPEREUR, DE TOUTES LES RUSSIES, SA MAJESTÉ LE ROI
DE SUEDE ET DE NORWÉGE, SON EXCELLENCE LE PRÉSIDENT DE LA CONFÉDÉRATION
SUISSE, SA MAJESTÉ L'EMPEREUR DES OTTOMANS ET SON
EXCELLENCE LE PRÉSIDENT DE LA RÉPUBLIQUE DE V ÉNÉZUÉLA,*

desirant assurer l'unification internationale et le perfectionnement du système métrique, ont resolu de conclure une Convention à cet effet et ont nommé pour leurs Plénipotentiaires, savoir:

wishing to assure the international unification and perfection of the metric system, have resolved to conclude a Convention to this effect and have named the following as their plenipotentiaries:

*SA MAJESTÉ L'EMPEREUR D'ALLEMAGNE, M. le Prince DE
HOHENLOHE-SCHILLINGSFÜRST, Grand-Croix de l'Ordre de l'Aigle Rouge
de Prusse et de l'Ordre de Saint-Hubert de Bavière, etc. etc.,
son Ambassadeur extraordinaire et plénipotentiaire à Paris; ……………………….*

Et SON EXCELLENCE LE PRÉSIDENT DE LA RÉPUBLIQUE

DE VÉNÉZUÉLA, M.le Docteur ELISEO ACOSTA;

lesquels, après s'être communiqué leurs pleins pouvoirs, trouvés en bonne et due forme, ont arrêté les dispositions suivantes:

who, having presented their credentials, found to be in good and due form, have decided upon the following arrangements:

ARTICLE PREMIER.

Les Hautes Parties contractantes s'engagent à fonder et entretenir, à frais communs, un *Bureau international des poids et mesures,* scientifique et permanent, dont le siége est à Paris.

The high contracting Parties undertake to create and maintain, at their common expense, an *International Bureau of Weights and Measures* with its seat in Paris

ART. 2.

Le Gouvernement français prendra les dispositions nécessaires pour faciliter l'acquisition ou, s'il y a lieu, la construction d'un bâtiment spécialement affecté à cette destination, dans les conditions déterminées par le Règlement annexé à la présente Convention.

ART. 3.

Le Bureau international fonctionnera sous la direction et la surveillance exclusives d'un *Comité international des poids et mesures,* placé lui-même sous l'autorité d'une *Conférence générale des poids et mesures* formée de délégués de tous les Gouvernements contractants.

The International Bureau shall operate under the exclusive direction and supervision of an International Committee for Weights and Measures itself placed under the authority of a General Conference on Weights and Measures formed of the delegates of all contracting governments.

here then follows the remaining Articles of the Convention and its associated Regulations.
Slightly revised in 1921, the Metre Convention remains the intergovernmental treaty under which international agreements on measurement units are made.

The original purpose of the Convention is thus clearly stated, it is a

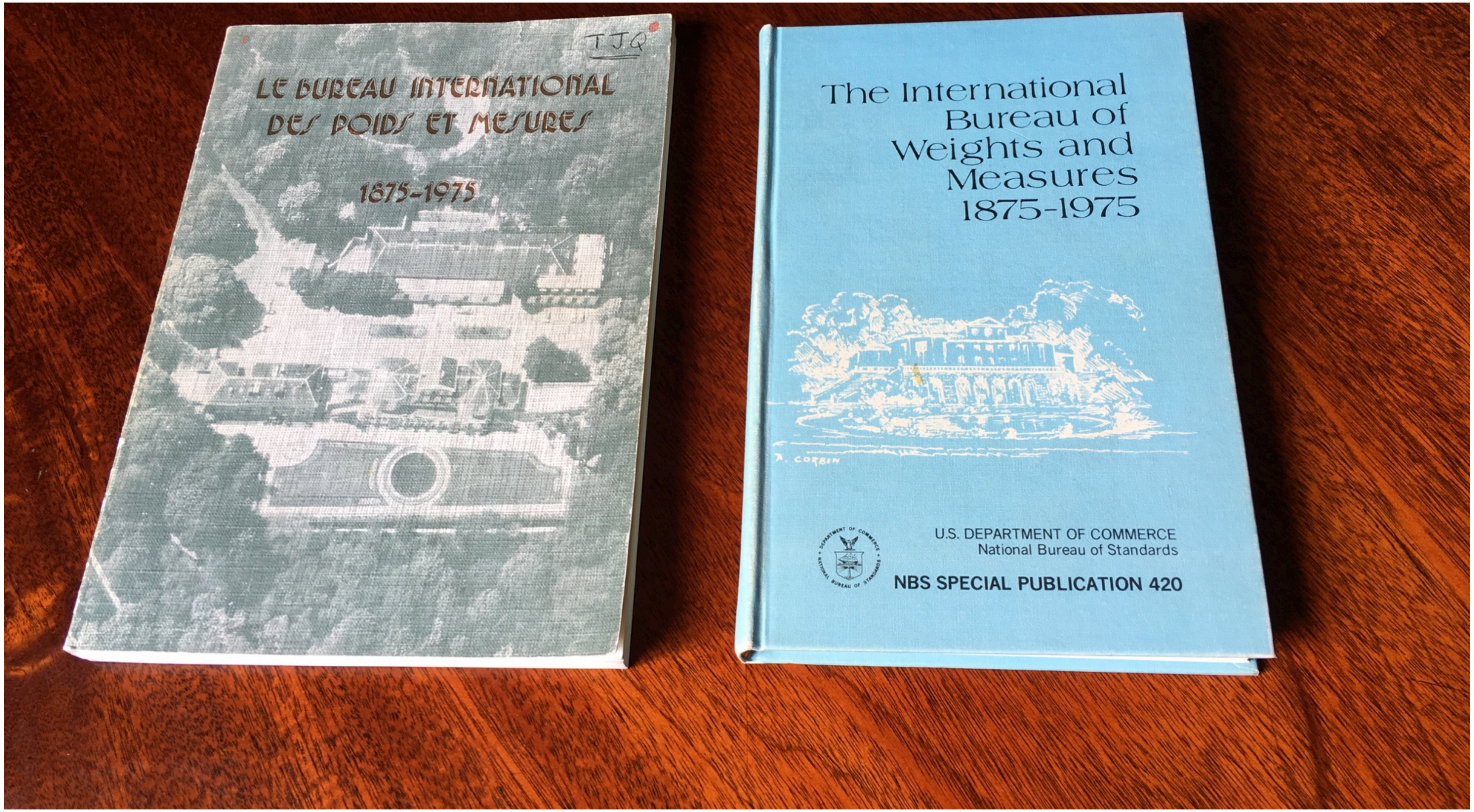
Convention to assure the international unification and perfection of the metric system

This is clearly the name of the organization created by the Metre Convention but in 1875 the practices and forms now common in the way in which international organizations are named had not yet developed. In modern terms, the Convention would probably have been named:

International organization to assure the international unification and perfection of the metric system

Unfortunately, the preamble to the Convention, added at the penultimate session of the Diplomatic Conference of 1875, is usually omitted in reproductions of the text of the Convention, so this important statement of its purpose seems to have been lost!

The result has been confusion and misunderstanding as to the name of the organization.

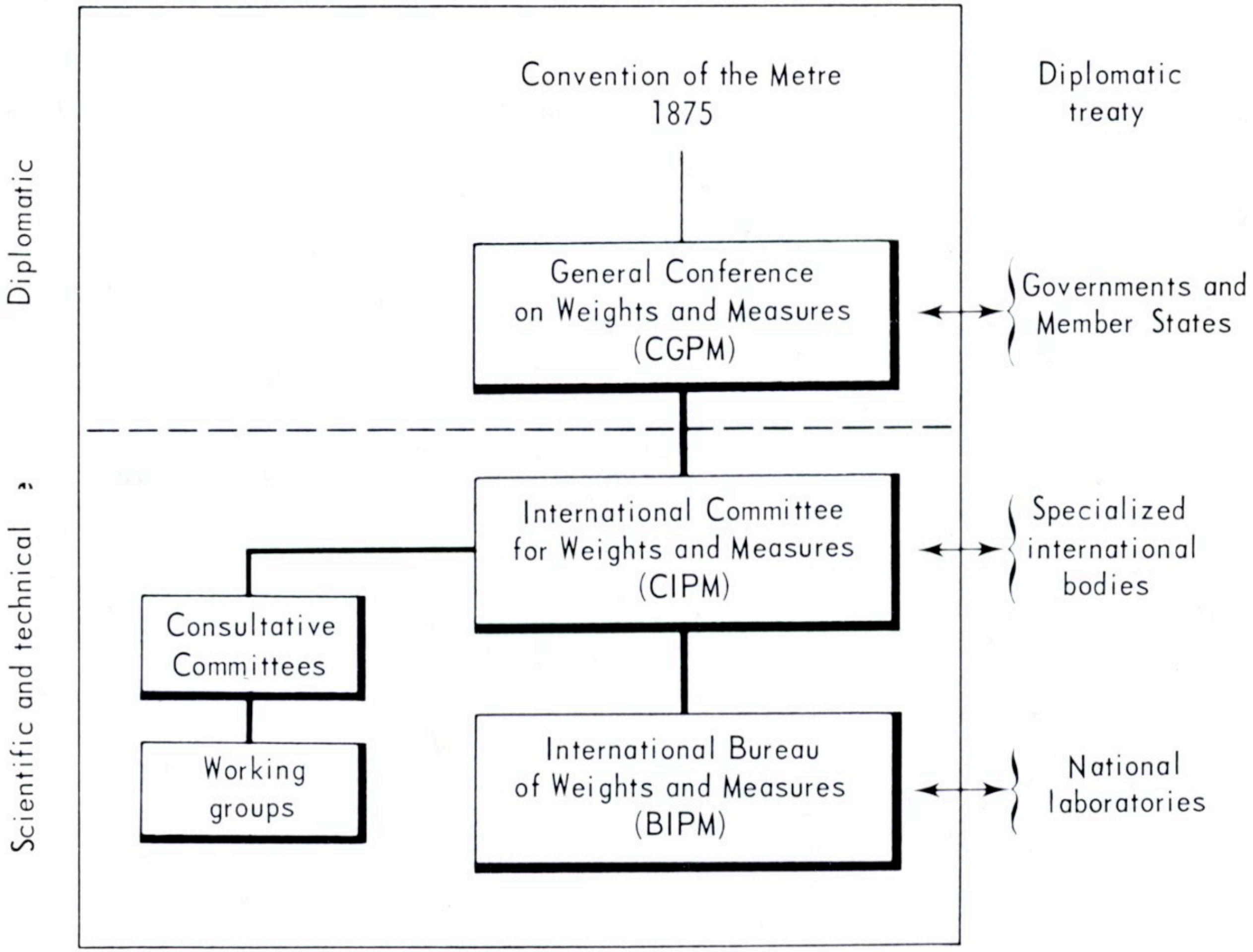

TJQ
LE BUREAU INTERNATIONAL
DES POIDS ET MESURES
1875-1975
The International
Bureau of
Weights and
Measures
1875-1975
A. CORBIN
U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
NBS SPECIAL PUBLICATION 420

The formal structure of the organization is in fact very simple and was set out quite clearly in the book published by the BIPM in 1975 on the occasion of the centenary of the signing of the Convention: *Le Bureau International des Poids et Mesures 1875-1975.*

This was translated into English and published by the National Bureau of Standards (now NIST) as NBS Special Publication 420 (248pp) *The International Bureau of Weights and measures 1875-1975.*
The following extracts set the scene:

Since 1875, the organs of the Metre Convention have not been subjected to change. However, by reason of the increasing complexity of scientific questions related to metrology, the CIPM established several Consultative Committees, starting in 1927. The relations among these organs, the member States, the specialized international organizations, and the national laboratories are shown below.

Note the Convention was modified in 1921 principally to bring electrical standards under the responsibility of the CIPM and BIPM but it also to allow future extensions of the range of activities to be decided by Member States as and when they wished. The modifications were almost all in the Appended Regulations of the Convention



The Metre Convention Organs. In 1975, there are seven Consultative Committees: Electricity, Photometry and Radiometry, Thermometry, Definition of the Metre, Definition of the Second, Ionizing Radiation, Units.

The *General Conference on Weights and Measures*, an intergovernmental conference comprising delegates of member States of the Metre Convention,[2] is the supreme authority which controls the administration of the BIPM; it has for its primary mission:

– to discuss and initiate the necessary measures to assure the propagation and development of the International System of Units (SI), the modern form of the Metric System;

– to ratify the results of new fundamental metrological determinations and to adopt various scientific resolutions of international importance;

– to adopt important decisions concerning the organization and development of the BIPM.

From 1889 to 1971, the CGPM met 14 times. The 15th CGPM coincides with the centennial of the Convention of the Metre.

The *International Committee for Weights and Measures* is charged with preparing and executing the decisions of the CGPM. It directly supervises the operation of the BIPM and oversees its work.

Originally composed of 14 members, a number raised to 18 in 1921, the CIPM assembles men of science and eminent metrologists of all different nationalities (app. 3, p. 233). Elected by the CGPM, these members sit in the CIPM in a personal capacity and they are not in any way official representatives of their countries. The CIPM met for the first time in April

The *International Bureau of Weights and Measures*, organ for executing the decisions of the CGPM and the CIPM, is a permanent laboratory and the world center of scientific metrology whose progress, particularly spectacular in our time, is intimately linked to the development of scientific discoveries, industrial technology, and international comparisons.

The primary mission of the BIPM is:

— to establish the basic standards and scales of the principal physical quantities, and to maintain international prototypes;

— to carry out comparisons of national and international standards;

— to assure coordination of the corresponding techniques of measurement;

— to carry out and coordinate relative determinations of fundamental physical constants.

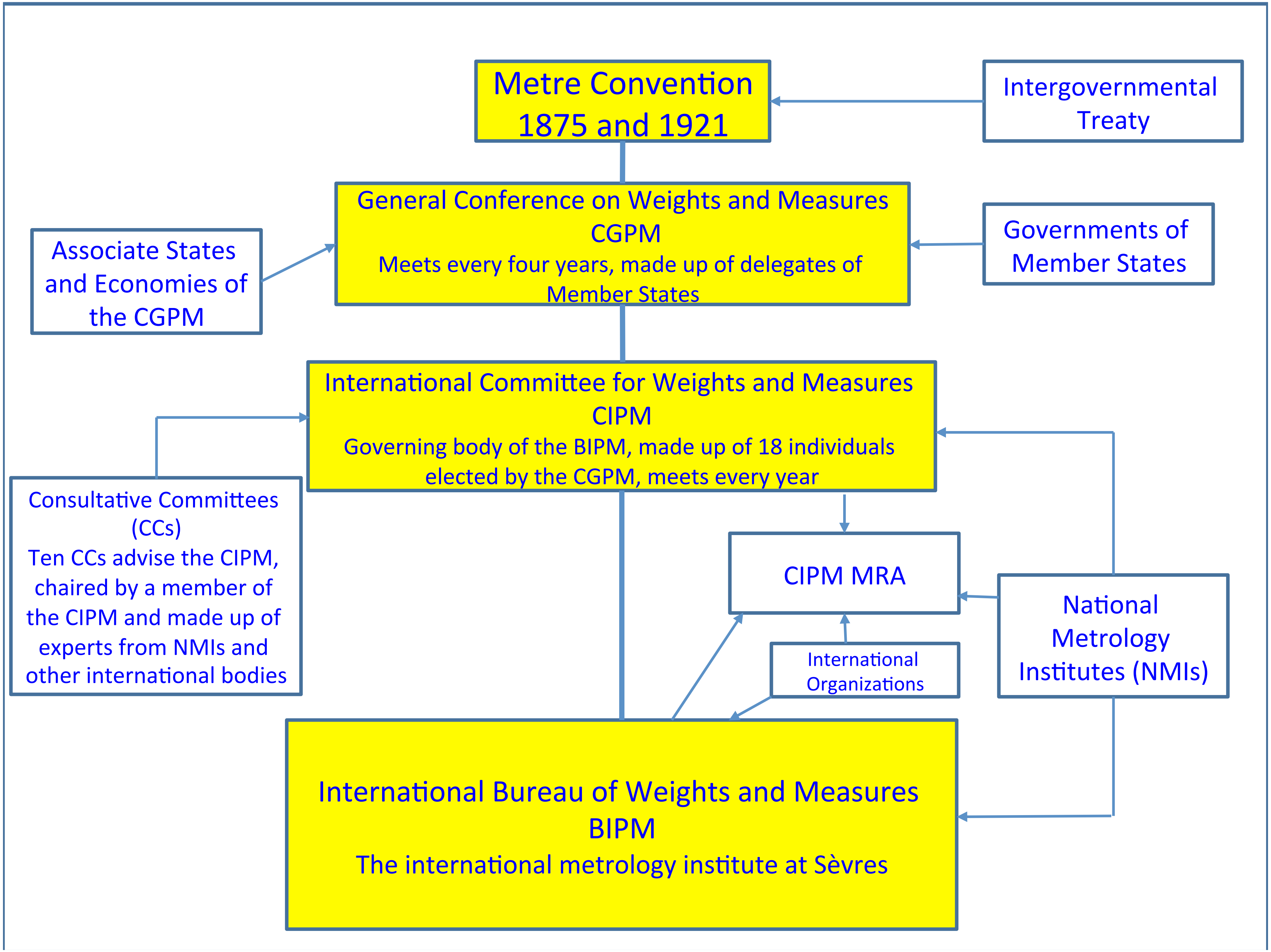
Le *Bureau International des Poids et Mesures*, organe d'exécution des décisions de la C.G.P.M. et du C.I.P.M., est un laboratoire permanent et le centre mondial de la métrologie scientifique dont les progrès, particulièrement spectaculaires à notre époque, sont intimement liés au développement des découvertes scientifiques, des techniques industrielles et des échanges internationaux.

A neutral and autonomous organ, the BIPM is not dependent on any of the existing intergovernmental organizations[3] and is not affiliated with any international union or association. It has been recognized in France as an establishment of public usefulness by the decree of October 28, 1876. On April 25, 1969, an Accord was concluded between the French Government and the CIPM relative to the grounds of the BIPM and to its privileges and immunities in French territory (Decree No. 70-820 of September 9, 1970).

This was known as the "Accord de Siège"; it was an agreement between the International Committee and the French government signed on April 25, 1969, in the form of a decree, No. 70–820 of September 9, 1970, published in the *Journal officiel de la République française*. This was relative to the seat of the International Bureau and its privileges and immunities

on French territory. The Accord of 1970 was modified by an exchange of letters dated 6 and 23 July, 2007, ratified by the law No. 2008–738 of July 28, 2008, published in the *Journal officiel* on July 30, 2008. This Accord de Siège makes explicit the status of the International Bureau referred to in Article 1 (1875) of the Metre Convention and Article 3 (1875) of the Regulations according to modern practice for international organizations, and is based on the provisions of the Vienna Convention of 1961 concerning diplomatic relations between states. The purpose of such a Convention and the subsequent Accord de Siège for the International Bureau was not only to establish its own privileges and immunities in France and those of its staff, but also in relation to those representatives of Member States coming to the Bureau and the entry into France of national standards coming to the Bureau for comparison or calibration.

Since 1975 the organs of the Metre Convention have not, of course, changed but the need to provide a much more complete and documented evidence of uniformity of world measurement standards has resulted in the organigram of 1975 becoming a little more complex

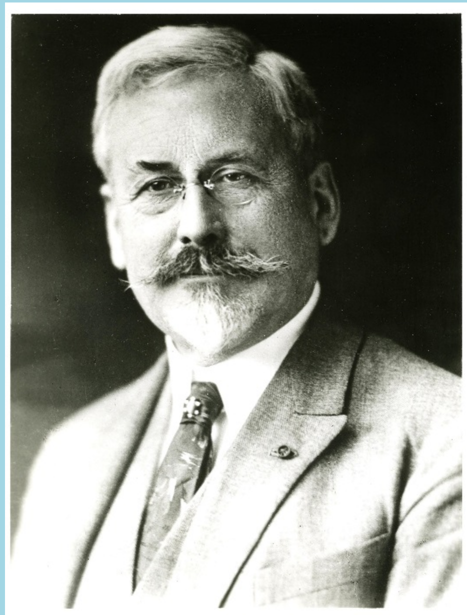

Metre Convention 1875 and 1921
Intergovernmental Treaty
General Conference on Weights and Measures CGPM
Meets every four years, made up of delegates of Member States
Associate States and Economies of the CGPM
Governments of Member States
International Committee for Weights and Measures CIPM
Governing body of the BIPM, made up of 18 individuals elected by the CGPM, meets every year
Consultative Committees (CCs)
Ten CCs advise the CIPM, chaired by a member of the CIPM and made up of experts from NMIs and other international bodies
CIPM MRA
National Metrology Institutes (NMIs)
International Organizations
International Bureau of Weights and Measures BIPM
The international metrology institute at Sèvres

Gilbert Govi, Director 1875-77

Ole-Jacob Broch, Director 1879-89

René Benoit, Director 1889-1915

General Carlos Ibanez

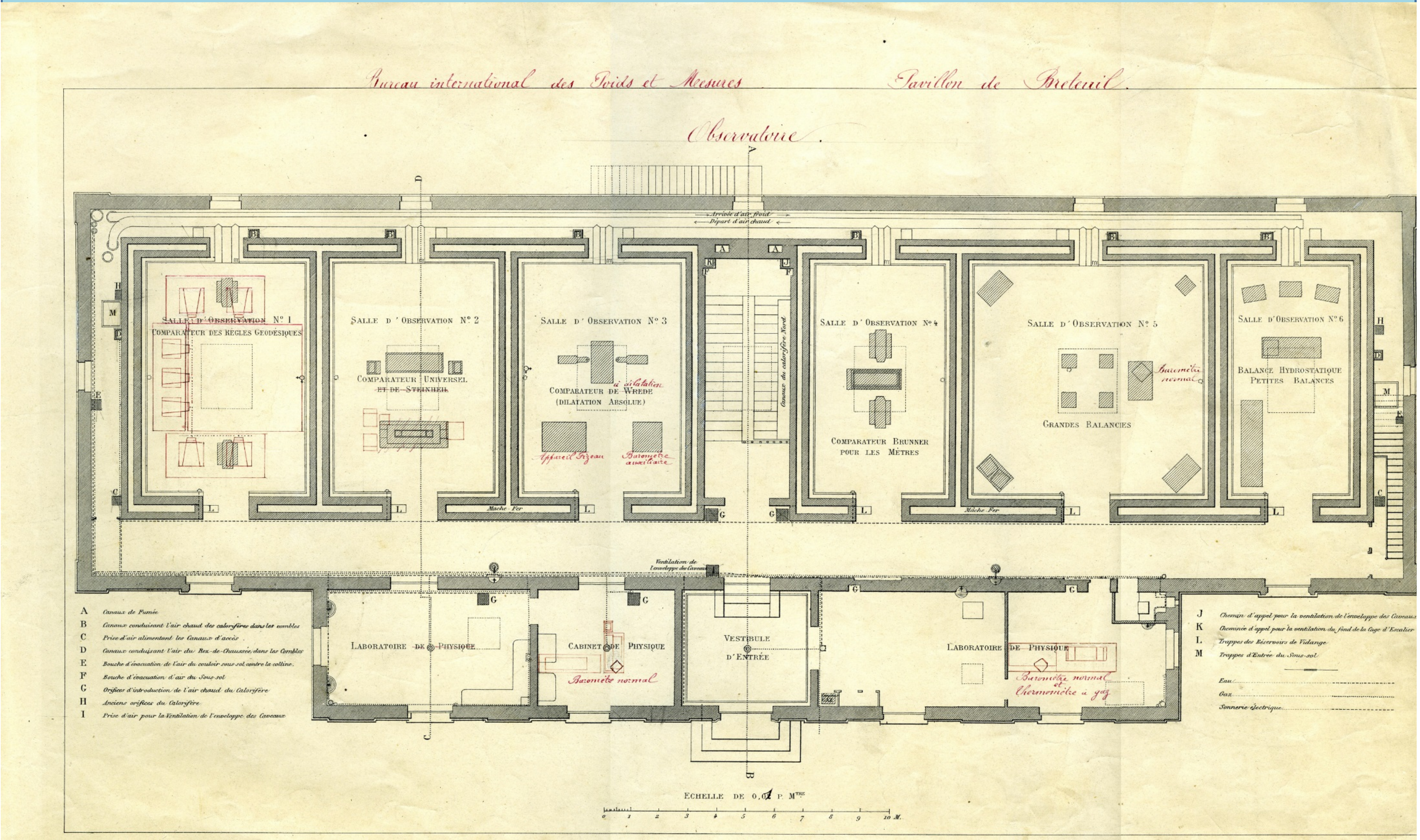


Ch. Ed. Guillaume, Director 1915-1936

The Pavillon de Breteuil in 1875 damaged in the Franco-Prussian war of 1870

The Pavillon de Breteuil in the 1920s


BUREAU INTERNATIONAL
DES POIDS ET MESURES
PAVILLON
DE BRETEUIL
LE PUBLIC
N'ENTRE PAS ICI



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Arrivée d'air froid
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Salle d'Observation N° 2
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Salle d'Observation N° 3
Comparateur de Wrede
à dilatation
(dilatation Absolue)
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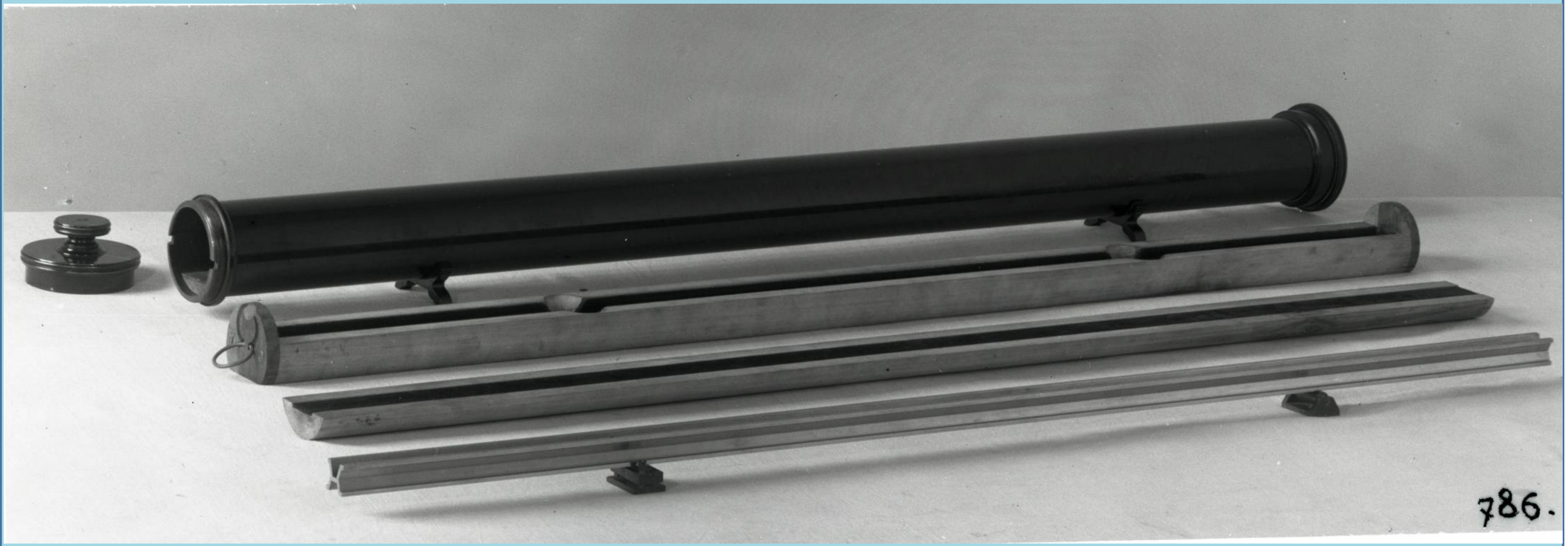
Eau
Gaz
Sonnerie électrique
Echelle de 0,01 p. Mtre
0 1 2 3 4 5 6 7 8 9 10 M.

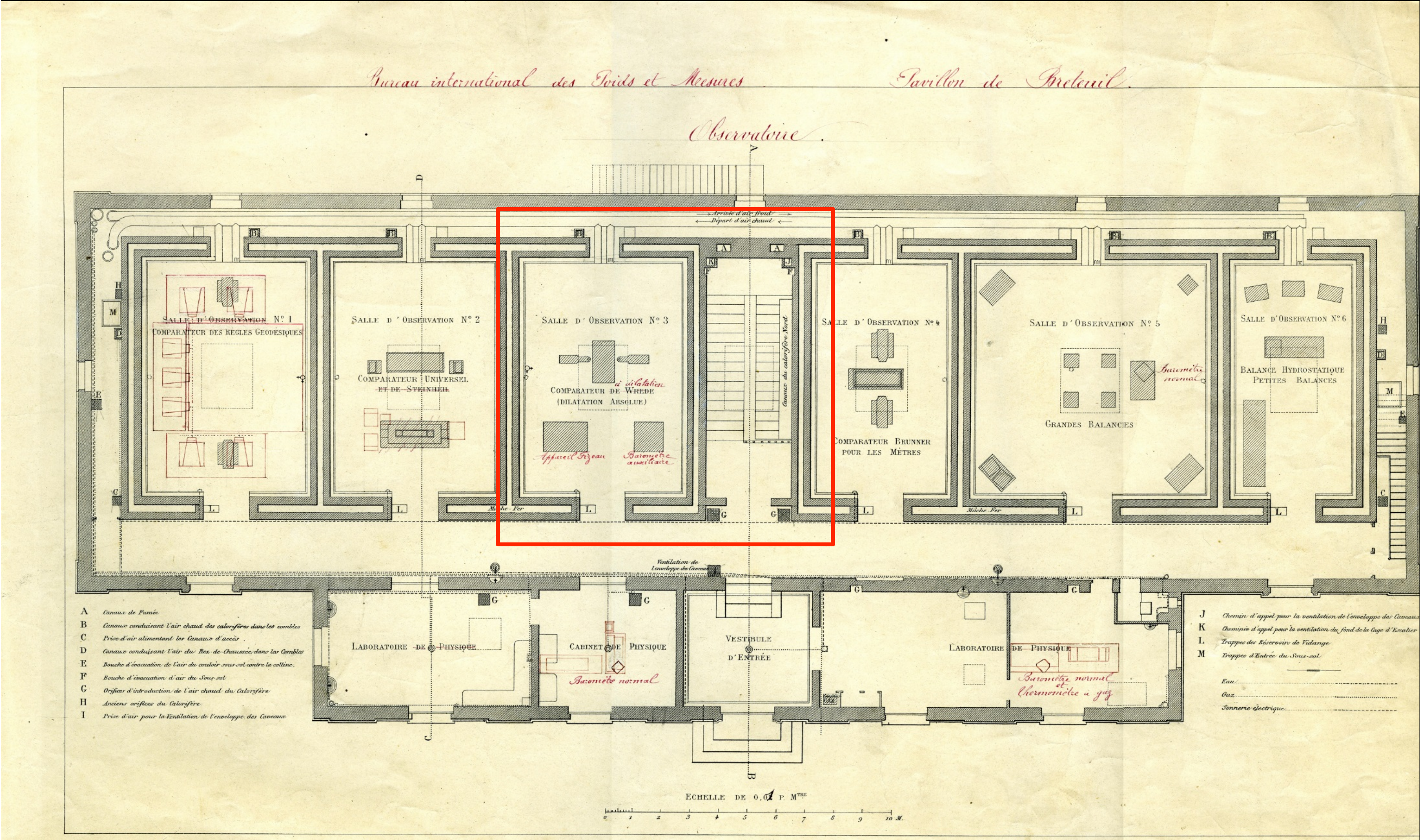
The safe in the vault of the prototypes at the BIPM where the kilogram and metre rested from 1889 until 1998


5.
Mètre international



The storage and carrying case of prototype metres

Image BIPM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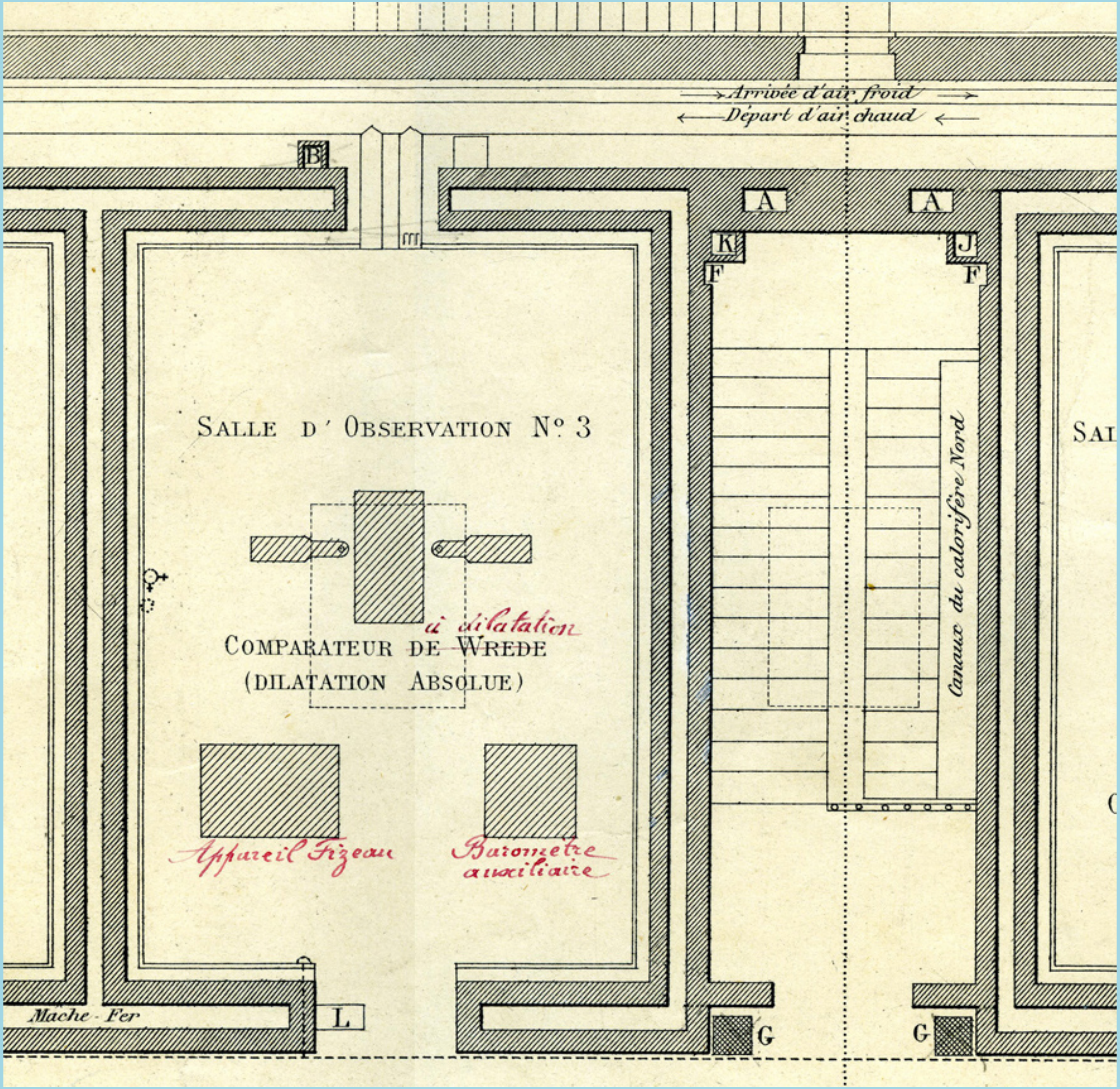

Arrivée d'air froid
Départ d'air chaud
B
A
A
K
J
F
F
SALLE D'OBSERVATION N° 3
à dilatation
COMPARATEUR DE ~~WREDE~~
(DILATATION ABSOLUE)
Canaux du calorifère Nord
Appareil Fizeau
Baromètre auxiliaire
Mache-Fer
L
G
G

Details of thermal-expansion comparator

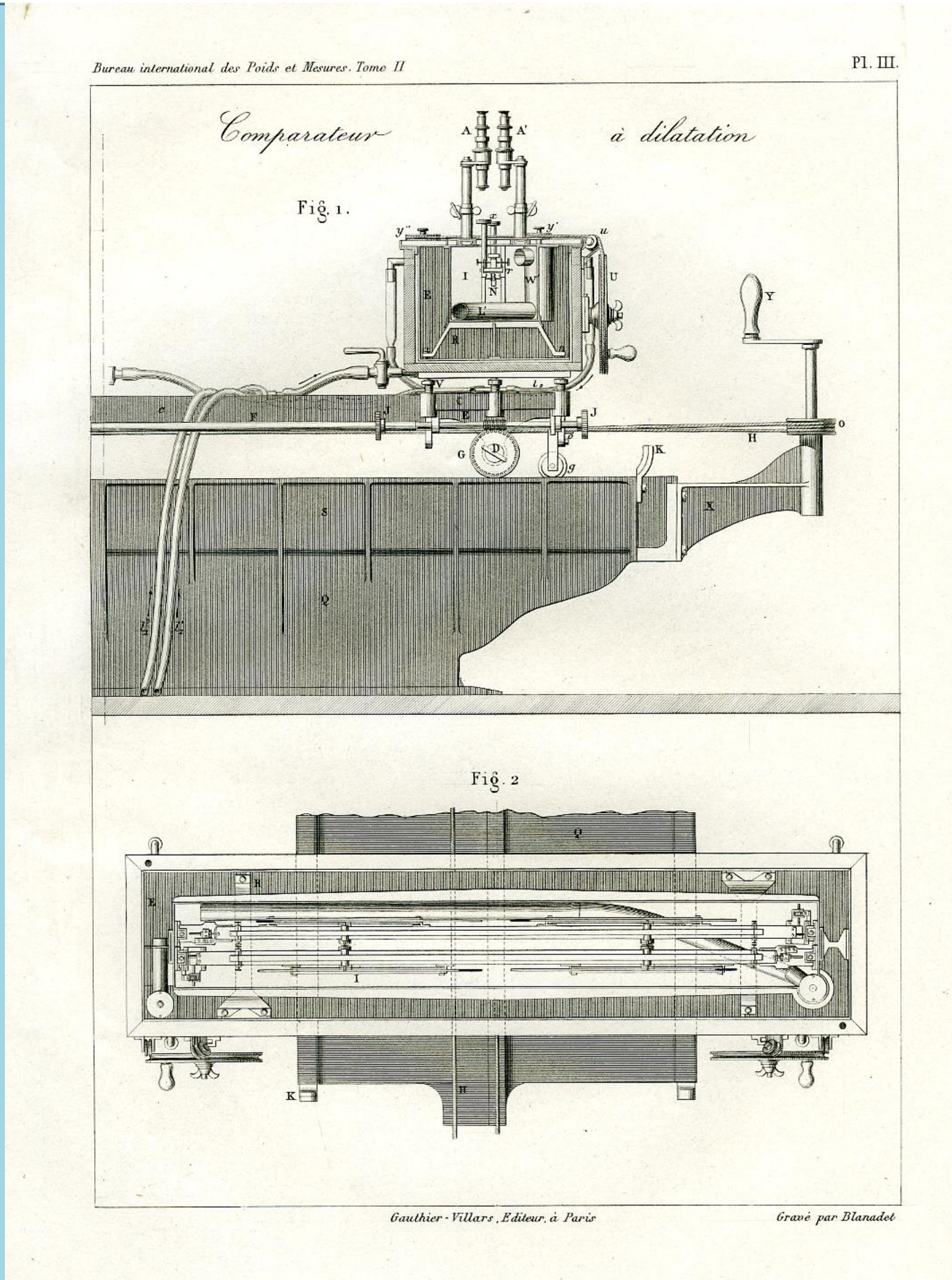


Image BIPM

Comparateur à dilatation

Fondations

Fig. 1.

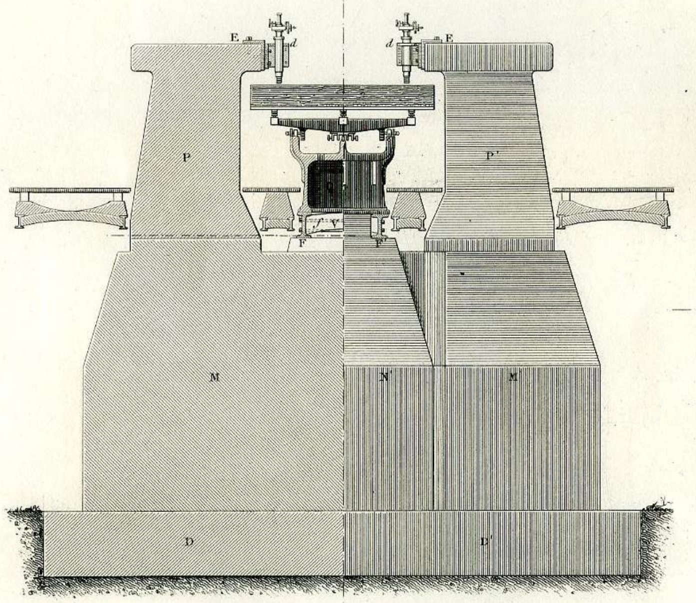
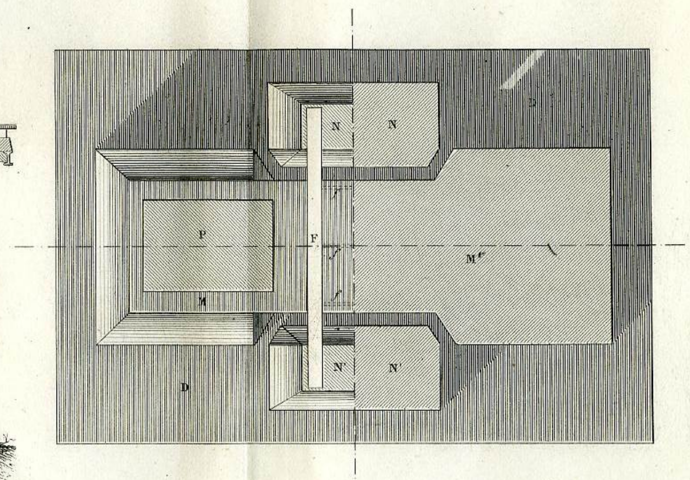
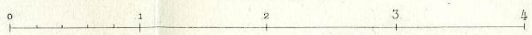


Fig. 2



Echelle $\frac{1}{40}$



Imp. Lemercier et C^{ie}

Gauthier-Villars, Editeur à Paris.

The primary barometer installed in one of the front rooms of the Observatoire, used for the hydrogen gas thermometry in the 1880s. It served as the BIPM primary barometer until the 1960s

Travaux et Mémoires Vol III, 1884.

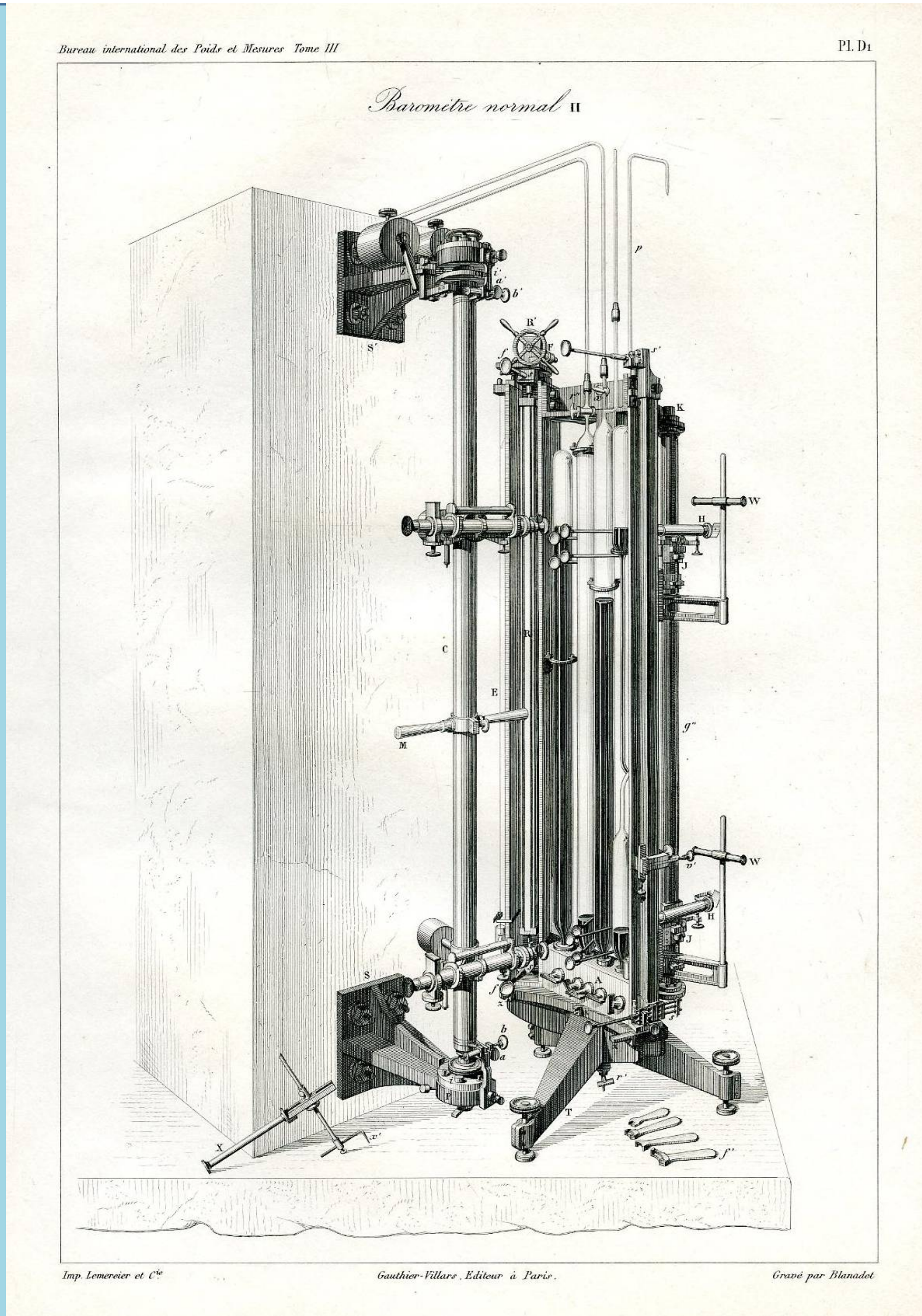
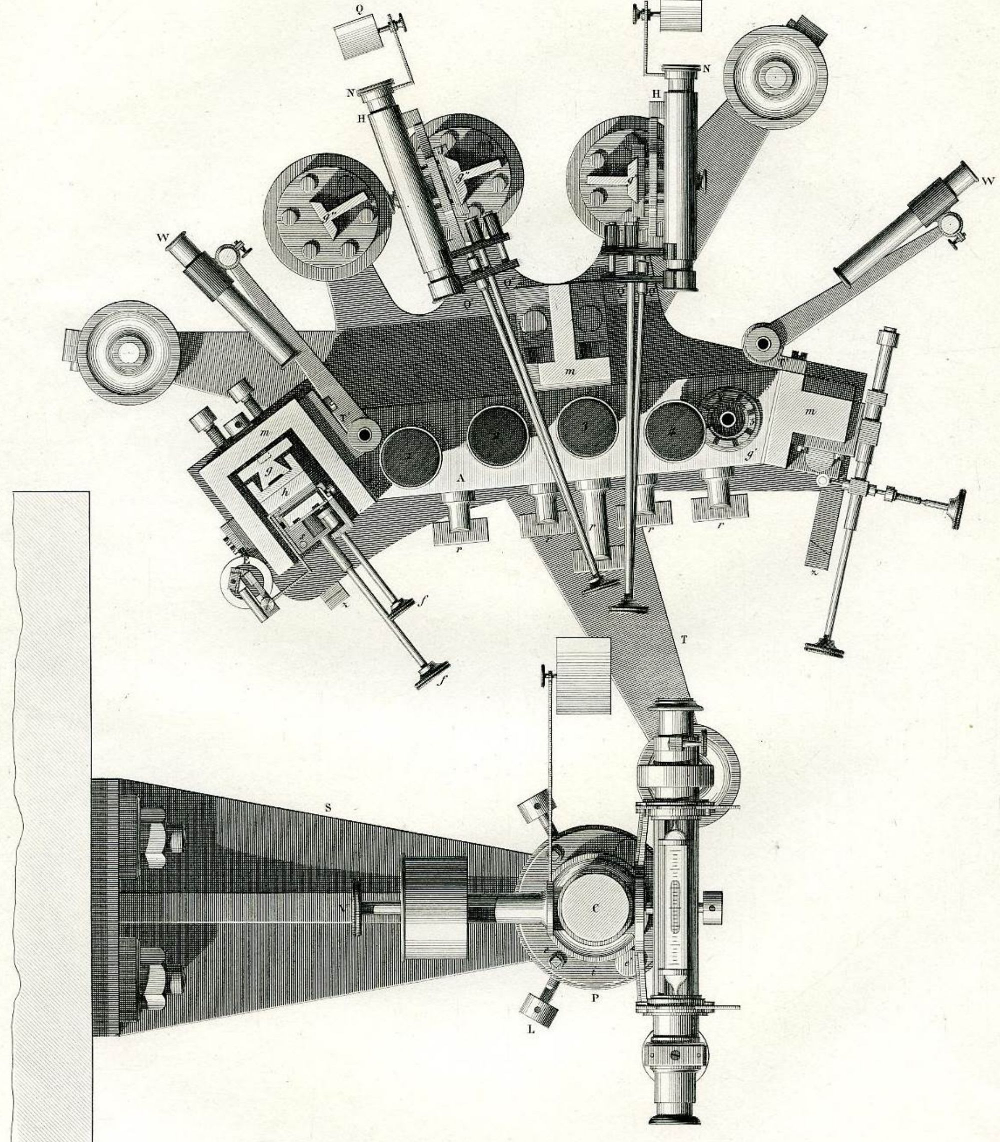
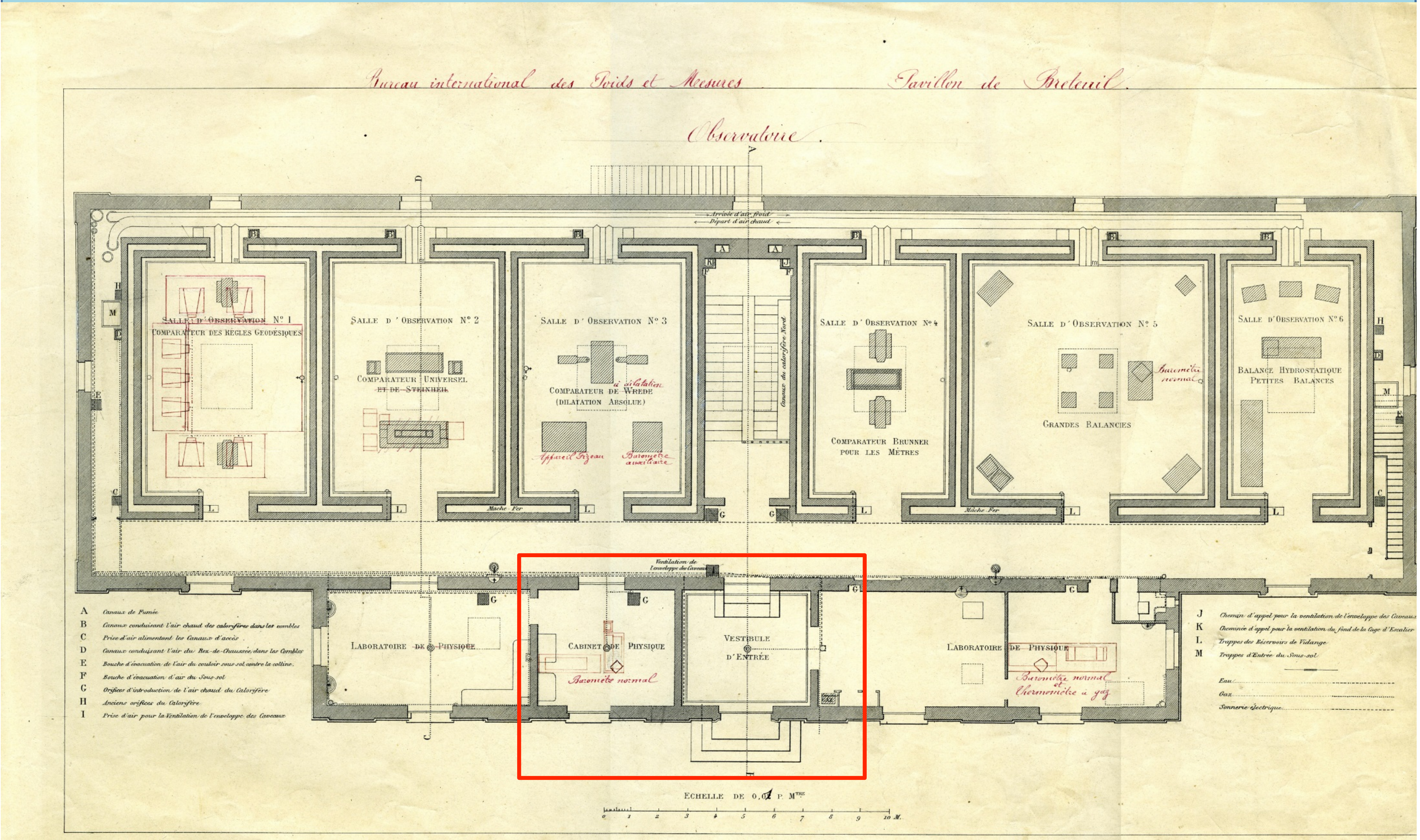


Image BIPM

Baromètre normal II



Imp. Lemercier et Cie Gauthier-Villars, Editeur à Paris Gravé par Blanadet



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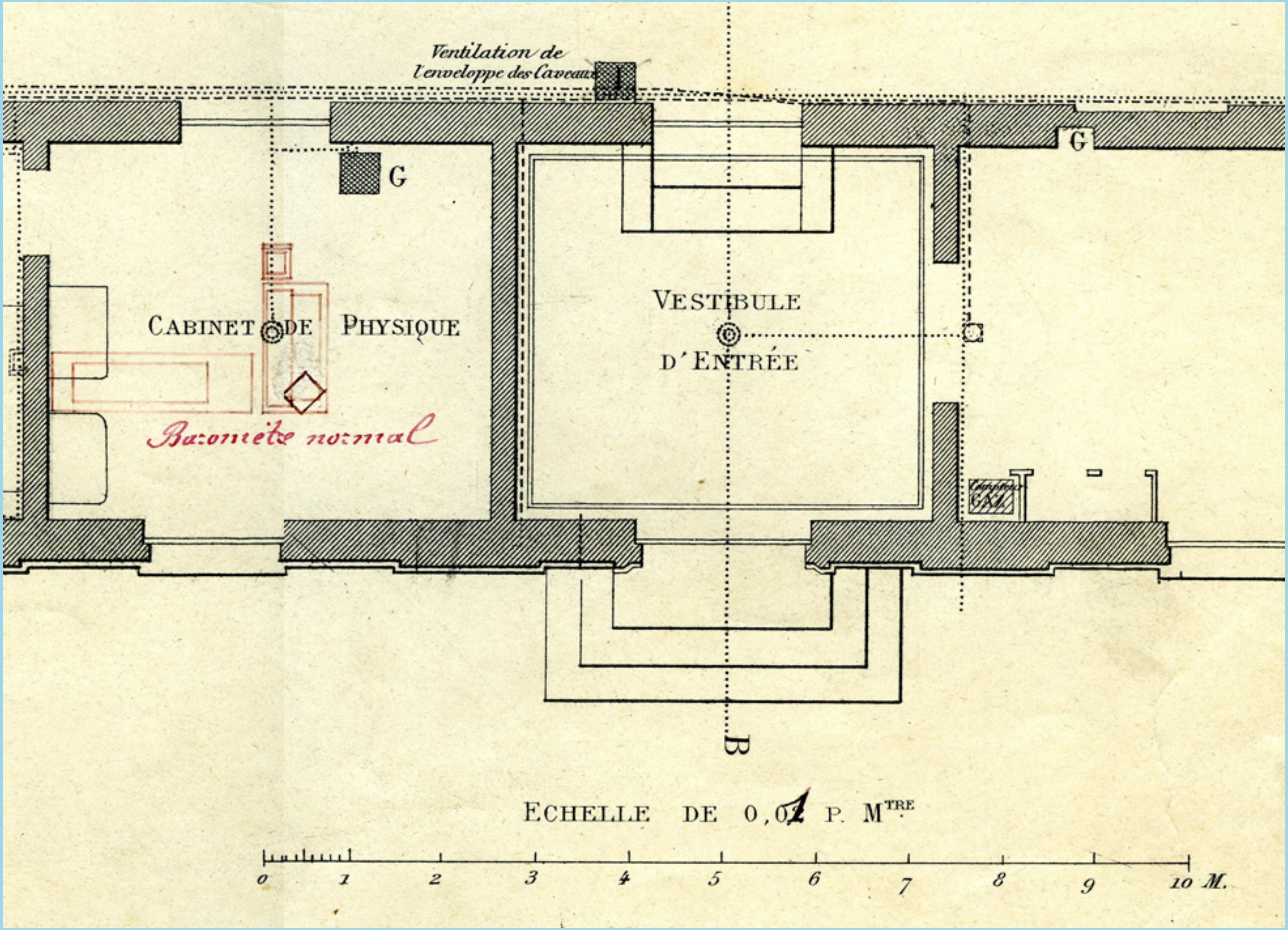
Ventilation de
l'enveloppe des Caveaux
G
G
CABINET DE PHYSIQUE
VESTIBULE
D'ENTRÉE
Baromètre normal
B
ECHELLE DE 0,01 P. MTRE
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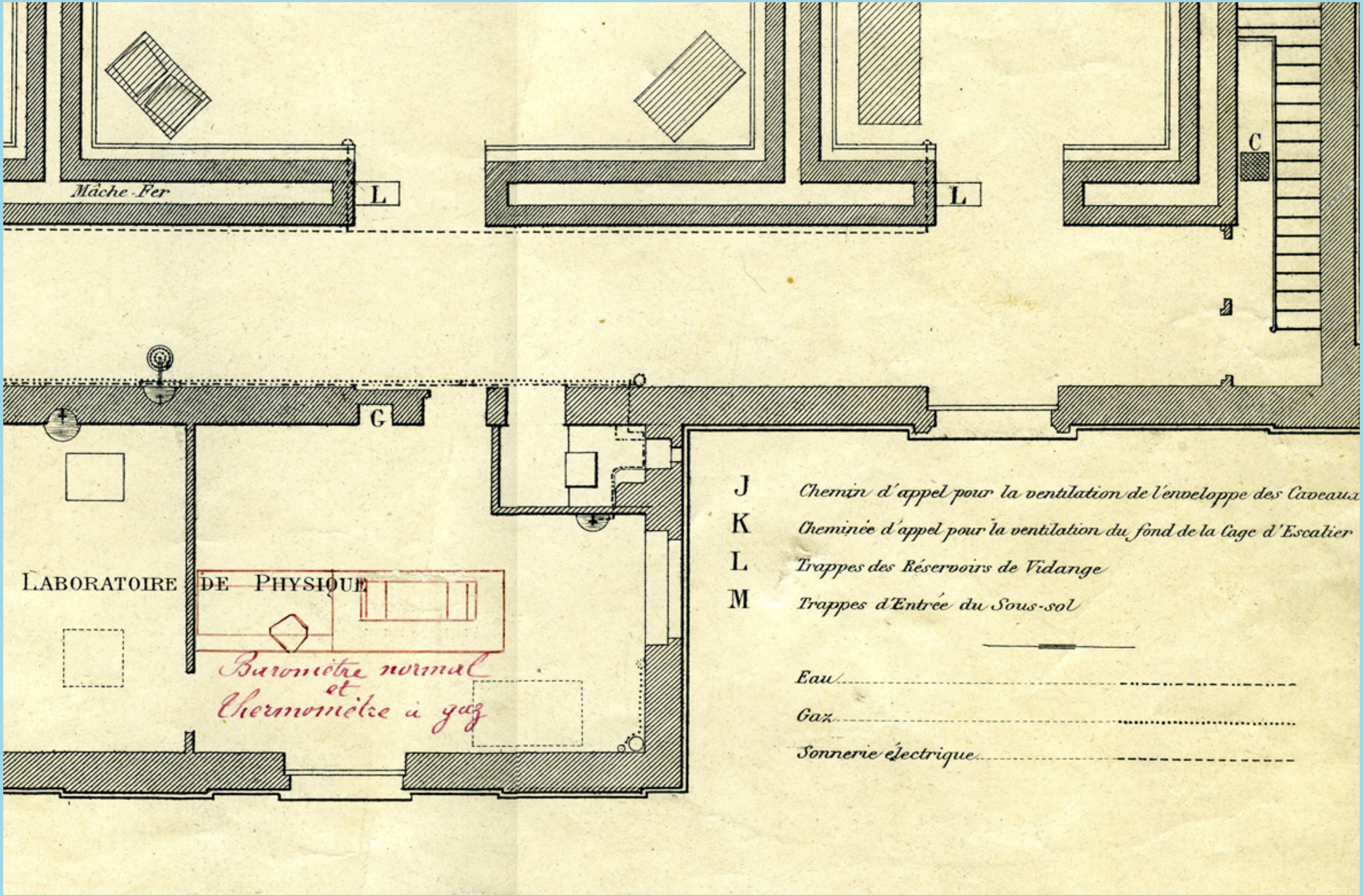
Mâche-Fer
L
L
C
G
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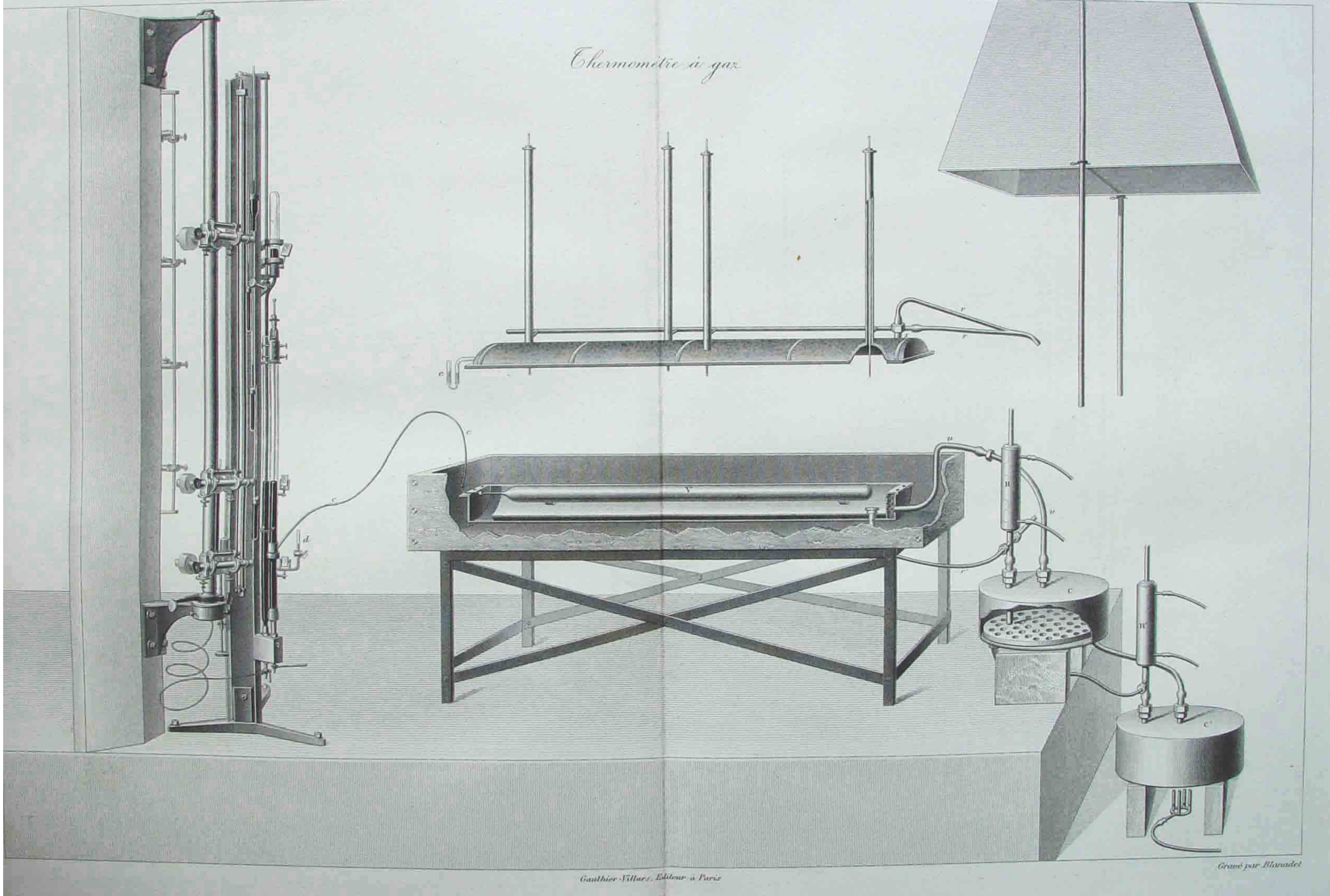
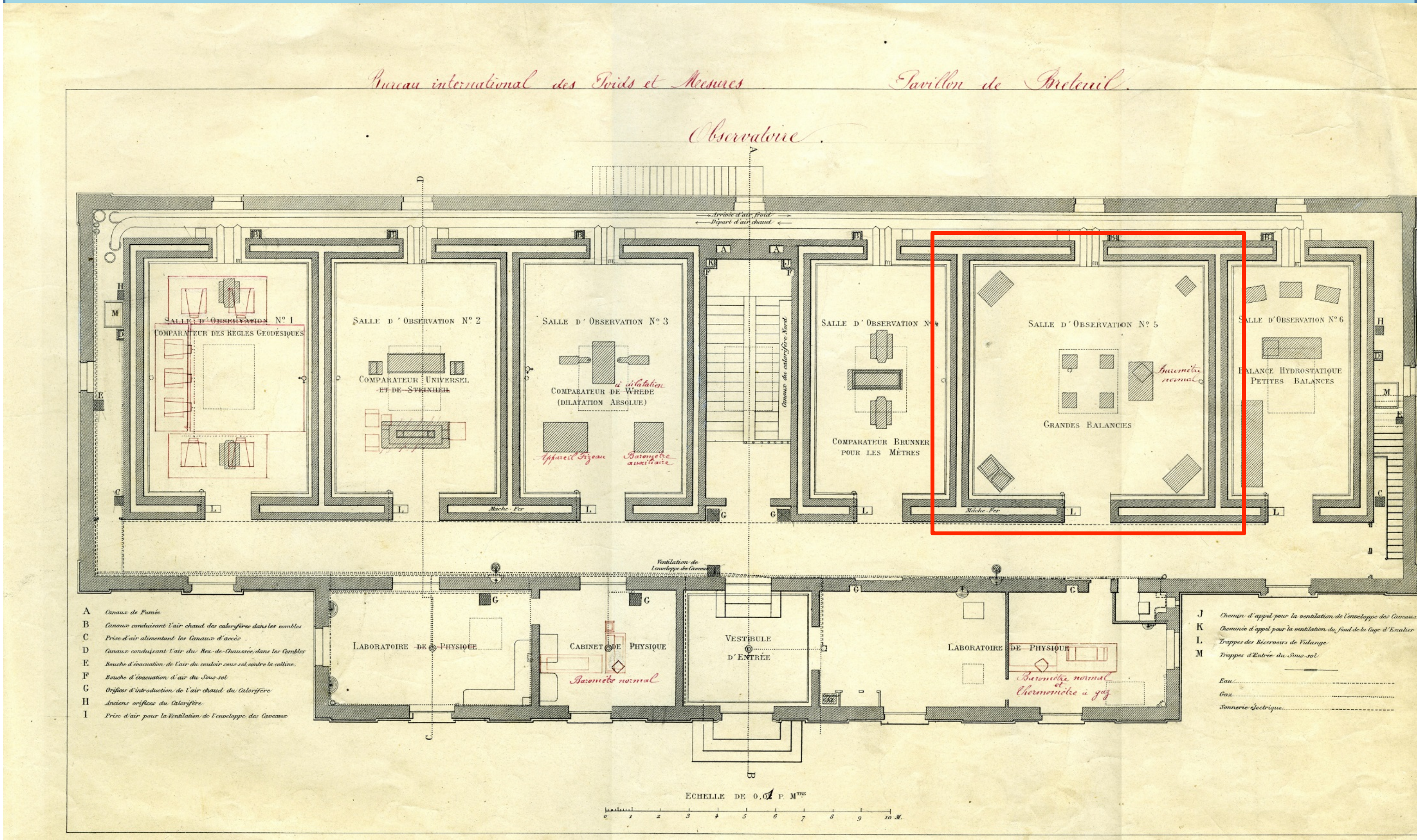
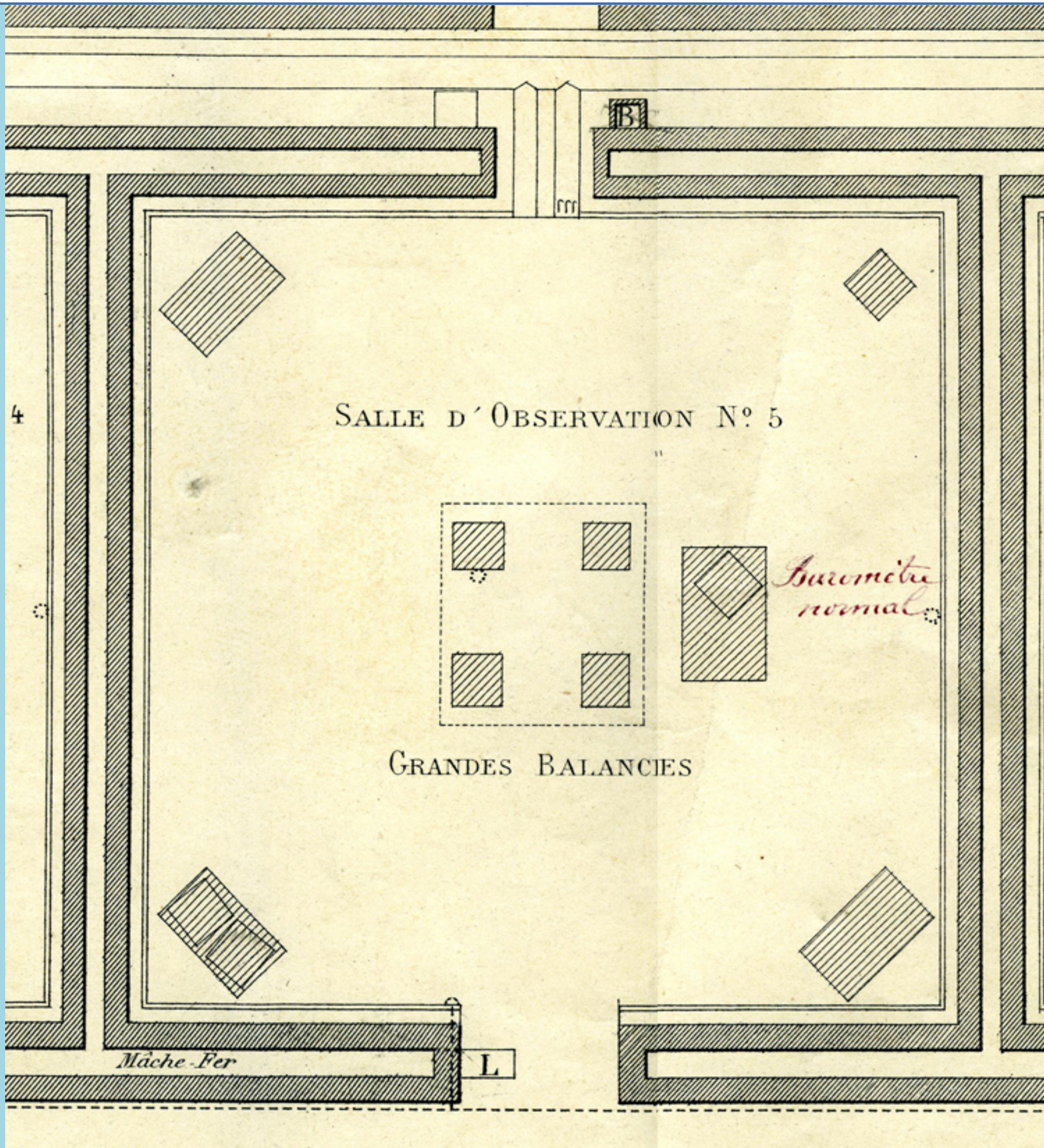
Thermomètre à gaz



Gravé par Blanadet

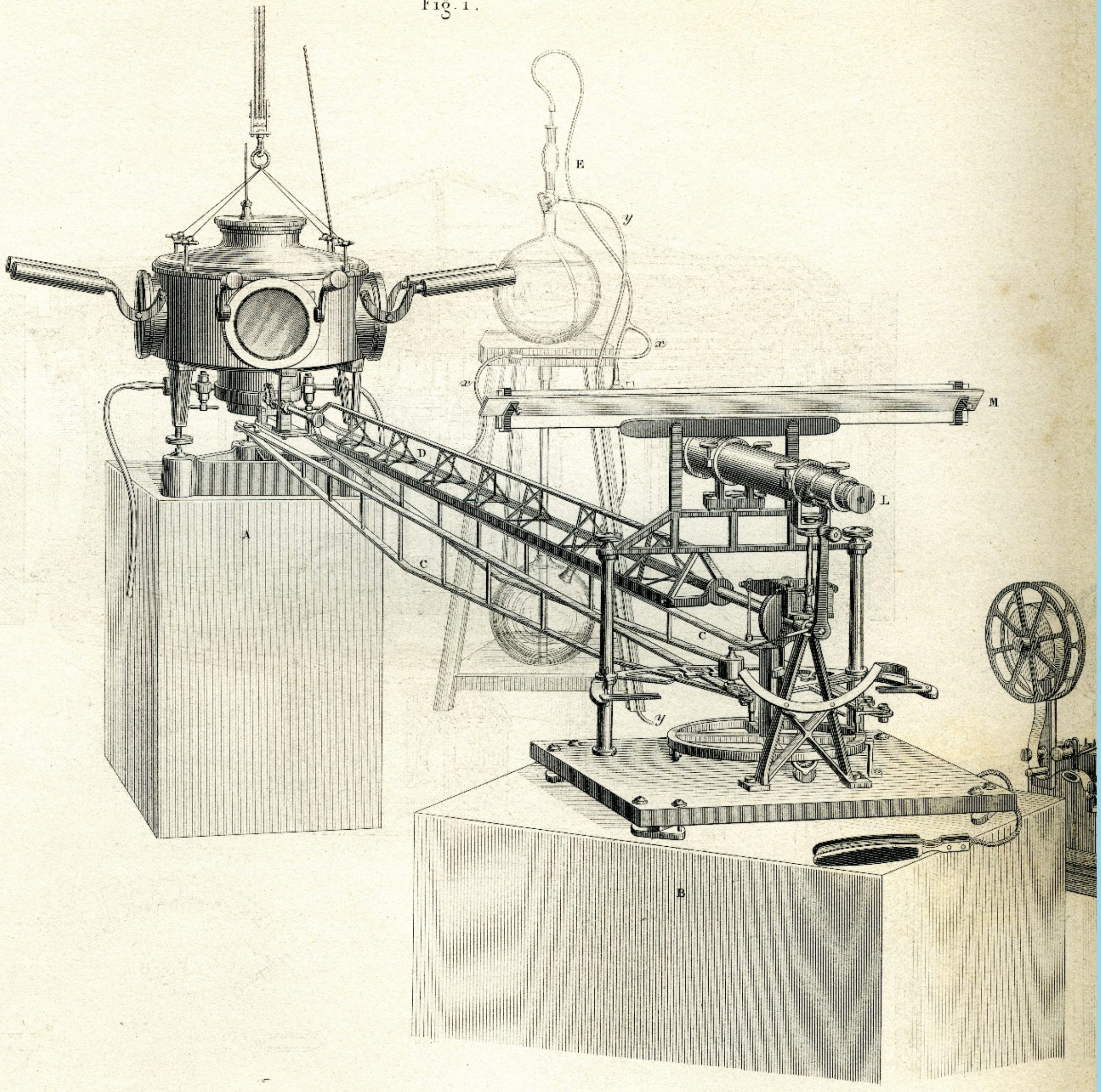
Gauthier-Villars, Éditeur à Paris


Bureau international des Poids et Mesures
Pavillon de Breteuil.
Observatoire.
Arrivée d'air froid
Départ d'air chaud
Salle d'Observation N° 1
Comparateur des Règles Géodésiques
Salle d'Observation N° 2
Comparateur Universel
Salle d'Observation N° 3
Comparateur de Wrede
(dilatation absolue)
Appareil Fizeau
Baromètre auxiliaire
Canaux du calorifère Nord
Salle d'Observation N° 4
Comparateur Brunner pour les Mètres
Salle d'Observation N° 5
Grandes Balances
Baromètre normal
Salle d'Observation N° 6
Balance Hydrostatique
Petites Balances
Ventilation de l'enveloppe des Caveaux
Laboratoire de Physique
Cabinet de Physique
Baromètre normal
Vestibule d'Entrée
Laboratoire de Physique
Baromètre normal et Thermomètre à gaz
A Canaux de Fumée
B Canaux conduisant l'air chaud des calorifères dans les combles
C Prise d'air alimentant les Canaux d'accès.
D Canaux conduisant l'air du Rez-de-Chaussée dans les Combles
E Bouche d'évacuation de l'air du couloir sous sol contre la colline.
F Bouche d'évacuation d'air du Sous-sol
G Orifices d'introduction de l'air chaud du Calorifère
H Anciens orifices du Calorifère
I Prise d'air pour la Ventilation de l'enveloppe des Caveaux
J Chemin d'appel pour la ventilation de l'enveloppe des Caveaux
K Cheminée d'appel pour la ventilation du fond de la Cage d'Escalier
L Trappes des Réservoirs de Vidange
M Trappes d'Entrée du Sous-sol
Eau
Gaz
Sonnerie électrique
Echelle de 0,01 p. Mtre
0 1 2 3 4 5 6 7 8 9 10 M.


B
SALLE D'OBSERVATION N° 5
4
Baromètre normal
GRANDES BALANCES
Mâche-Fer
L

Balance

Fig. 1.



Bunge

Fig. 2.

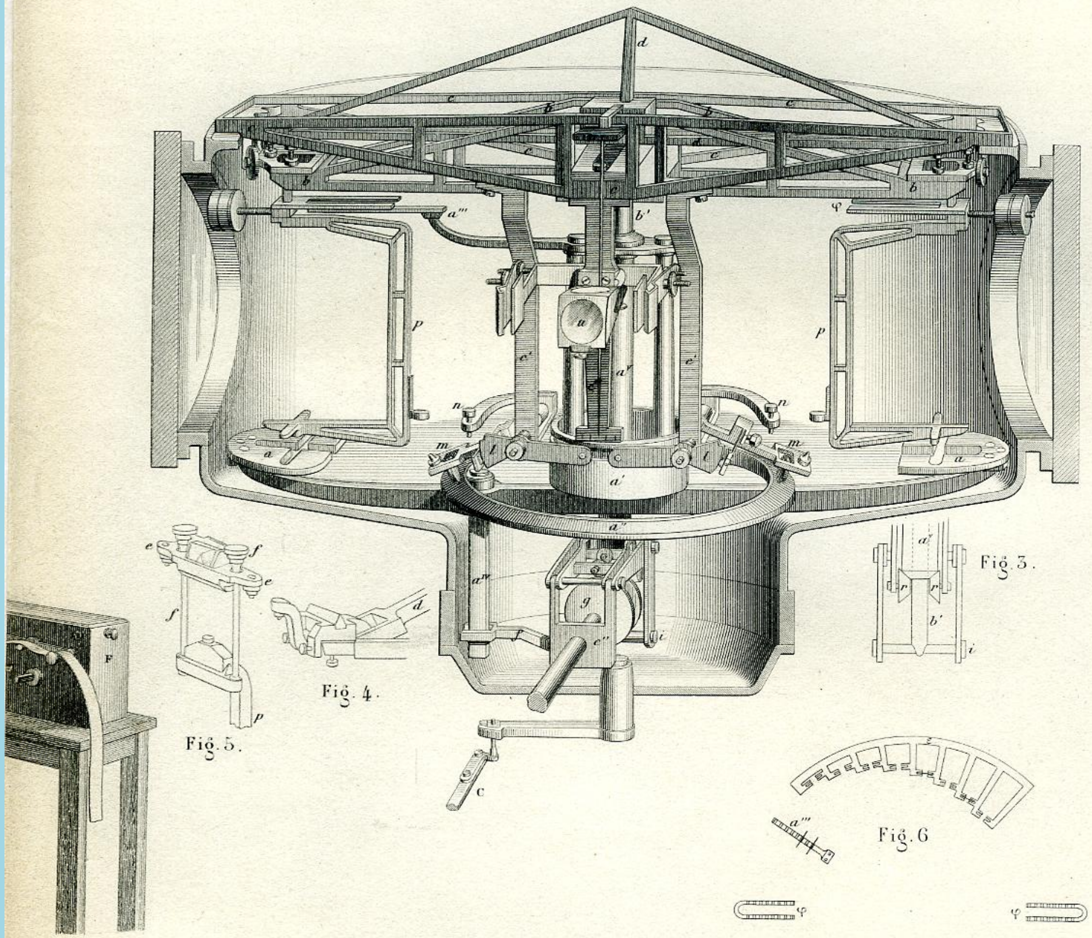


Fig. 3.

Fig. 4.

Fig. 5.

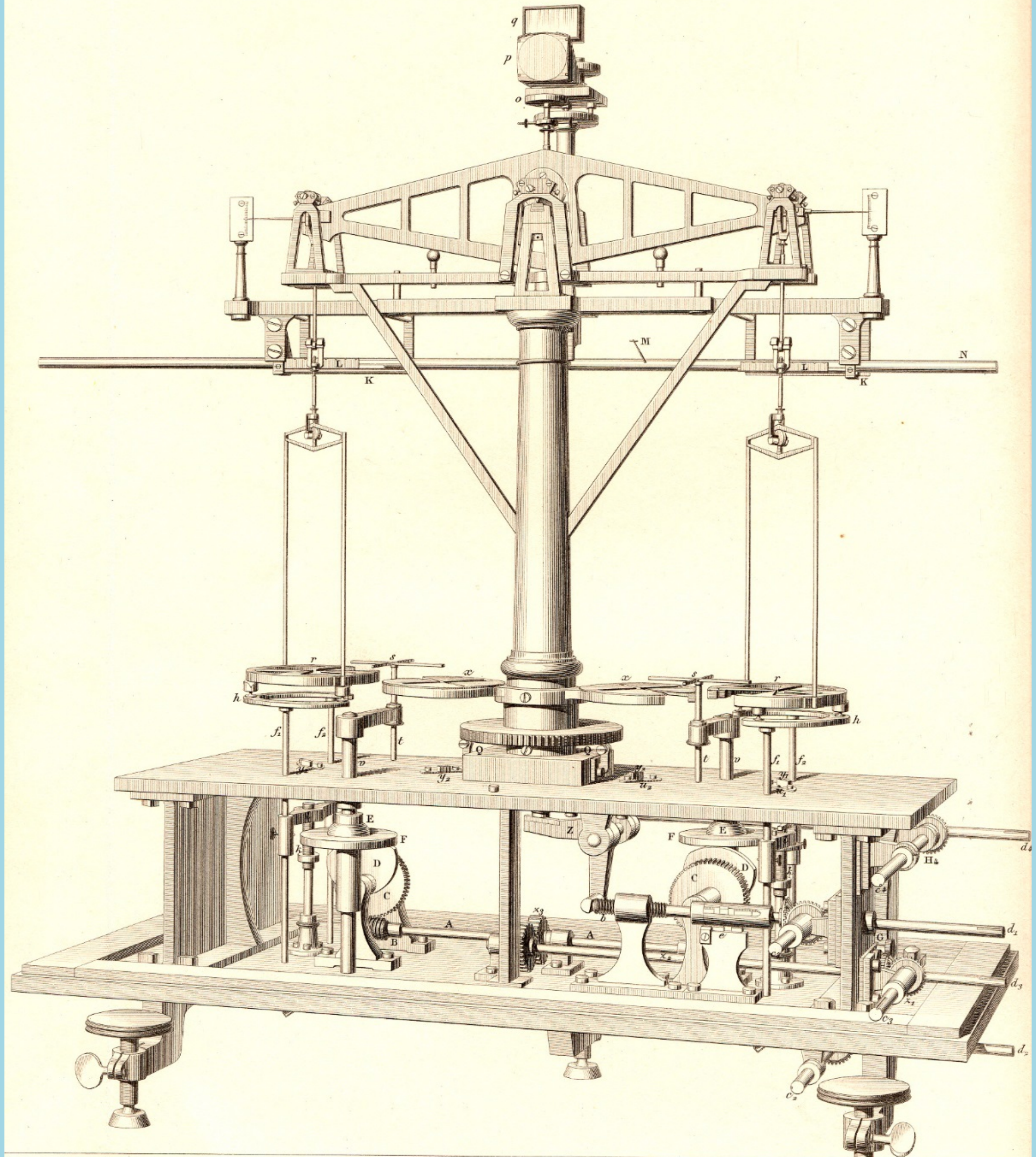
Fig. 6

fils, éditeurs.

Gravé par Blanadet

PESÉES

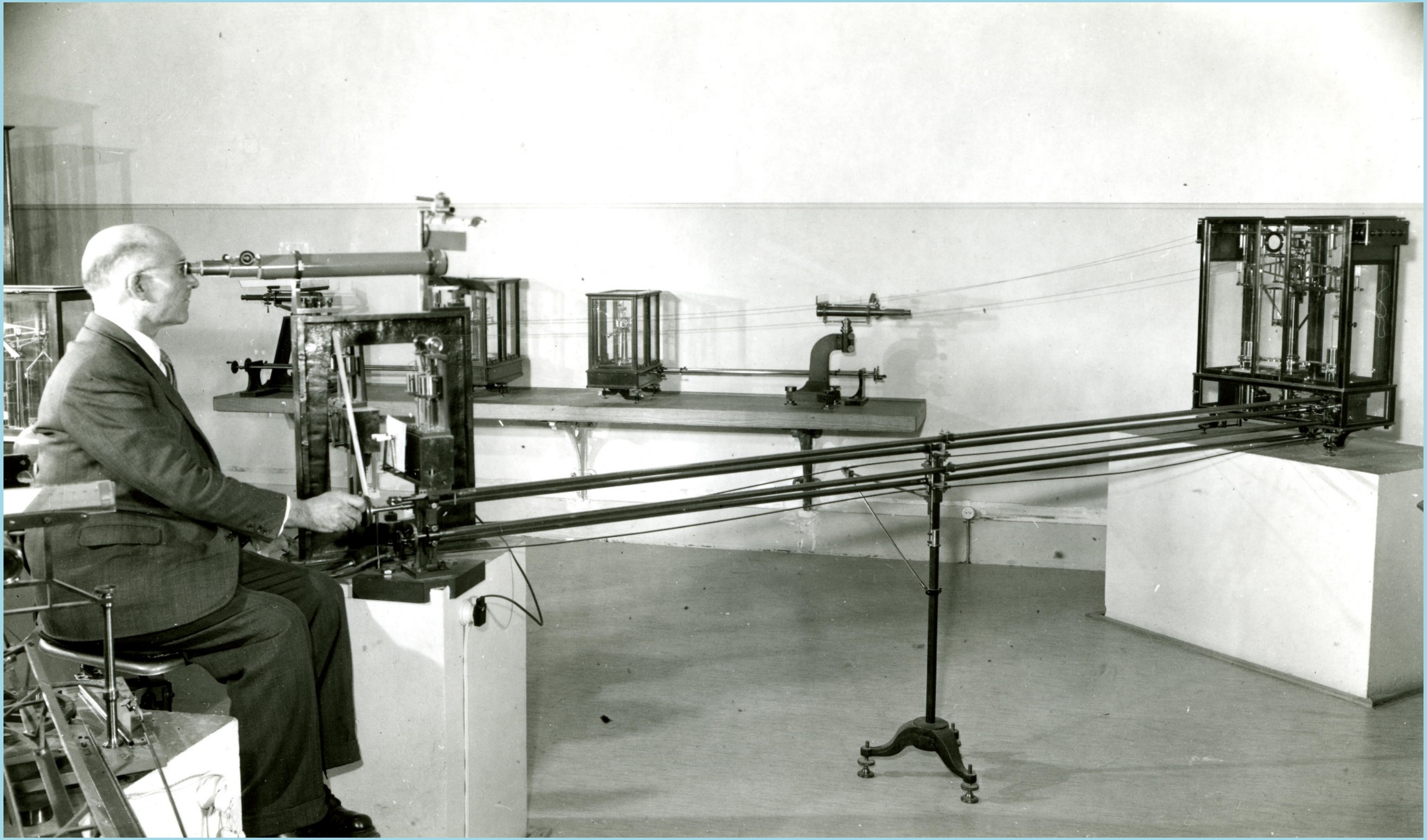
Balance Ruprecht N° 1



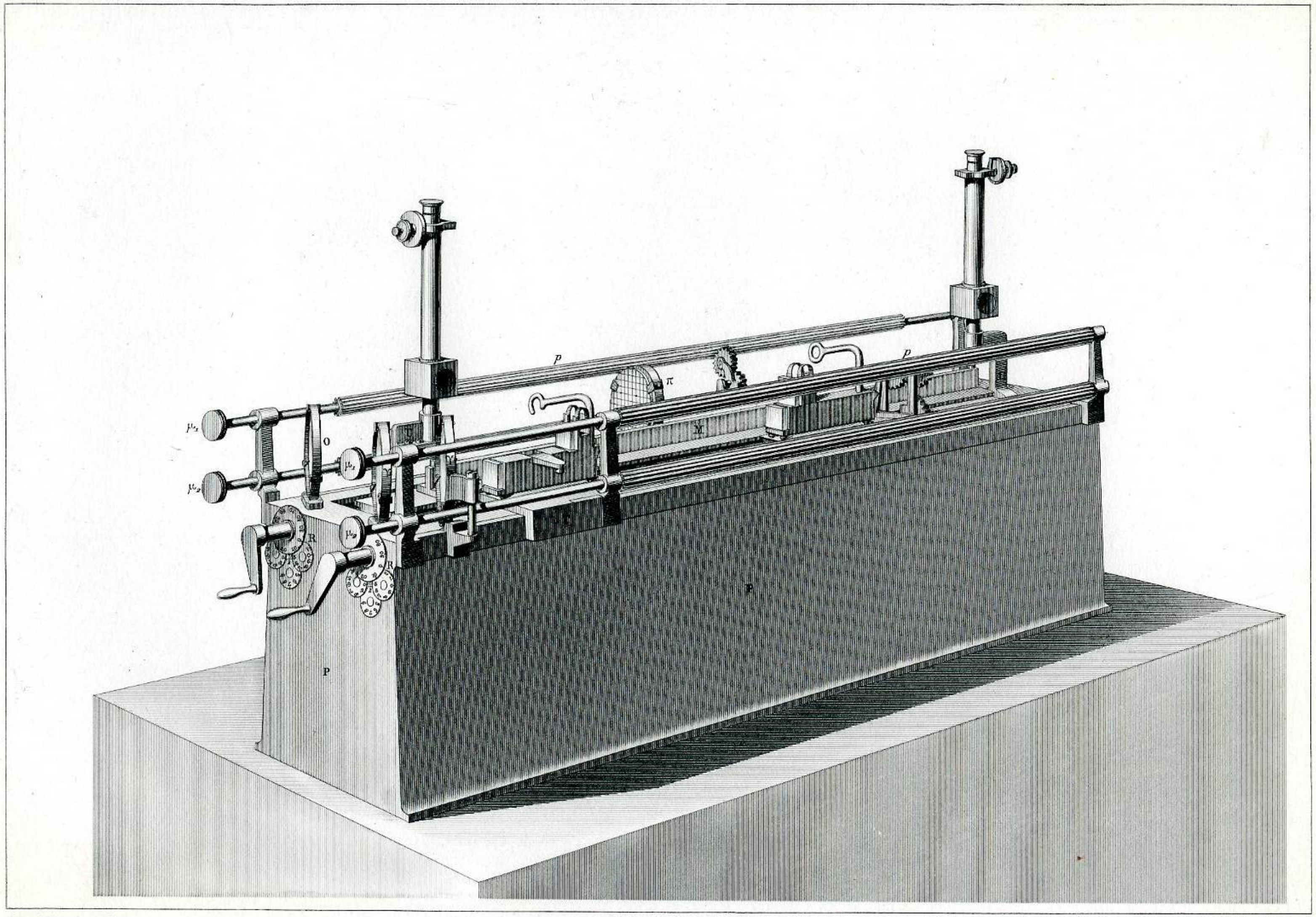
Imp. Eudes Paris

Gauthier-Villars, Editeur à Paris

Gravé par Blanadet



Bureau international des Poids et Mesures. Tome XI *Pl. II*



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

1892 A A Michelson measured the new International Prototype of the Metre in terms of the wavelength of the red line of cadmium

Gould (American), Chaney (British), Arndtsen (Norwegian), Thalen (Swedish), Wild (Russian), Foerster (German), Hirsch (Swiss), Benoit (Director BIPM French), Bertrand (French), de Bodola (Hungarian), de Mercado (Portugese), St.-C. Hepites (Roumanian)

The International Committee for Weights and Measures on the steps of the Grand Salle, Pavillon de Breteuil, September 1894

The International Committee for Weights and Measures on the steps of the Grand Salle, Pavillon de Breteuil, October 1994

Delegates to the 2nd General Conference, 4 – 14 September 1895, in front of the Pavillon de Breteuil:
From left to right back row: J.R Benoît *Director BIPM*, K. Prytz (Denmark), F. Garibay (Mexico), L. de Bodola (Hungary), Sone Arasuke (Japan), **G. Ferraris (Italy),** St. C. Hepites (Roumania), M. Markovitch (Serbia), E. Rousseau (Belgium), M. de Stern (Germany), P. Chappuis (BIPM), M. Duplan (Switzerland) G. Tresca (Conservatoire), C. E. Guillaume (BIPM), M. Cobo de Guzman (Spain).
From right to left front row: P. Arrillaga (Spain), H. de Macedo (Portugal), A. Hirsch (Switzerland) *Secretary CIPM*, W. Foerster (Germany) *President CIPM*, M. Marey *President of the Conference*, J. Bertrand, (France), V. von Lang (Austria), R. Thalen (Sweden), A. Arndtsen (Norway).

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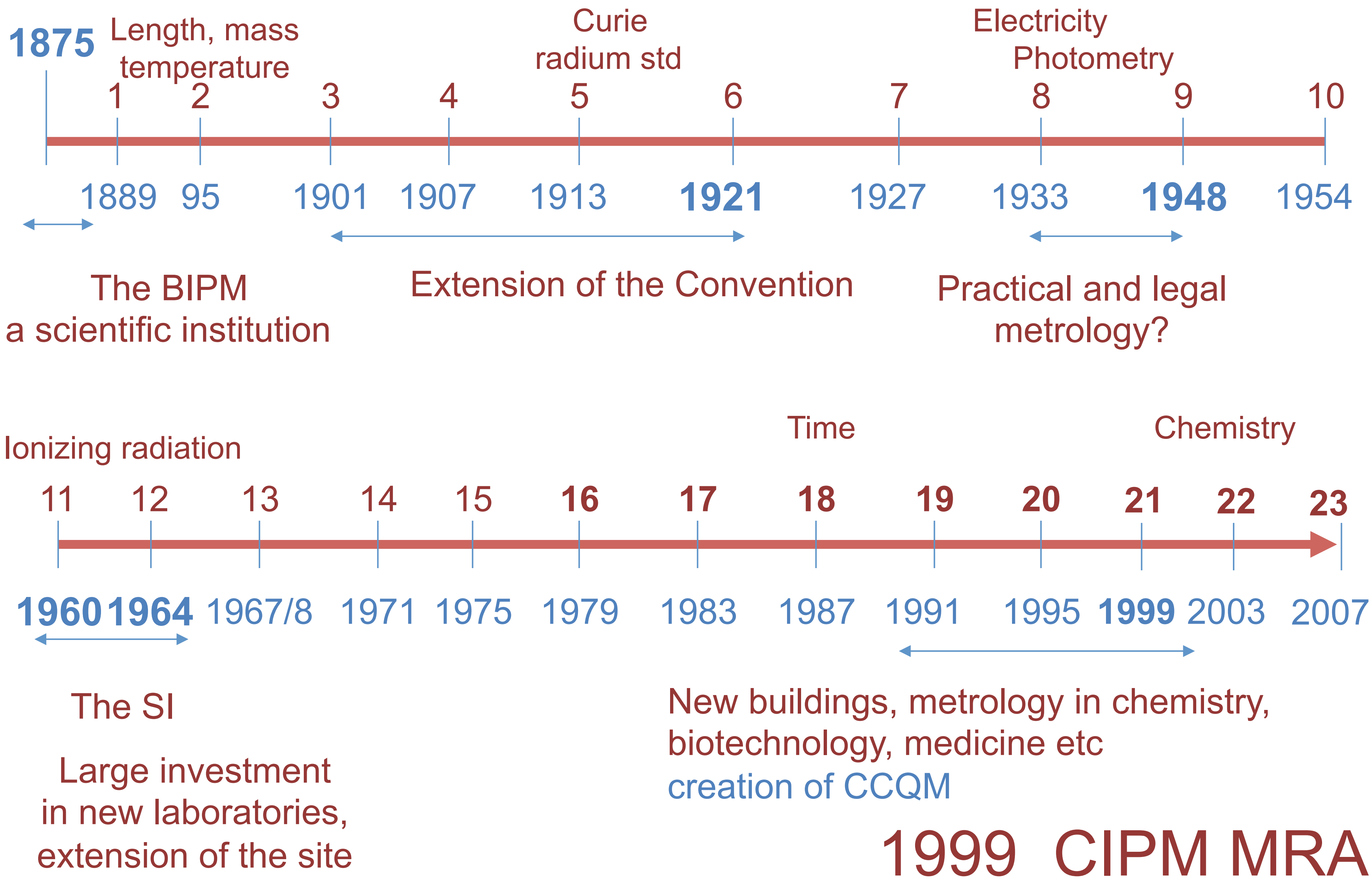
CGPMs from the 1st in 1889 to the 23nd in 2007 and the evolution of the Metre Convention and the work of the BIPM



The CIPM Mutual Recognition Arrangement (CIPM MRA) was signed in October 1999 by Directors of 38 NMIs and one International Organization. It is now signed by the Directors of 98 NMIs, 4 International Organizations and 152 secondary metrology institutes.

The results of the 900 key comparisons and some 24000 calibration and measurement capabilities are on the public BIPM Key Comparison Database (KCDB).

Reconnaissance mutuelle

des étalons nationaux de mesure
et des certificats d'étalonnage et de mesurage
émis par les laboratoires nationaux de métrologie

Paris, le 14 octobre 1999

Mutual recognition

of national measurement standards
and of calibration and measurement certificates
issued by national metrology institutes

Paris, 14 October 1999

Comité international des poids et mesures

Bureau international des poids et mesures	Organisation intergouvernementale de la Convention du Mètre

The essential points

The Mutual Recognition Arrangement (MRA) has been drawn up by the International Committee of Weights and Measures (CIPM), under the authority given to it in the Metre Convention, for signature by directors of the national metrology institutes (NMIs) of Member States of the Convention.

Objectives

- to establish the degree of equivalence of national measurement standards maintained by NMIs;
- to provide for the mutual recognition of calibration and measurement certificates issued by NMIs;
- thereby to provide governments and other parties with a secure technical foundation for wider agreements related to international trade, commerce and regulatory affairs.

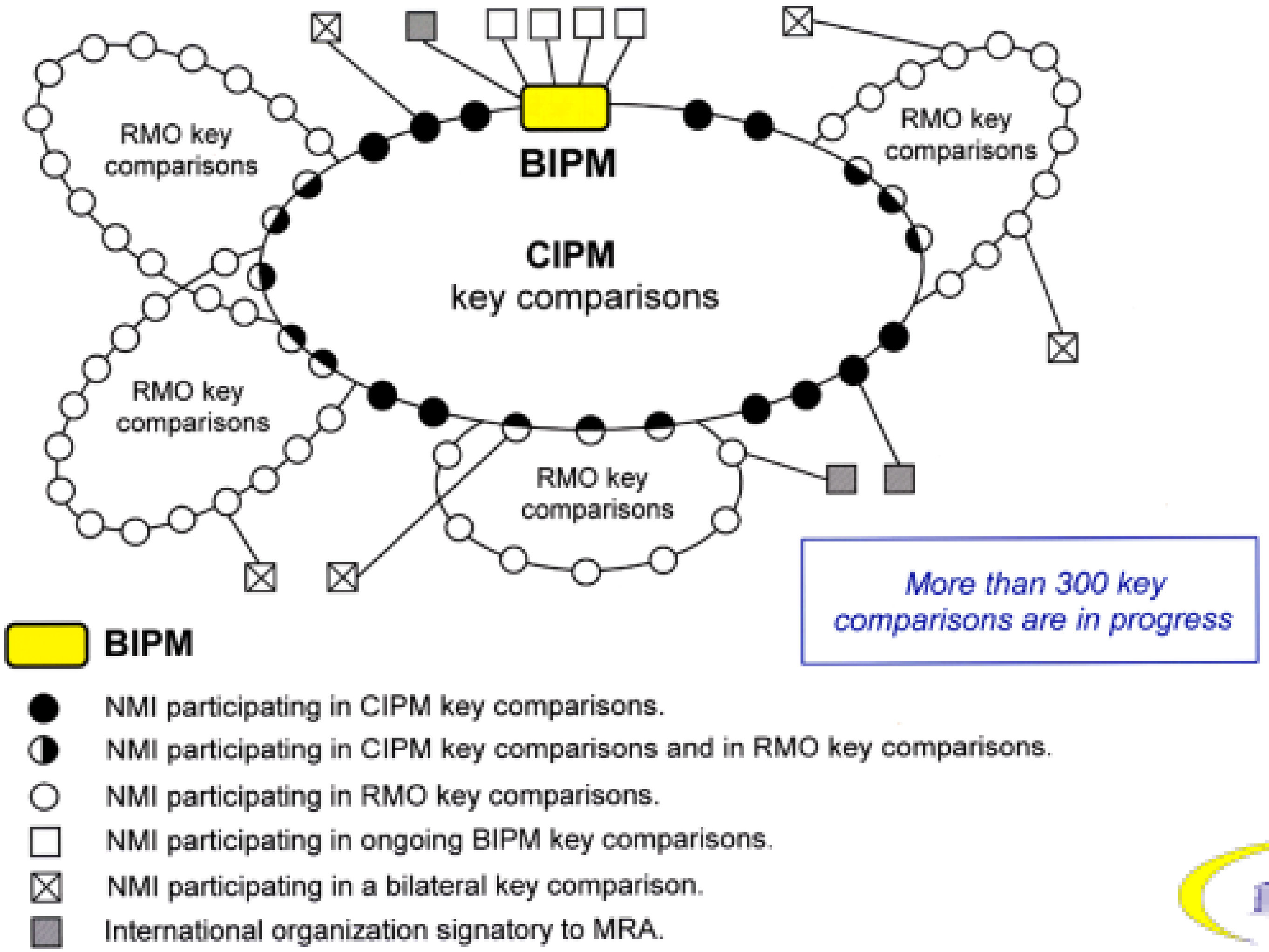
Process

- international comparisons of measurements, to be known as key comparisons;
- supplementary international comparisons of measurements;
- quality systems and demonstrations of competence by NMIs.

Outcome

- statements of the measurement capabilities of each NMI in a database maintained by the BIPM and publicly available on the Web.

Scheme for key comparisons



BIPM
February 2001

Engagement

Les directeurs des LNM qui signent l'arrangement de reconnaissance mutuelle le font avec l'approbation des autorités appropriées de leur pays. Par là même, ils :

- acceptent les procédures rédigées dans l'arrangement et visant à établir la base de données ;
- reconnaissent les résultats des comparaisons clés et supplémentaires, inscrits dans la base de données ;
- reconnaissent les possibilités en matière de mesures et d'étalonnages des autres laboratoires participant à l'arrangement, et inscrites dans la base de données.

Engagement

NMI directors sign the MRA with the approval of the appropriate authorities in their own country and thereby:

- accept the process specified in the MRA for establishing the database;
- recognize the results of key and supplementary comparisons as stated in the database;
- recognize the calibration and measurement capabilities of other participating NMIs as stated in the database.

RECONNAISSANCE MUTUELLE

DES ÉTALONS NATIONAUX DE MESURE

ET DES CERTIFICATS D'ÉTALONNAGE ET DE MESURAGE

ÉMIS PAR LES LABORATOIRES NATIONAUX DE MÉTROLOGIE

Arrangement rédigé par le Comité international des poids et mesures (CIPM) en vertu de l'autorité qui lui est conférée par les États membres de la Convention du Mètre

MUTUAL RECOGNITION

OF NATIONAL MEASUREMENT STANDARDS

AND OF CALIBRATION AND MEASUREMENT CERTIFICATES

ISSUED BY NATIONAL METROLOGY INSTITUTES

Arrangement drawn up by the International Committee of Weights and Measures under the authority given to it in the Metre Convention

Ce document sera soumis à la signature des directeurs des laboratoires nationaux de métrologie (LNM) des États membres de la Convention du Mètre, à partir du 14 octobre 1999, date de leur réunion à l'occasion de la 21^{e} Conférence générale des poids et mesures.

This document will be open for signature by directors of the national metrology institutes (NMIs) of the Member States of the Metre Convention starting from 14th October 1999, at a meeting of directors that will take place on the occasion of the 21st General Conference of Weights and Measures.

Nom/*Name* **Signature**	**LNM**/*NMI**	**État**/*State*	**BIPM Signature**
[illegible]	CSIR-NML	South Africa	
E. Göbel	PTB/BAM	Germany	

*Tous les laboratoires et instituts mentionnés dans cette colonne participent à cet arrangement.
This arrangement covers all the institutes listed here.

Nom/*Name*	Signature	LNM/*NMI*	État/*State*	BIPM Signature
Helge Kildal		Norwegian Metrology and Accreditation Service (JV)	Norway	
Chris Sutton		Measurement Standards Laboratory of New Zealand	New Zealand	
Menno Plantenga		NMi Van Swinden laboratory	the Netherlands	
Krzysztof Mordziński		Central Office of Measures	Poland	
Fernando Farinha		IPQ	PORTUGAL	
PAUL DARVARIU		INM	ROMANIA	
JOHN RAE		NPL	UK.	
Vladimir Krutikov		VNIIM VNIIFTRI VNIIOFI VNIIMS VNIIR UNIIM SNIIM	Russian Federation	
LAM Kong Hong		PSB	Singapore	

Pages supplémentaires, numérotées I, II, III et IV, des signatures des directeurs de laboratoires nationaux de métrologie apposées le 14 octobre 1999

Additional pages labelled I, II, III, and IV, of signatures of directors of national metrology institutes, affixed on 14 October, 1999

Nom/*Name*	**Signature**	**LNM**/*NMI*	**État**/*State*	**BIPM Signature**
J. Valdés	[signature]	INTI	Argentina	[signature]
B.D. Inglis	[signature]	NML-CSIRO	AUSTRALIA.	
A. LEITNER	[signature]	BEV	Austria	
Ih. Strashimirov	[signature]	NCM	Bulgaria.	
H. VOORHOF	[signature]	Service Métrologie	Belgique	
MARCO ANTONIO LIMA	[signature]	INMETRO	BRASIL	
Janusz Lusztyk	[signature]	INMS/NRC	CANADA	
[signature]		NIM	China	
Myung Sai Chung	[signature]	KRISS	Rep. of Korea	
KIM CARNEIRO	[signature]	DFM	DANEMARK	
Garcia Jose Roca, Alyce	[signature]	CEM	ESPAÑA	
Karen H. Brown	[signature]	NIST	United States	

Air France Concorde over the Atlantic at Mach 2.03 and 18 km altitude on 7 March 1999 en route for New York (photo TJQ)


AIR FRANCE

BIPM
Bureau International des Poids & Mesures

Home Key and supplementary comparisons Calibration and Measurement Capabilities - CMCs

KCDB home > **Free search results**

The BIPM key comparison database

KCDB

Refine your search

CMC AREA

PHYSICS

Result of the search

Your query 'length' produced more than 1000 results New search

[<< Prev]16 17 18[Next >>]

United States, NIST (National Institute of Standards and Technology)

Complete CMCs in Length for United States (.PDF file)

Line standards. Precision line scale: line spacing, L, **0.002 mm to 1000 mm**
Absolute expanded uncertainty (k = 2, level of confidence 95%) in nm: **(3 + 0.1*L*)**
Line scale interferometer
Illumination: reflection only
Approved on 14 June 2004
Internal NMI service identifier: NIST/8

Line standards. Stage micrometer: line spacing, L, **0.002 mm to 100 mm**
Absolute expanded uncertainty (k = 2, level of confidence 95%) in nm: **(3 + 0.1*L*)**
Line scale interferometer
Illumination: reflection only
Approved on 14 June 2004
Internal NMI service identifier: NIST/9

Some approved calibration capabilities of NIST in length measurements

- Switzerland (68)
- Finland (59)
- United Kingdom (56)
- Turkey (51)
- Italy (50)
- Poland (48)
- Spain (45)
- Sweden (41)
- Austria (29)
- France (27)
- Slovenia (24)
- Slovakia (22)
- Romania (21)
- Hungary (20)
- Bulgaria (18)
- Croatia (18)
- Belgium (17)
- Portugal (16)
- Denmark (15)
- Ireland (13)
- Norway (11)
- Lithuania (9)
- Serbia (9)
- Latvia (6)
- Greece (5)
- APMP (383)
  - Japan (62)
  - China (52)
  - Korea, Republic of (48)
  - India (47)
  - Chinese Taipei (41)
  - Singapore (37)
  - Thailand (34)
  - New Zealand (22)
  - Hong Kong, China (13)
  - Viet Nam (9)
  - Malaysia (7)
  - Australia (6)
  - Indonesia (5)

Mechanical comparison
Internal NMI service identifier: NIST/17

Diameter standards. Internal cylinder (ring): diameter L, **2 mm to 100 mm**
Absolute expanded uncertainty (*k* = 2, level of confidence 95%) in nm: **(85 + 0.4*L*), *L* in mm, values range from 86 nm to 125 nm**
Mechanical comparison
Internal NMI service identifier: NIST/18

Diameter standards. Sphere (ball): diameter L, **1 mm to 30 mm**
Absolute expanded uncertainty (*k* = 2, level of confidence 95%) in nm: **Q[21, 0.5*L*], *L* in mm, values range from 21 nm to 26 nm**
Mechanical stylus & laser displacement interferometer scale
Internal NMI service identifier: NIST/19

Surface texture. Groove or step-height standard: step height H, **0.007 µm to 25 µm**
Absolute expanded uncertainty (*k* = 2, level of confidence 95%) in nm: **Q[1, 7*H*], *H* in µm, values range from 1 nm to 175 nm**
Stylus instrument
Internal NMI service identifier: NIST/35

Miscellaneous complex geometry. Hardness indenter: radius, **180 µm to 220 µm**
Absolute expanded uncertainty (*k* = 2, level of confidence 95%) in µm: **0.4**
Stylus instrument
Internal NMI service identifier: NIST/61

Reference materials. Linewidth, photomask - SRM 473: linewidth, **0.5 µm to 30 µm**
Absolute expanded uncertainty (*k* = 2, level of confidence 95%) in nm: **37**
Optical microscopy & laser displacement interferometer scale
Internal NMI service identifier: NIST/79

Reference materials. Pitch, photomask (magnification standard) - SRM 473: pitch, **2 µm to 60 µm**
Absolute expanded uncertainty (*k* = 2, level of confidence 95%) in nm: **10**
Optical microscopy & laser displacement interferometer scale
Internal NMI service identifier: NIST/80

More approved calibration capabilities of NIST in length measurements

The advent of the CIPM-MRA

- Boeing has recently been one of the first industrial corporations to take advantage of the CIPM-MRA
- Boeing utilizes the CIPM-MRA equivalence data to support our global measurement system
- We rely on the peer reviewed NMI capabilities to support our emergent technologies

A slide from a presentation by a Vice-President of Boeing at a symposium in Paris on the 10th Anniversary in 2009 of the signing of the CIPM MRA

The Metre Convention, the BIPM and the development of measurement standards from 1791 to the New SI in 2018

Part 2

The development of measurement standards from 1791 to the New SI in 2018

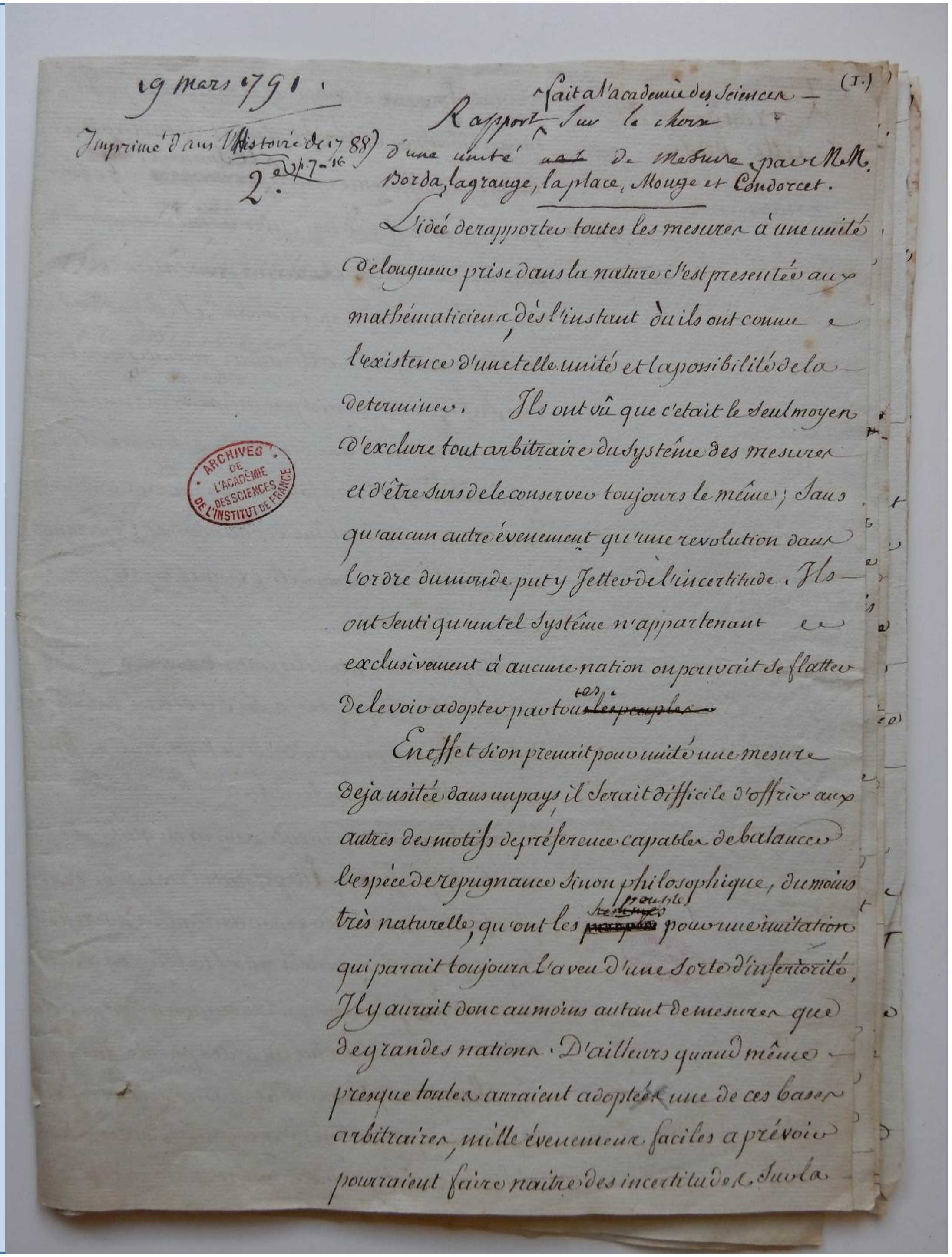
Terry Quinn

Emeritus Director *Bureau International des Poids et Mesures* (BIPM)

Development of units from 1791 to the proposed New SI in 2018

- The proposals of the Académie des sciences in 1791
- Maxwell in 1870
- CIPM 1891 on linking the length of the metre to natural standards
- Michelson measures the wavelength of light in terms of the metre at the BIPM 1892
- Measurements by Benoit and Fabry in 1906, definition of the Ångstrom in 1927
- Practical electrical units starting from 1891, International Practical Units of 1908
- International temperature Scales of 1927, ITS-27 ITS-48 and ITS-90, definition of the kelvin
- Definition of the ampere and candela 1948
- New definitions of the metre and second in 1960
- The International System of Units 1960
- Atomic definition of the second 1967
- Definition of the mole in 1971 – statements by Jan de Boer
- New definition of the candela 1979
- New definition of the metre in 1983

First page of the Report to the *Académie des Sciences* on the choice of a unit of measurement by Borda, Lagrange, Laplace, Monge and Condorcet
19 March 1791



19 mars 1791.

Imprimé dans l'Histoire de 1788) 2.e p. 7-16

(1.)

Rapport fait à l'académie des Sciences sur le choix d'une unité de Mesure, par MM. Borda, lagrange, laplace, Monge et Condorcet.

L'idée de rapporter toutes les mesures à une unité de longueur prise dans la nature s'est presentée aux mathématiciens dès l'instant où ils ont connu l'existence d'une telle unité et la possibilité de la determiner. Ils ont vû que c'etait le seul moyen d'exclure tout arbitraire du système des mesures et d'être surs de le conserver toujours le même ; sans qu'aucun autre évenement qu'une revolution dans l'ordre du monde put y jetter de l'incertitude. Ils ont senti qu'un tel système n'appartenant exclusivement à aucune nation on pouvait se flatter de le voir adopter par tous ~~les peuples~~ ces

En effet si on prenait pour unité une mesure deja usitée dans un pays il serait difficile d'offrir aux autres des motifs de préference capables de balancer l'espèce de repugnance sinon philosophique, du moins très naturelle, qu'ont les ~~peuples~~ [illegible] pour une imitation qui parait toujours l'aveu d'une sorte d'inferiorité. Il y aurait donc au moins autant de mesures que de grandes nations. D'ailleurs quand même presque toutes auraient adoptées une de ces bases arbitraires, mille évenemens faciles à prévoir pourraient faire naitre des incertitudes sur la

Borda, lagrange, laplace, Monge et Condorcet.

L'idée de rapporter toutes les mesures à une unité de longueur prise dans la nature s'est presentée aux mathématiciens dès l'instant où ils ont connu l'existence d'une telle unité et la possibilité de la determiner. Ils ont vû que c'etait le seul moyen d'exclure tout arbitraire du système des mesures et d'être surs de le conserver toujours le même; sans qu'aucun autre évenement qu'une revolution dans l'ordre du monde put y jetter de l'incertitude. Ils ont senti qu'un tel système n'appartenant exclusivement à aucune nation on pouvait se flatter de le voir adopter par tous ~~les peuples~~ [les]

"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."

les autres vices du systeme des mes…

entrainerait une incomodité presque égale pour le plus grand nombre.

On peut reduire a trois les unités ~~[illegible]~~ qui paraissent les plus propres a servir de base la longueur du pendule, un quart du cercle de l'equateur, enfin un quart du meridien terrestre.

La longueur du pendule a paru en général meriter la préference. Elle présente l'avantage d'être plus facile a determiner et par consequent à verifier, si quelques accidens arrivés aux étalons en amenaient la necessité. De plus ceux qui voudraient adopter cette mesure déja établie chez un autre peuple ou qui après l'avoir adoptée auraient besoin de la verifier ne seraient pas obligés d'envoyer des observateurs a l'endroit où la premiere opération aurait été faite.

En effet la loi des longueurs du pendule est e (2.)

^certaine assez ^ confirmée par l'experience

assez ~~[illegible]~~ pour être employée dans des opérations

sans avoir à craindre que ~~[illegible]~~ des erreurs imperceptibles.

"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."

affecter une sorte de ~~[illegible]~~ prééminence.

Nous concluons ~~enfin~~ en conséquence, à présenter ce rapport à l'assemblée nationale en la priant de vouloir bien decreter les opérations proposées et les mesures nécessaires pour l'exécution de celles qui doivent s'étendre sur le territoire de l'Espagne.

fait à l'academie le 19 Mars 1791.

Borda Lagrange Laplace

Monge Condorcet

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

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. Fortin

The Kilogram of the Archives.

Photo TJQ

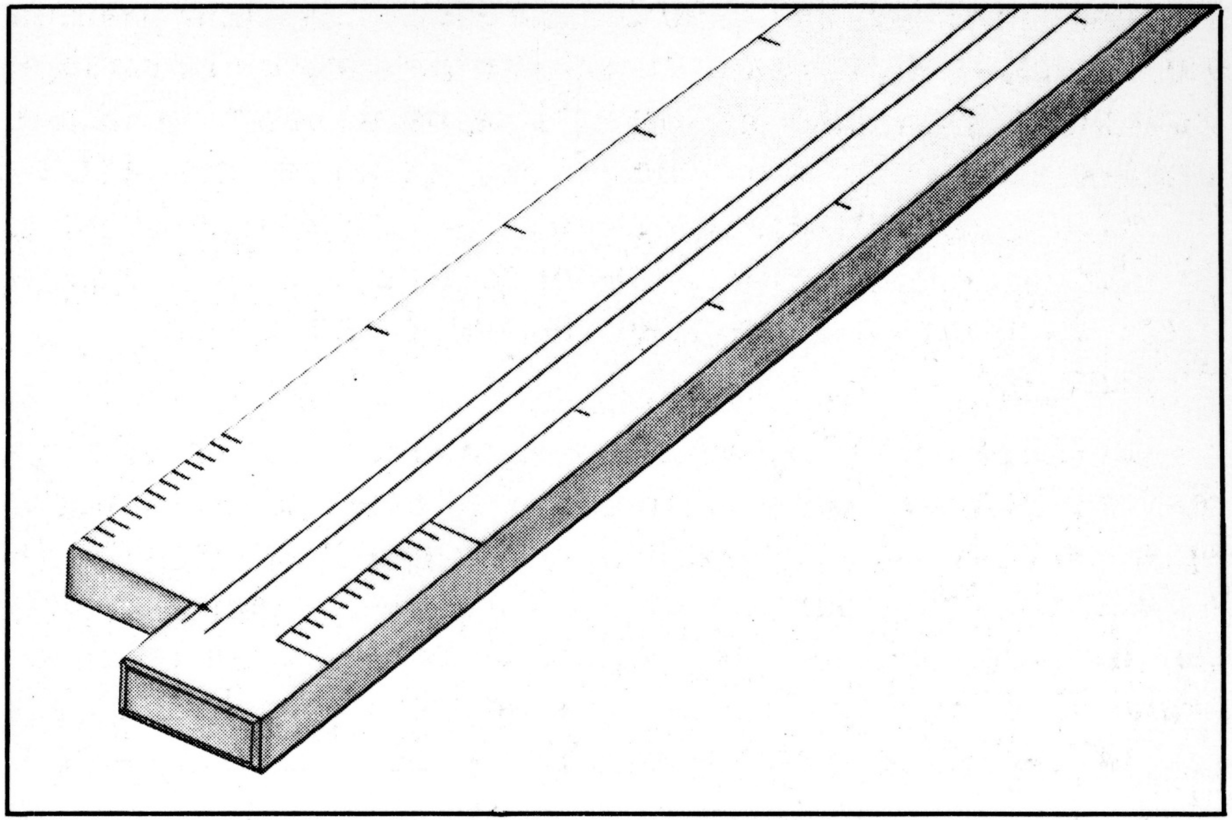


Fig. 1. — L'une des extrémités de la Toise du Pérou ou de l'Académie (1735).

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.

After 1795 what were the real definitions of the metre and kilogram?

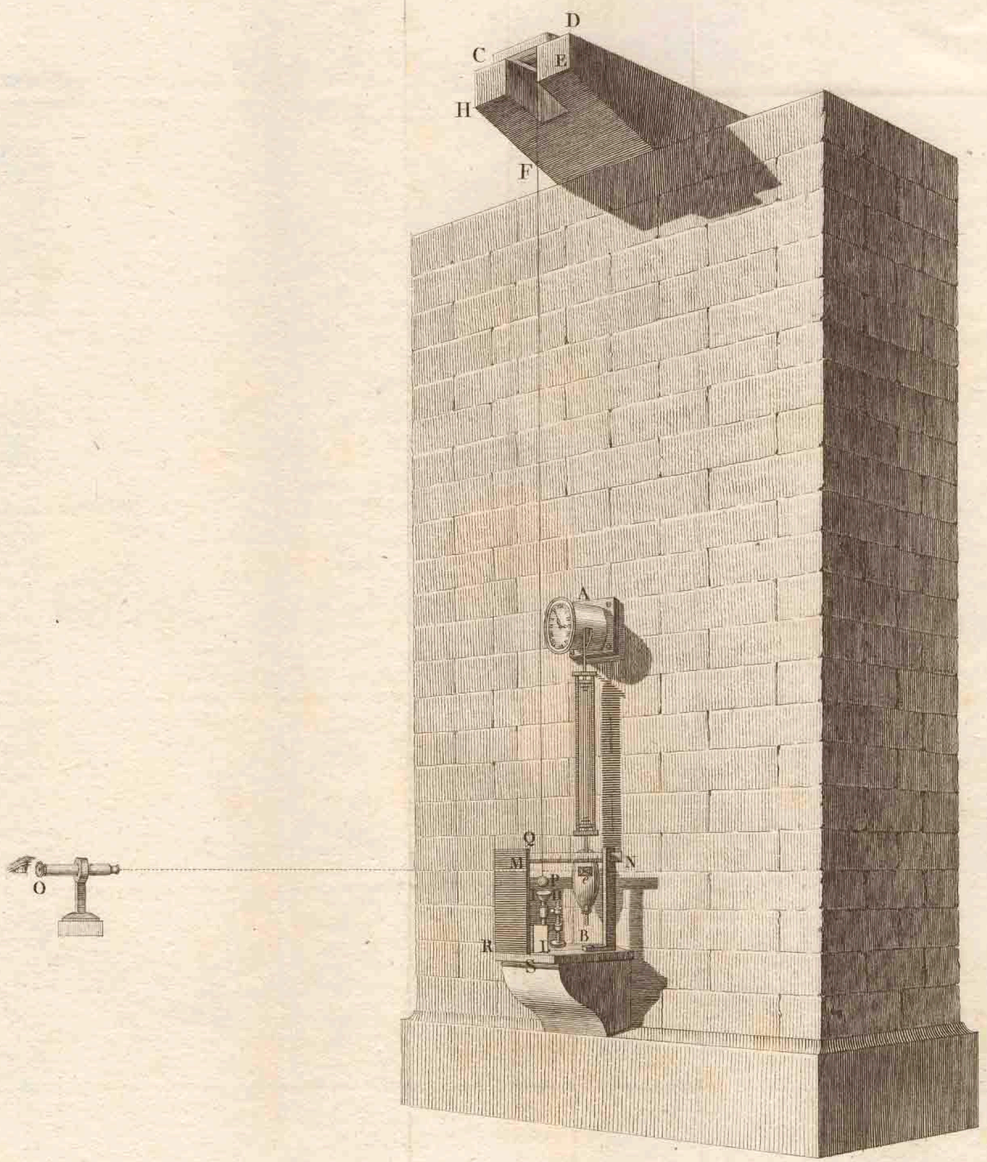
The metre is one ten millionth of the quarter of the terrestrial meridian which, deduced from the measurements of Pierre-Francois Méchain and Jean-Baptiste Delambre, was:

5 130 740 toise du Pérou, thus

1 mètre = 443,296 lignes of the toise du Pérou
or was it
the length of the Metre of the Archives

The kilogram is the mass of one cubic decimetre of water at the temperature of melting ice
or was it
the mass of the Kilogram of the Archives.

Photo TJQ



Gravé par E. Collin, Quai des Augustins, N.° 23.

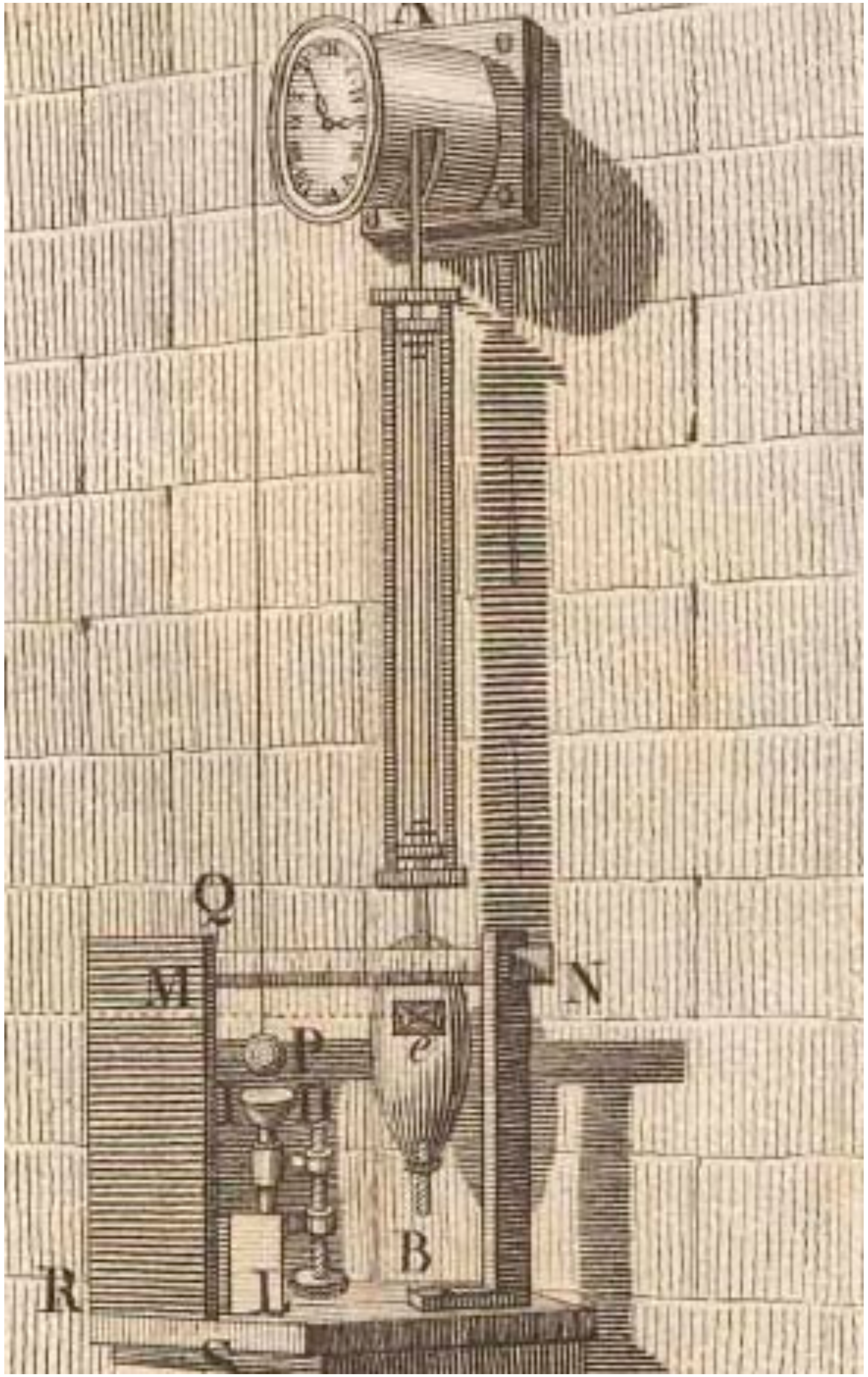


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Tableau des vingt expériences.

	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	

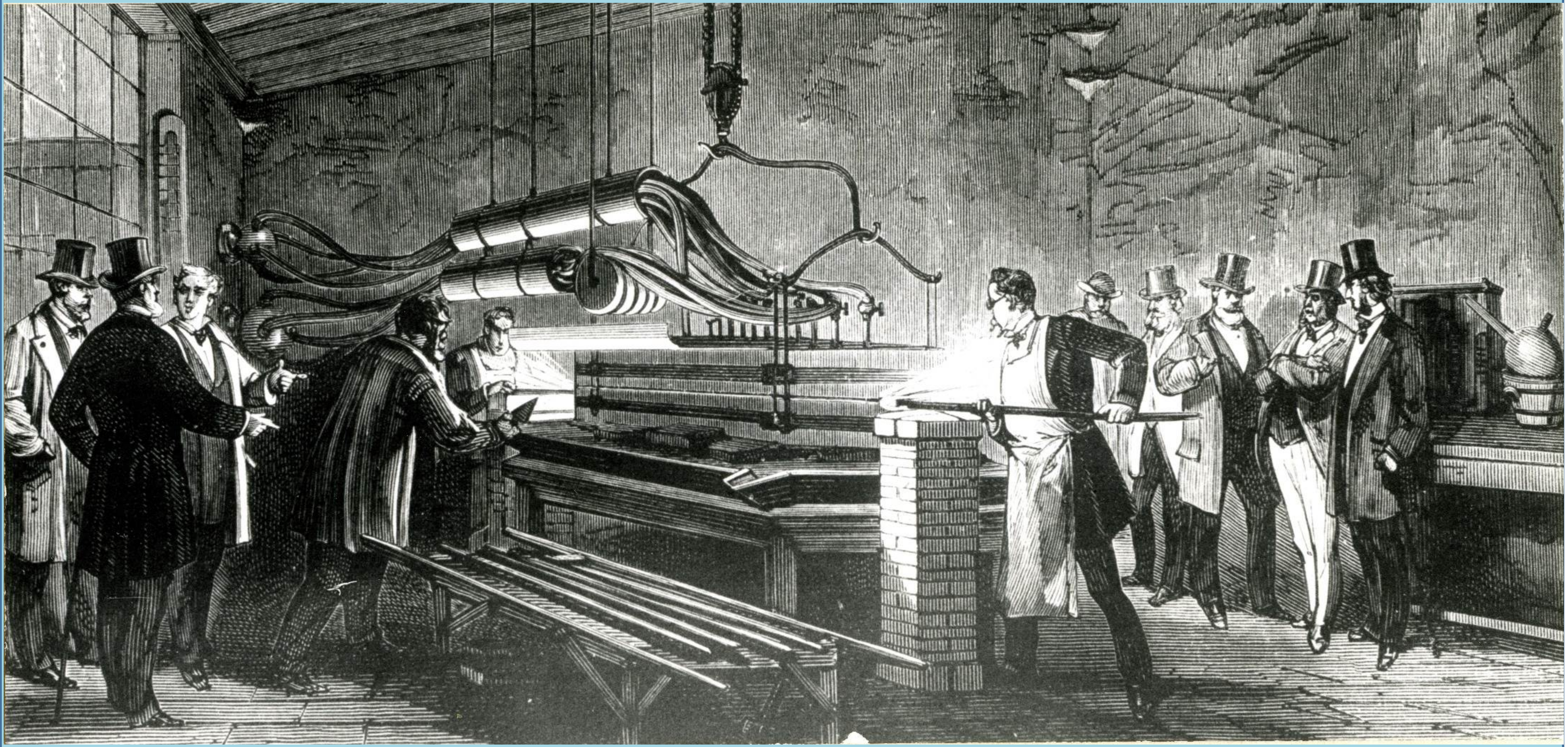
Relative standard deviation about the mean: 5 ppm!

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

Meanwhile, back to 1873

Starting in 1872/73 the details of the proposed new metric standards of the Metre and Kilogram were worked out at meetings of the *International Metre Commission* and the French Section of the Commission was given the task of actually preparing them.

A huge amount of work was undertaken by the French Section, after 1875 in collaboration with the International Committee for Weights and Measures. The new prototypes were finally adopted by the First General Conference on Weights and Measures in 1889 and deposited in the vault of the BIPM where they rest until this day.



The casting of one of the 1874 Conservatoire alloy in the presence of high dignitaries including the President of the Republic, from a contemporary newspaper account.

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

The safe in the vault of the prototypes at the BIPM where the kilogram and metre rested from 1889 until 1998

1st CGPM, 1889

▮ Sanction of the international prototypes of the metre and the kilogram (CR, 34-38)*

The Conférence Générale des Poids et Mesures,

considering

- the "Compte rendu of the President of the Comité International des Poids et Mesures (CIPM)" and the "Report of the CIPM", which show that, by the collaboration of the French section of the International Metre Commission and of the CIPM, the fundamental measurements of the international and national prototypes of the metre and of the kilogram have been made with all the accuracy and reliability which the present state of science permits;
- that the international and national prototypes of the metre and the kilogram are made of an alloy of platinum with 10 per cent iridium, to within 0.0001;
- the equality in length of the international Metre and the equality in mass of the international Kilogram with the length of the Metre and the mass of the Kilogram kept in the Archives of France;
- that the differences between the national Metres and the international Metre lie within 0.01 millimetre and that these differences are based on a hydrogen thermometer scale which can always be reproduced thanks to the stability of hydrogen, provided identical conditions are secured;
- that the differences between the national Kilograms and the international Kilogram lie within 1 milligram;
- that the international Metre and Kilogram and the national Metres and Kilograms fulfil the requirements of the Metre Convention,

sanctions

A. As regards international prototypes:

1. The Prototype of the metre chosen by the CIPM. This prototype, at the temperature of melting ice, shall henceforth represent the metric unit of length.
2. The Prototype of the kilogram adopted by the CIPM. This prototype shall henceforth be considered as the unit of mass.
3. The hydrogen thermometer centigrade scale in terms of which the equations of the prototype Metres have been established.

B. As regards national prototypes: .....

...

B. En ce qui concerne les *prototypes nationaux* :

1° Les mètres en platine iridié, dont les équations, par rapport au prototype international, sont renfermées dans la limite de 0,01 de millimètre, avec une erreur probable ne dépassant pas ± 0,0002 de millimètre;

2° Les kilogrammes en platine iridié, dont les équations sont renfermées dans la limite de 1 milligramme, avec une erreur probable ne dépassant pas ± 0,005 de milligramme.

C. En ce qui concerne les *équations des prototypes nationaux* :

Les équations des prototypes nationaux, telles qu'elles ont été déterminées au Bureau international, sous la direction du Comité international, et inscrites dans le Rapport de ce Comité et sur les certificats accompagnant ces prototypes.

B. En ce qui concerne les *prototypes nationaux* :

1° Les mètres en platine iridié, dont les équations, par rapport au prototype international, sont renfermées dans la limite de 0,01 de millimètre, avec une erreur probable ne dépassant pas ± 0,0002 de millimètre;

2° Les kilogrammes en platine iridié, dont les équations sont renfermées dans la limite de 1 milligramme, avec une erreur probable ne dépassant pas ± 0,005 de milligramme.

Deletions adopted by 12 votes to 5 at the Conference

C. En ce qui concerne les *équations des prototypes nationaux* :

Les équations des prototypes nationaux, telles qu'elles ont été déterminées au Bureau international, sous la direction du Comité international, et inscrites dans le Rapport de ce Comité et sur les certificats accompagnant ces prototypes.

▮ Declaration on the unit of mass and on the definition of weight; conventional value of g_n (CR, 70)

Taking into account the decision of the Comité International des Poids et Mesures of 15 October 1887, according to which the kilogram has been defined as unit of mass;

Taking into account the decision contained in the sanction of the prototypes of the Metric System, unanimously accepted by the Conférence Générale des Poids et Mesures on 26 September 1889;

Considering the necessity to put an end to the ambiguity which in current practice still exists on the meaning of the word *weight*, used sometimes for *mass*, sometimes for *mechanical force*;

The Conference declares

1. The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram;
2. The word "weight" denotes a quantity of the same nature as a "force": the weight of a body is the product of its mass and the acceleration due to gravity; in particular, the standard weight of a body is the product of its mass and the standard acceleration due to gravity;
3. The value adopted in the International Service of Weights and Measures for the standard acceleration due to gravity is 980.665 cm/s^2, value already stated in the laws of some countries.

3rd CGPM 1901

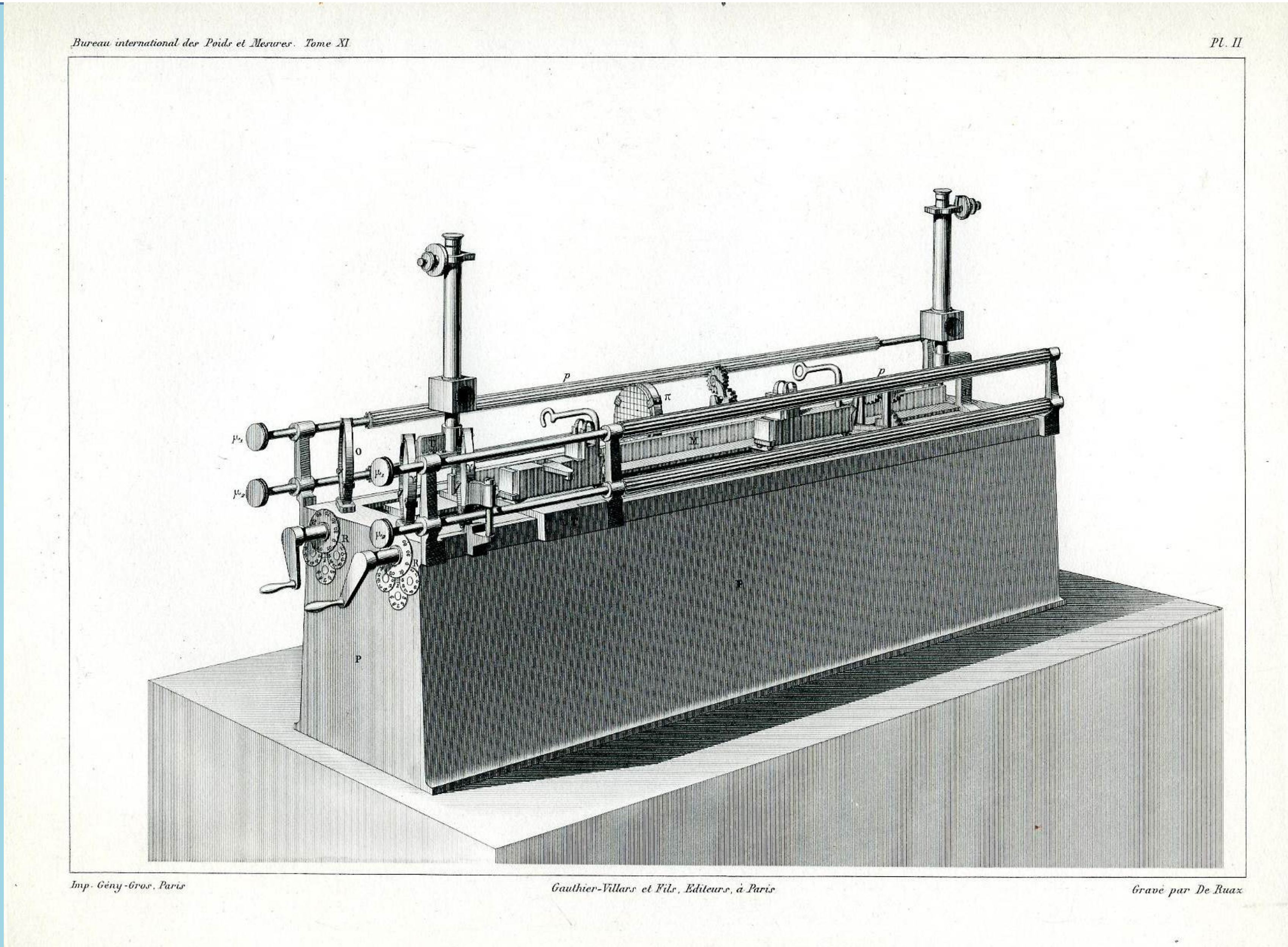
7th CGPM, 1927

▮ Definition of the metre by the international Prototype (CR, 49)*

The unit of length is the metre, defined by the distance, at 0°, between the axes of the two central lines marked on the bar of platinum-iridium kept at the Bureau International des Poids et Mesures and declared Prototype of the metre by the 1st Conférence Générale des Poids et Mesures, this bar being subject to standard atmospheric pressure and supported on two cylinders of at least one centimetre diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm from each other.

"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.



1892 A A Michelson measured the new International Prototype of the Metre in terms of the wavelength of the red line of cadmium

The result obtained by Michelson in 1892 was that the metre equals

1 553 163.8 times the wavelength of the red emission line of cadmium.

This was much improved a few years later in 1906 by the Director of the BIPM Benoît and Fabry who found the number **1 553 164.13** with an estimated uncertainty of a few tenths of a micrometre differing by only 0.2 μm from that of Michelson.

This is equivalent to saying that the wavelength of this light is **0.64384696** micrometres.

This same value was taken by the 7th General Conference in 1927 to define the Angström so that

$$\lambda_{cd} = \mathbf{6438.4696}\ \text{Å}$$

Finally in 1960, when the metre was redefined in terms of the wavelength of the orange line of krypton and the value taken was chosen to be consistent with the 1927 value for the Angström and hence consistent with Benoît and Fabry's result in 1906 which was itself very close to Michelson's in 1892.

Why did they wait nearly seventy years before making this important change, already foreseen in 1891?

Development of units from 1791 to the proposed New SI in 2018

- The proposals of the Académie des sciences in 1791
- Maxwell in 1870
- CIPM 1891 on linking the length of the metre to natural standards
- Michelson measures the wavelength of light in terms of the metre at the BIPM 1892
- Measurements by Benoit and Fabry in 1906, definition of the Ångstrom in 1927
- Practical electrical units starting from 1891, International Practical Units of 1908
- International temperature Scales of 1927, ITS-27 ITS-48 and ITS-90, definition of the kelvin
- Definition of the ampere and candela 1948
- New definitions of the metre and second in 1960
- The International System of Units 1960
- Atomic definition of the second 1967
- Definition of the mole in 1971 – statements by Jan de Boer
- New definition of the candela 1979
- New definition of the metre in 1983

CIPM 1946

Definitions of electric units (PV, **20**, 132-133)

Resolution 2

...

4. (A) Definitions of the mechanical units which enter the definitions of electric units:

Unit of force. — The unit of force [in the MKS (metre, kilogram, second) system] is the force which gives to a mass of 1 kilogram an acceleration of 1 metre per second, per second.

Joule (unit of energy or work). — The joule is the work done when the point of application of 1 MKS unit of force [newton] moves a distance of 1 metre in the direction of the force.

Watt (unit of power). — The watt is the power which in one second gives rise to energy of 1 joule.

(B) Definitions of electric units. The Comité International des Poids et Mesures (CIPM) accepts the following propositions which define the theoretical value of the electric units:

Ampere (unit of electric current). — The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} MKS unit of force [newton] per metre of length.

Volt (unit of potential difference and of electromotive force). — The volt is the potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

The definitions contained in this Resolution were ratified in 1948 by the 9th CGPM (CR, 49), which also adopted the name newton (Resolution 7) for the MKS unit of force.

Maxwell!

The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge *e* to be 1.602 176 620 8xx $\times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

Volt (unit of potential difference and of electromotive force). — The volt is the potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

Ohm (unit of electric resistance). — The ohm is the electric resistance between two points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force.

Coulomb (unit of quantity of electricity). — The coulomb is the quantity of electricity carried in 1 second by a current of 1 ampere.

Farad (unit of capacitance). — The farad is the capacitance of a capacitor between the plates of which there appears a potential difference of 1 volt when it is charged by a quantity of electricity of 1 coulomb.

Henry (unit of electric inductance). — The henry is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at the rate of 1 ampere per second.

Weber (unit of magnetic flux). — The weber is the magnetic flux which, linking a circuit of one turn, would produce in it an electromotive force of 1 volt if it were reduced to zero at a uniform rate in 1 second.

CIPM, 1946

▮ Definitions of photometric units (PV, **20**, 119-122)*

Resolution

…

4. The photometric units may be defined as follows:

New candle (unit of luminous intensity). — The value of the new candle is such that the brightness of the full radiator at the temperature of solidification of platinum is 60 new candles per square centimetre.

New lumen (unit of luminous flux). — The new lumen is the luminous flux emitted in unit solid angle (steradian) by a uniform point source having a luminous intensity of 1 new candle.

5. …

* The two definitions contained in this Resolution were ratified in 1948 by the 9th CGPM, which also approved the name candela given to the "new candle" (CR, 54). For the lumen the qualifier "new" was later abandoned.
This definition was modified in 1967 by the 13th CGPM (Resolution 5, see p. 154).

▮ Triple point of water; thermodynamic scale with a single fixed point; unit of quantity of heat (joule) (CR, 55 and 63)

Resolution 3

1. With present-day techniques, the triple point of water is capable of providing a thermometric reference point with an accuracy higher than can be obtained from the melting point of ice.

   In consequence the Comité Consultatif de Thermométrie et Calorimétrie (CCTC) considers that the zero of the centesimal thermodynamic scale must be defined as the temperature 0.0100 degree below that of the triple point of water.

2. The CCTC accepts the principle of an absolute thermodynamic scale with a single fundamental fixed point, at present provided by the triple point of pure water, the absolute temperature of which will be fixed at a later date.

   The introduction of this new scale does not affect in any way the use of the International Scale, which remains the recommended practical scale.

3. The unit of quantity of heat is the joule.

Note: It is requested that the results of calorimetric experiments be as far as possible expressed in joules. If the experiments are made by comparison with the rise of temperature of water (and that, for some reason, it is not possible to avoid using the calorie), the information necessary for conversion to joules must be provided. The CIPM, advised by the CCTC, should prepare a table giving, in joules per degree, the most accurate values that can be obtained from experiments on the specific heat of water.

A table, prepared in response to this request, was approved and published by the CIPM in 1950 (PV, **22**, 92).

10th CGPM, 1954

■ **Definition of the thermodynamic temperature scale** (CR, 79)*

Resolution 3

The 10th Conférence Générale des Poids et Mesures decides to define the thermodynamic temperature scale by choosing the triple point of water as the fundamental fixed point, and assigning to it the temperature 273.16 degrees Kelvin, exactly.

* The 13th CGPM in 1967 explicitly defined the kelvin (Resolution 4, see p. 154).

■ **Definition of the SI unit of thermodynamic temperature (kelvin)** (CR, 104 and *Metrologia*, 1968, **4**, 43)*

Resolution 4

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering that it is useful to formulate more explicitly the definition of the unit of thermodynamic temperature contained in Resolution 3 of the 10th CGPM (1954),

decides to express this definition as follows:

"The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water."

* See Recommendation 5 (CI-1989) of the CIPM on the International Temperature Scale of 1990, p. 163.

The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be 1.380 648 52xx $\times 10^{-23}$ when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

CIPM, 1956

▮ Definition of the unit of time (second) (PV, **25**, 77)*

Resolution 1

In virtue of the powers invested in it by Resolution 5 of the 10th Conférence Générale des Poids et Mesures, the Comité International des Poids et Mesures,

considering

1. that the 9th General Assembly of the International Astronomical Union (Dublin, 1955) declared itself in favour of linking the second to the tropical year,
2. that, according to the decisions of the 8th General Assembly of the International Astronomical Union (Rome, 1952), the second of ephemeris time (ET) is the fraction

$$\frac{12\,960\,276\,813}{408\,986\,496} \times 10^{-9}$$ of the tropical year for 1900 January 0 at 12 h ET,

decides

"The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

* This definition was abrogated in 1967 by the 13th CGPM (Resolution 1, see p. 153).

11th CGPM, 1960

Definition of the metre (CR, 85)*

Resolution 6

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the international Prototype does not define the metre with an accuracy adequate for the present needs of metrology,
- that it is moreover desirable to adopt a natural and indestructible standard,

decides

1. The metre is the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton 86 atom.
2. The definition of the metre in force since 1889, based on the international Prototype of platinum-iridium, is abrogated.
3. The international Prototype of the metre sanctioned by the 1st CGPM in 1889 shall be kept at the BIPM under the conditions specified in 1889.

* This definition was abrogated in 1983 by the 17th CGPM (Resolution 1, see p. 160).

Definition of the unit of time (second) (CR, 86)*

Resolution 9

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- the powers given to the Comité International des Poids et Mesures (CIPM) by the 10th CGPM to define the fundamental unit of time,
- the decision taken by the CIPM in 1956,

ratifies the following definition:

"The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

* This definition was abrogated in 1967 by the 13th CGPM (Resolution 1, see p. 153).

Système International d'Unités (CR, 87)*

Resolution 12

The 11th Conférence Générale des Poids et Mesures (CGPM),

considering

- Resolution 6 of the 10th CGPM, by which it adopted six base units on which to establish a practical system of measurement for international use:

length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	degree Kelvin	°K
luminous intensity	candela	cd

- Resolution 3 adopted by the Comité International des Poids et Mesures (CIPM) in 1956,
- the recommendations adopted by the CIPM in 1958 concerning an abbreviation for the name of the system, and prefixes to form multiples and submultiples of the units,

decides

1. the system founded on the six base units above is called the "Système International d'Unités";
2. the international abbreviation of the name of the system is: SI;
3. names of multiples and submultiples of the units are formed by means of the following prefixes:

Multiplying factor	Prefix	Symbol	Multiplying factor	Prefix	Symbol
1 000 000 000 000 = 10^{12}	tera	T	0.1 = 10^{-1}	deci	d
1 000 000 000 = 10^{9}	giga	G	0.01 = 10^{-2}	centi	c
1 000 000 = 10^{6}	mega	M	0.001 = 10^{-3}	milli	m
1 000 = 10^{3}	kilo	k	0.000 001 = 10^{-6}	micro	μ
100 = 10^{2}	hecto	h	0.000 000 001 = 10^{-9}	nano	n
10 = 10^{1}	deca	da	0.000 000 000 001 = 10^{-12}	pico	p

4. the units listed below are used in the system, without excluding others which might be added later.

Supplementary units

plane angle	radian	rad
solid angle	steradian	sr

* The CGPM later abrogated certain of its decisions and extended the list of prefixes, see notes below.

The name and symbol for the unit of thermodynamic temperature was modified by the 13th CGPM in 1967 (Resolution 3, see p. 153).

A seventh base unit, the mole, was adopted by the 14th CGPM in 1971 (Resolution 3, see p. 156).

Further prefixes were adopted by the 12th CGPM in 1964 (Resolution 8, see p. 152), the 15th CGPM in 1975 (Resolution 10, see p. 158) and the 19th CGPM in 1991 (Resolution 4, see p. 164).

The 20th CGPM in 1995 abrogated the class of supplementary units in the SI (Resolution 8, see p. 164). These are now considered as derived units.

Derived units

area	square metre	m^2	
volume	cubic metre	m^3	
frequency	hertz	Hz	1/s
mass density (density)	kilogram per cubic metre	kg/m^3	
speed, velocity	metre per second	m/s	
angular velocity	radian per second	rad/s	
acceleration	metre per second squared	m/s^2	
angular acceleration	radian per second squared	rad/s^2	
force	newton	N	$kg \cdot m/s^2$
pressure (mechanical stress)	newton per square metre	N/m^2	
kinematic viscosity	square metre per second	m^2/s	
dynamic viscosity	newton-second per square metre	$N \cdot s/m^2$	
work, energy, quantity of heat	joule	J	$N \cdot m$
power	watt	W	J/s
quantity of electricity (side bar)	coulomb	C	$A \cdot s$
tension (voltage), potential difference, electromotive force	volt	V	W/A
electric field strength	volt per metre	V/m	
electric resistance	ohm	Ω	V/A
capacitance	farad	F	$A \cdot s/V$
magnetic flux	weber	Wb	$V \cdot s$
inductance	henry	H	$V \cdot s/A$
magnetic flux density	tesla	T	Wb/m^2
magnetic field strength	ampere per metre	A/m	
magnetomotive force	ampere	A	
luminous flux	lumen	lm	$cd \cdot sr$
luminance	candela per square metre	cd/m^2	
illuminance	lux	lx	lm/m^2

The 13th CGPM in 1967 (Resolution 6, see p. 154) specified other units which should be added to the list. In principle, this list of derived units is without limit.

Modern practice is to use the phrase "amount of heat" rather than "quantity of heat", because the word quantity has a different meaning in metrology.

Modern practice is to use the phrase "amount of electricity" rather than "quantity of electricity" (see note above).

13th CGPM, 1967/68

SI unit of time (second) (CR, 103 and *Metrologia*, 1968, **4**, 43)

Resolution 1

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the definition of the second adopted by the Comité International des Poids et Mesures (CIPM) in 1956 (Resolution 1) and ratified by Resolution 9 of the 11th CGPM (1960), later upheld by Resolution 5 of the 12th CGPM (1964), is inadequate for the present needs of metrology,
- that at its meeting of 1964 the CIPM, empowered by Resolution 5 of the 12th CGPM (1964), recommended, in order to fulfil these requirements, a caesium atomic frequency standard for temporary use,
- that this frequency standard has now been sufficiently tested and found sufficiently accurate to provide a definition of the second fulfilling present requirements,
- that the time has now come to replace the definition now in force of the unit of time of the Système International d'Unités by an atomic definition based on that standard,

decides

1. The SI unit of time is the second defined as follows:

   "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom";

2. Resolution 1 adopted by the CIPM at its meeting of 1956 and Resolution 9 of the 11th CGPM are now abrogated.

At its 1997 meeting, the CIPM affirmed that this definition refers to a caesium atom at rest at a thermodynamic temperature of 0 K.

- The second, symbol s, is the SI unit of time. It is implicitly defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine splitting frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1} for periodic phenomena.

SI unit of luminous intensity (candela) (CR, 104 and *Metrologia*, 1968, **4**, 43-44)*

* This definition was abrogated by the 16th CGPM in 1979 (Resolution 3, see p. 158).

Resolution 5

The 13th Conférence Générale des Poids et Mesures (CGPM),

considering

- the definition of the unit of luminous intensity ratified by the 9th CGPM (1948) and contained in the "Resolution concerning the change of photometric units" adopted by the Comité International des Poids et Mesures in 1946 (PV, **20**, 119) in virtue of the powers conferred by the 8th CGPM (1933),
- that this definition fixes satisfactorily the unit of luminous intensity, but that its wording may be open to criticism,

decides to express the definition of the candela as follows:

"The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre."

13th CGPM 1967/68

■ **International Atomic Time, function of CIPM** (CR, 77-78 and *Metrologia*, 1972, **8**, 35)

Resolution 1

The 14th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the second, unit of time of the Système International d'Unités, has since 1967 been defined in terms of a natural atomic frequency, and no longer in terms of the time scales provided by astronomical motions,
- that the need for an International Atomic Time (TAI) scale is a consequence of the atomic definition of the second,
- that several international organizations have ensured and are still successfully ensuring the establishment of the time scales based on astronomical motions, particularly thanks to the permanent services of the Bureau International de l'Heure (BIH),
- that the BIH has started to establish an atomic time scale of recognized quality and proven usefulness,
- that the atomic frequency standards for realizing the second have been considered and must continue to be considered by the Comité International des Poids et Mesures (CIPM) helped by a Consultative Committee, and that the unit interval of the International Atomic Time scale must be the second realized according to its atomic definition,
- that all the competent international scientific organizations and the national laboratories active in this field have expressed the wish that the CIPM and the CGPM should give a definition of International Atomic Time, and should contribute to the establishment of the International Atomic Time scale,
- that the usefulness of International Atomic Time entails close coordination with the time scales based on astronomical motions,

requests the CIPM

1. to give a definition of International Atomic Time,
2. to take the necessary steps, in agreement with the international organizations concerned, to ensure that available scientific competence and existing facilities are used in the best possible way to realize the International Atomic Time scale and to satisfy the requirements of users of International Atomic Time.

The definition of TAI was given by the CCDS in 1970 (now the CCTF), see p. 155.

16th CGPM, 1979

■ **SI unit of luminous intensity (candela)** (CR, 100 and *Metrologia*, 1980, **16**, 56)

Resolution 3

The 16th Conférence Générale des Poids et Mesures (CGPM),

considering

- that despite the notable efforts of some laboratories there remain excessive divergences between the results of realizations of the candela based upon the present black body primary standard,
- that radiometric techniques are developing rapidly, allowing precisions that are already equivalent to those of photometry and that these techniques are already in use in national laboratories to realize the candela without having to construct a black body,
- that the relation between luminous quantities of photometry and radiometric quantities, namely the value of 683 lumens per watt for the spectral luminous efficacy of monochromatic radiation of frequency 540×10^{12} hertz, has been adopted by the Comité International des Poids et Mesures (CIPM) in 1977,
- that this value has been accepted as being sufficiently accurate for the system of luminous photopic quantities, that it implies a change of only about 3 % for the system of luminous scotopic quantities, and that it therefore ensures satisfactory continuity,
- that the time has come to give the candela a definition that will allow an improvement in both the ease of realization and the precision of photometric standards, and that applies to both photopic and scotopic photometric quantities and to quantities yet to be defined in the mesopic field,

Photopic vision is detected by the cones on the retina of the eye, which are sensitive to a high level of luminance ($L >$ ca. 10 cd/m^2) and are used in daytime vision. Scotopic vision is detected by the rods of the retina, which are sensitive to low level luminance ($L <$ ca. 10^{-3} cd/m^2), used in night vision. In the domain between these levels of luminance both cones and rods are used, and this is described as mesopic vision.

decides

1. The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.
2. The definition of the candela (at the time called new candle) adopted by the CIPM in 1946 by reason of the powers conferred by the 8th CGPM in 1933, ratified by the 9th CGPM in 1948, then amended by the 13th CGPM in 1967, is abrogated.

The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or kg^{-1} m^{-2} s^3 cd sr, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

14^{th} CGPM 1971

SI unit of amount of substance (mole) (CR, 78 and *Metrologia*, 1972, **8**, 36)*

Resolution 3

The 14th Conférence Générale des Poids et Mesures (CGPM),

considering the advice of the International Union of Pure and Applied Physics, of the International Union of Pure and Applied Chemistry, and of the International Organization for Standardization, concerning the need to define a unit of amount of substance,

* At its 1980 meeting, the CIPM approved the report of the 7th meeting of the CCU (1980) specifying that, in this definition, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

decides

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is "mol".
2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
3. The mole is a base unit of the Système International d'Unités.

The mole, symbol mol, is the SI 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. It is defined by taking the fixed numerical value of the Avogadro constant N_A to be 6.022 140 857xx $\times 10^{23}$ when expressed in the unit mol^{-1}

Coordinated Universal Time (UTC) (CR, 104 and *Metrologia*, 1975, **11**, 180)

Resolution 5

The 15th Conférence Générale des Poids et Mesures,

considering that the system called "Coordinated Universal Time" (UTC) is widely used, that it is broadcast in most radio transmissions of time signals, that this wide diffusion makes available to the users not only frequency standards but also International Atomic Time and an approximation to Universal Time (or, if one prefers, mean solar time),

notes that this Coordinated Universal Time provides the basis of civil time, the use of which is legal in most countries,

judges that this usage can be strongly endorsed.

15th CGPM 1975

In introducing the definition to the Conference, the then Secretary of the International Committee, Jan de Boer, made the following remarks:

"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."

As regards 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."

He ended by saying:

"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."

17th CGPM, 1983

▮ **Definition of the metre** (CR, 97 and *Metrologia*, 1984, **20**, 25)

Resolution 1

The 17th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the present definition does not allow a sufficiently precise realization of the metre for all requirements,
- that progress made in the stabilization of lasers allows radiations to be obtained that are more reproducible and easier to use than the standard radiation emitted by a krypton 86 lamp,
- that progress made in the measurement of the frequency and wavelength of these radiations has resulted in concordant determinations of the speed of light whose accuracy is limited principally by the realization of the present definition of the metre,
- that wavelengths determined from frequency measurements and a given value for the speed of light have a reproducibility superior to that which can be obtained by comparison with the wavelength of the standard radiation of krypton 86,
- that there is an advantage, notably for astronomy and geodesy, in maintaining unchanged the value of the speed of light recommended in 1975 by the 15th CGPM in its Resolution 2 (c = 299 792 458 m/s),
- that a new definition of the metre has been envisaged in various forms all of which have the effect of giving the speed of light an exact value, equal to the recommended value, and that this introduces no appreciable discontinuity into the unit of length, taking into account the relative uncertainty of $\pm 4 \times 10^{-9}$ of the best realizations of the present definition of the metre,
- that these various forms, making reference either to the path travelled by light in a specified time interval or to the wavelength of a radiation of measured or specified frequency, have been the object of consultations and deep discussions, have been recognized as being equivalent and that a consensus has emerged in favour of the first form,
- that the Comité Consultatif pour la Définition du Mètre (CCDM) is now in a position to give instructions for the practical realization of such a definition, instructions which could include the use of the orange radiation of krypton 86 used as standard up to now, and which may in due course be extended or revised,

The relative uncertainty given here corresponds to three standard deviations in the data considered.

decides

1. The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second,
2. The definition of the metre in force since 1960, based upon the transition between the levels $2p_{10}$ and $5d_5$ of the atom of krypton 86, is abrogated.

17th CGPM, 1983

Definition of the metre (CR, 97 and *Metrologia*, 1984, **20**, 25)

Resolution 1

The 17th Conférence Générale des Poids et Mesures (CGPM),

considering

- that the present definition does not allow a sufficiently precise realization of the metre for all requirements,
- that progress made in the stabilization of lasers allows radiations to be obtained that are more reproducible and easier to use than the standard radiation emitted by a krypton 86 lamp,
- that progress made in the measurement of the frequency and wavelength of these radiations has resulted in concordant determinations of the speed of light whose accuracy is limited principally by the realization of the present definition of the metre,
- that wavelengths determined from frequency measurements and a given value for the speed of light have a reproducibility superior to that which can be obtained by comparison with the wavelength of the standard radiation of krypton 86,
- that there is an advantage, notably for astronomy and geodesy, in maintaining unchanged the value of the speed of light recommended in 1975 by the 15th CGPM in its Resolution 2 (c = 299 792 458 m/s),
- that a new definition of the metre has been envisaged in various forms all of which have the effect of giving the speed of light an exact value, equal to the recommended value, and that this introduces no appreciable discontinuity into the unit of length, taking into account the relative uncertainty of $\pm 4 \times 10^{-9}$ of the best realizations of the present definition of the metre,
- that these various forms, making reference either to the path travelled by light in a specified time interval or to the wavelength of a radiation of measured or specified frequency, have been the object of consultations and deep discussions, have been recognized as being equivalent and that a consensus has emerged in favour of the first form,
- that the Comité Consultatif pour la Définition du Mètre (CCDM) is now in a position to give instructions for the practical realization of such a definition, instructions which could include the use of the orange radiation of krypton 86 used as standard up to now, and which may in due course be extended or revised,

The relative uncertainty given here corresponds to three standard deviations in the data considered.

decides

1. The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second,
2. The definition of the metre in force since 1960, based upon the transition between the levels $2p_{10}$ and $5d_5$ of the atom of krypton 86, is abrogated.

The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit m/s, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.

18th CGPM, 1987

▮ Forthcoming adjustment to the representations of the volt and of the ohm (CR, 100 and *Metrologia*, 1988, **25**, 115)

Resolution 6

The 18th Conférence Générale des Poids et Mesures,

considering

- that worldwide uniformity and long-term stability of national representations of the electrical units are of major importance for science, commerce and industry from both
- that many national laboratories use the Josephson effect and are beginning to use the quantum Hall effect to maintain, respectively, representations of the volt and of the ohm, as these offer the best guarantees of long-term stability,
- that because of the importance of coherence among the units of measurement of the various physical quantities the values adopted for these representations must be as closely as possible in agreement with the SI,
- that the results of recent and current experiment will permit the establishment of an acceptable value, sufficiently compatible with the SI, for the coefficient which relates each of these effects to the corresponding electrical unit,

invites the laboratories whose work can contribute to the establishment of the quotient voltage/frequency in the case of the Josephson effect and of the quotient voltage/current for the quantum Hall effect to vigorously pursue these efforts and to communicate their results without delay to the Comité International des Poids et Mesures, and

instructs the Comité International des Poids et Mesures to recommend, as soon as it considers it possible, a value for each of these quotients together with a date for them to be put into practice simultaneously in all countries; these values should be announced at least one year in advance and would be adopted on 1 January 1990.

CIPM, 1988

▮ **Representation of the volt by means of the Josephson effect** (PV, **56**, 44 and *Metrologia*, 1989, **26**, 69)

Recommendation 1

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

- that a detailed study of the results of the most recent determinations leads to a value of 483 597.9 GHz/V for the Josephson constant, K_J, that is to say, for the quotient of frequency divided by the potential difference corresponding to the $n = 1$ step in the Josephson effect,
- that the Josephson effect, together with this value of K_J, can be used to establish a reference standard of electromotive force having a one-standard-deviation uncertainty with respect to the volt estimated to be 4 parts in 10^7, and a reproducibility which is significantly better,

recommends

- that 483 597.9 GHz/V exactly be adopted as a conventional value, denoted by K_{J-90} for the Josephson constant, K_J,
- that this new value be used from 1 January 1990, and not before, to replace the values currently in use,
- that this new value be used from this same date by all laboratories which base their measurements of electromotive force on the Josephson effect, and
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with the new adopted value,

is of the opinion that no change in this recommended value of the Josephson constant will be necessary in the foreseeable future, and

draws the attention of laboratories to the fact that the new value is greater by 3.9 GHz/V, or about 8 parts in 10^6, than the value given in 1972 by the Comité Consultatif d'Électricité in its Declaration E-72.

■ **Representation of the ohm by means of the quantum Hall effect** (PV, **56**, 45 and *Metrologia*, 1989, **26**, 70)

At its 89th meeting in 2000, the CIPM approved the declaration of the 22nd meeting of the CCEM on the use of the value of the von Klitzing constant, see p. 166.

Recommendation 2

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

- that most existing laboratory reference standards of resistance change significantly with time,
- that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,
- that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau i = 1 in the quantum Hall effect,
- that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

- that 25 812.807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,
- that this value be used from 1 January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,
- that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},
- that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the technical guidelines for reliable measurements of the quantized Hall resistance drawn up by the Comité Consultatif d'Électricité and published by the Bureau International des Poids et Mesures, and

is of the opinion that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

The NPL Ayrton-Jones current balance

First publication of the watt balance idea by Bryan Kibble.

The first publication of Bryan's idea for the watt balance appeared in the Proceedings of the Conference "Atomic Masses and Fundamental Constants 5 (usually known as AMCO-5) held in Paris in May 1975 on the occasion of the Centenary of the Metre Convention, see:

B.P. Kibble, Division of Electrical Science, National Physical Laboratory, "A measurement of the gyromagnetic ratio of the proton by the strong field method", *Atomic Masses and Fundamental Constants 5*, Sanders J. H. and Wapstra A. H., Eds., Plenum Press, 1976, pages 549 and 550.

The watt balance idea appeared in the final paragraph of his article, it is reproduced in the next slide

4 A SUGGESTION FOR A DIFFERENT WAY OF REALISING THE AMPERE

A major aim of these measurements is to determine the ratio of the maintained ampere to the SI ampere, denoted by K, by combining the result with that of the weak field method (Cohen and Taylor 1973). We take this opportunity to draw attention to a possible way of determining K directly which needs only minor modifications to the strong field apparatus described above.

At its meeting in June 2016 the CCU decided to adopt the name **Kibble balance** for the watt balance

Consider a coil carrying a current i which encloses a magnetic flux Φ. Then the energy of interaction is $W = -i\Phi$ and if Φ is a function of displacement of the coil, y, then a component of force exists

$$F_y = \frac{\partial W}{\partial y} = -i\frac{\partial \Phi(y)}{\partial y}.$$

which may be determined in SI units by opposing it with a mass M in a gravitational acceleration g

$$Mg = -i\frac{\partial \Phi}{\partial y} \quad . \qquad (1)$$

Suppose that the coil, in a separate measurement, moves with velocity dy/dt in the same flux Φ. Then an e.m.f. V' is generated,

$$V' = -\frac{\partial \Phi}{\partial t} = -\frac{\partial \Phi}{\partial y}\frac{dy}{dt}. \qquad (2)$$

Eliminating $\partial\Phi/\partial y$ between (1) and (2), we have

$$Mg\frac{dy}{dt} = iV' = \frac{VV'}{R} \qquad (3)$$

where i is known in terms of the potential drop V it produces across a resistor R. V, V' and R would be measured in the maintained units of the laboratory; these are related to the SI units of (3) by

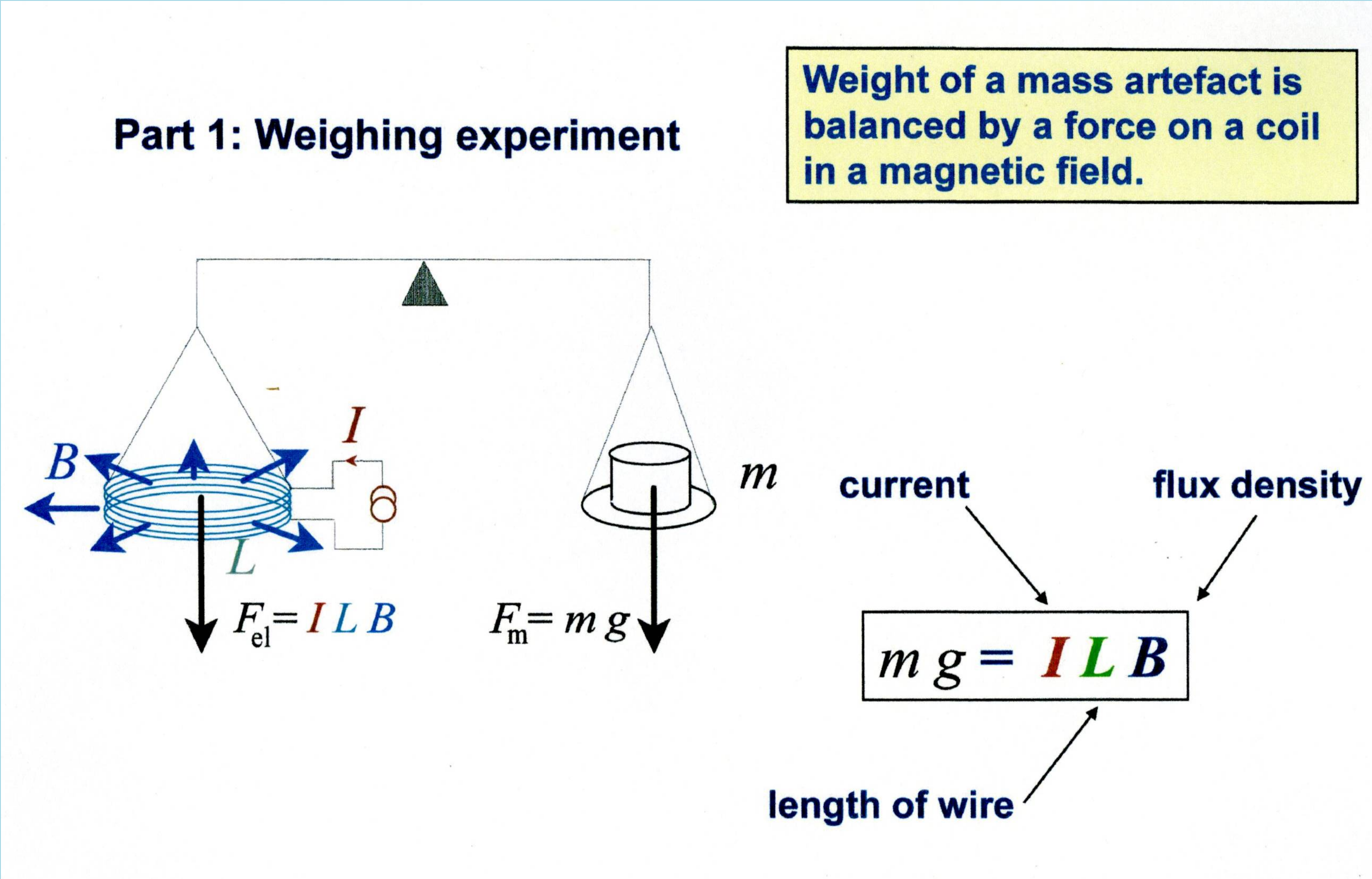
$$\frac{VV'}{R} = K^2\frac{\Omega_{MAINTAINED}}{\Omega_{SI}}\left(\frac{VV'}{R}\right)_{MAINTAINED}$$

and Ω maintained/ Ω SI can be considered as determined by the calculable capacitor with an uncertainty of about 1 in 10^7. Hence from (3)

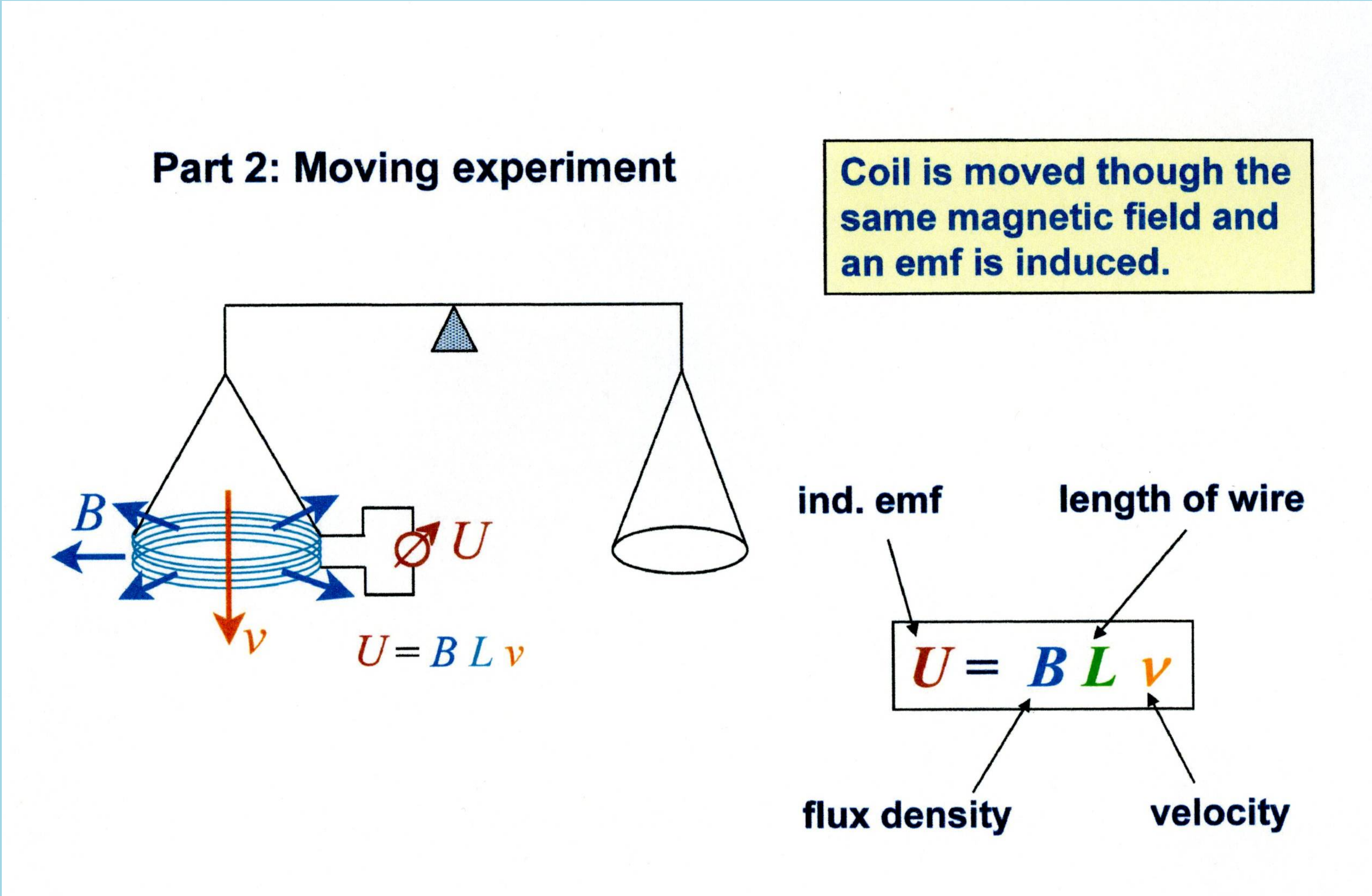
$$K^2 = Mg\frac{dy}{dt}\left(\frac{R}{VV'}\right)_{MAINTAINED}\frac{\Omega_{SI}}{\Omega_{MAINTAINED}}$$

In practice we cannot measure an instantaneous velocity dy/dt or potential V' but an average over a well-defined time interval of both quantities, $\Delta y/\Delta t$ and $\bar{V}' = 1/\Delta t\int_0^{\Delta t} V'dt$ is equally exact. Of course, precise measurement is simplified if dy/dt and V' are as constant as possible – perhaps to 1 in 10^4 or 1 in 10^5. The mean velocity $\Delta y/\Delta t$ could be measured with very great accuracy with a laser interferometer. The detailed distribution of Φ is not required, nor any dimensions of the coil, provided that both are stable for the short time between the weighing and moving with constant velocity parts of the experiment.

The Kibble balance



But we cannot directly measure either *L* or *B* with sufficient accuracy



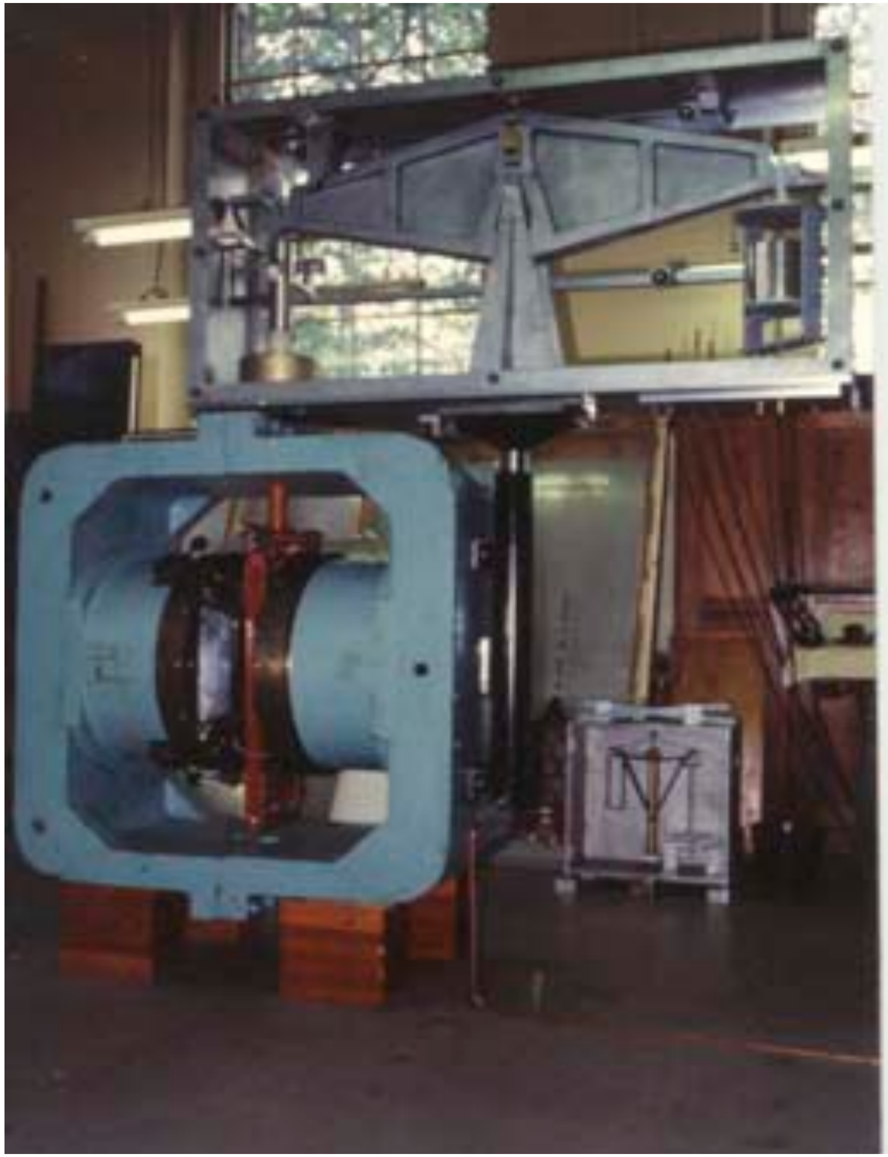
Combining the equations from the two configurations gives $mgv = IU$
Taking advantage of the Josephson effect, which gives a voltage $U = nfh/2e$ and the quantum-Hall effect, which gives an electrical resistance $R = h/ie^2$ we can write

$$IU = in^2f^2h/4 \text{ so that } \quad mgv = in^2f^2h/4$$

or

$$h = 4mgv/in^2f^2$$

NPL Watt balance

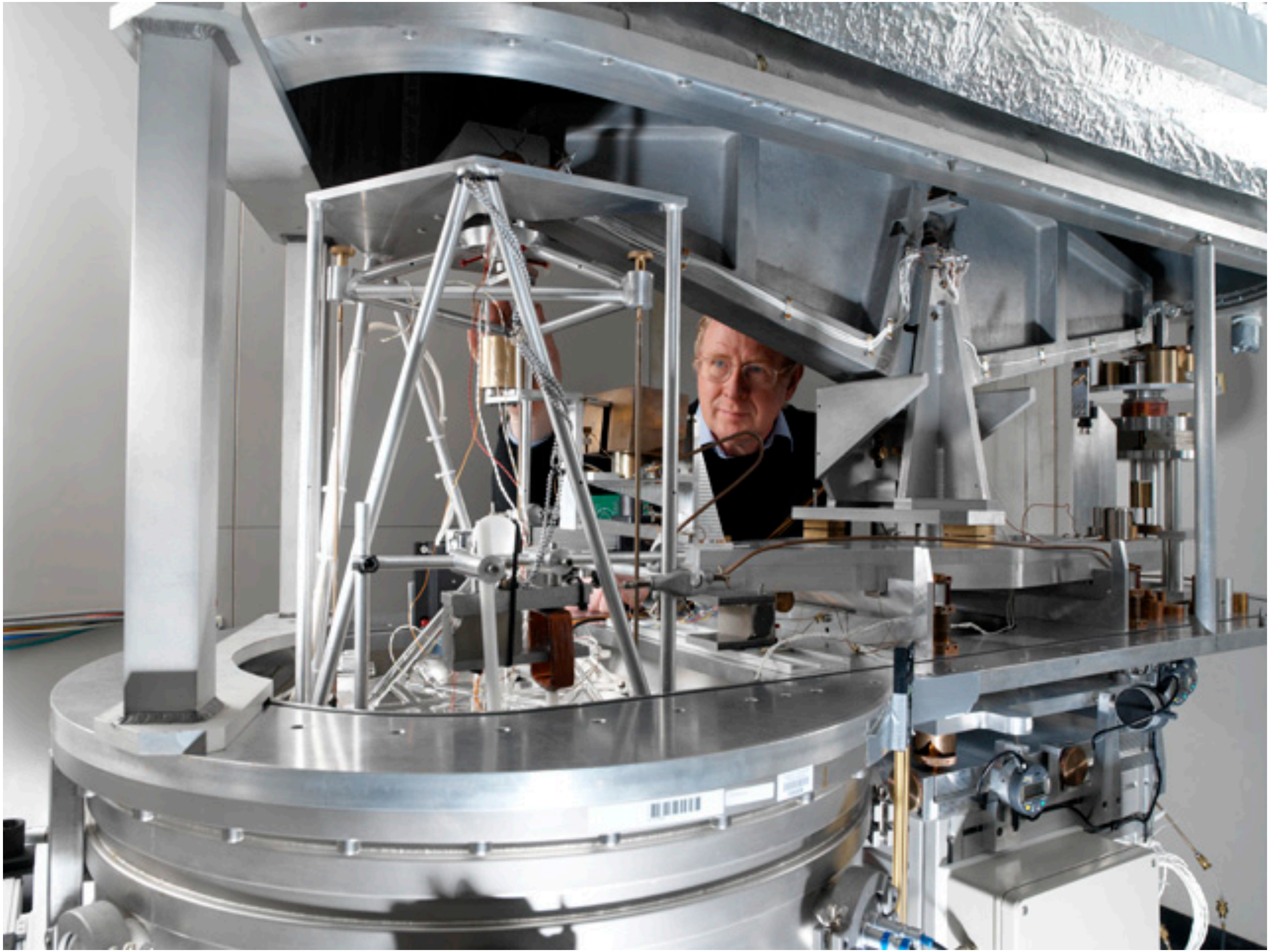


First watt balance

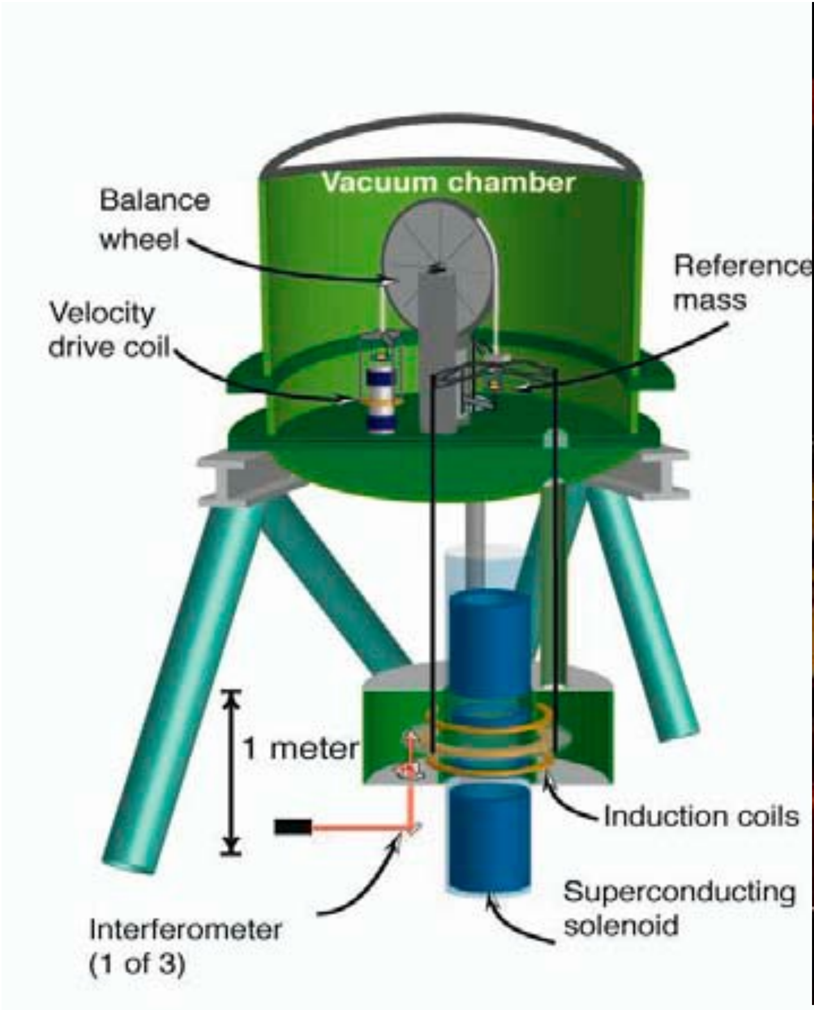
1 kg

Permanent magnet

Double rectangular coil



NIST Watt balance



Largest watt balance

Lowest published uncertainty

1 kg

Superconducting magnet

The possibility of defining the kilogram in terms of the Planck constant opened the way to a complete redefinition of the SI in terms of constants of nature.

We plan to define the SI in a new way, based on a set of seven defining constants, drawn from the fundamental constants of physics and other constants of nature, from which the definitions of the seven base units are deduced.

Each of these defining constants will be assigned a fixed numerical value.

What does it mean to define the numerical value of a fundamental constant of physics – surely these are fixed by nature?

The value of a constant of physics is indeed fixed by nature but its numerical value depends on the size of the unit with which we choose to measure it, take for example the speed of light:

the speed of light, *c* may be written:

$c = 299\,792\,458$ metres per second

or $c = 983\,571\,056.4$ feet per second

or $c = 327\,857\,018.8$ yards per second

the 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 size of the unit, equal to 299 792 458 in the case of the metre. This is the current definition of the metre, since the change in 1983. The numerical value now has zero uncertainty.
3. We have thus defined the metre in terms of a fixed numerical value for the speed of light.

How do we make practical use of such a definition?

We need to find an equation of physics that links the speed of light to length without including any unknown constants or quantities that themselves depend on length, such an equation is

$$c = \lambda f$$

Where λ is the wavelength of a light of frequency f.

We could also of course simply measure the time taken for a light signal to travel from one place to another but this is not practical for short distances.

The 1983 definition of the metre became practical only when technology advanced so that the frequency of visible or near infra-red light could be measured to high accuracy.

Today there exists an official list of wavelengths and frequencies of a wide range of optical and infra-red atomic and molecular transitions to which lasers can be locked. This list is known as the "*mise en pratique* of the definition of the metre. Some of them are so precise that they can also be used as secondary representations of the second.

Let us now look at the Planck constant, *h*

$$h = 6.626\,0703 \times 10^{-34} \text{ kg m}^2 \text{ s}^{-1}$$

value of *h* = numerical value × unit

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

1. If we define the unit kg m^2 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, this is what we are doing at present with watt balances and silicon spheres.

2. However, if the metre and the second are already independently defined, we can 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. We just have to make sure we choose the right value i.e., one that is really consistent with the present definition of the kilogram. This is why we do it in two independent ways.

The key question is however the following: How can we be sure that the numerical value we choose for these defining constants are the right ones, i.e., that when the new definitions are implemented there will not be a step change in the size of the units?

h = 6.626 0703 × 10^{-34} kg m^2 s^{-1}

value of h = numerical value × unit

The value of h is a constant of nature.

1. If we define the unit kg m^2 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, this is what we are doing at present with watt balances and silicon spheres.

2. However, if the metre and the second are already independently defined, we can 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. We just have to make sure we choose the right value i.e., one that is really consistent with the present definition of the kilogram. This is why we do it in two independent ways.

The first is by means of a watt balance, which we now call the **Kibble balance** in which electrical power is compared with
mechanical power to give a value for ***h***

The second is via measurements of the crystal density of silicon, which gives a value for the Avogadro constant N_A which is linked to h through the following equation:

$$N_A h = [c\alpha^2/2R_\infty][M_u A_r(e)],$$

where α, R_∞, M_u and $A_r(e)$ are the fine structure constant (known to parts in 10^{10}), the Rydberg for infinite mass (parts in 10^{12}), the molar mass constant (exact) and the relative atomic mass of the electron (parts in 10^{10}) respectively.

For the silicon crystal density we have:

$$N_A = n\, M(\mathrm{Si})/\rho\, a^3$$

Where n is the number of atoms per unit cell of silicon, M(Si) the molar mass of silicon, ρ the density of the sample of silicon and a its lattice constant so that, remembering that

$$\boldsymbol{N_A h = [c\alpha^2/2R_\infty][M_u\, A_r(\mathrm{e})]},$$

$$\boldsymbol{h_{(\mathrm{silicon})} = [c\alpha^2/2R_\infty][M_u\, A_r(\mathrm{e})]\, \rho\, a^3 / n\, M(\mathrm{Si})}$$

The important question is how well do these two methods of arriving at a value for *h* agree?

The answer is just within the respective uncertainties of the experimental measurements, namely, two parts in 10^8.

$$h_{(\text{watt balance})} = 4mgv/in^2f^2$$

$$h_{(\text{silicon})} = [c\alpha^2/2R_\infty][M_u\, A_r(\text{e})]\, \rho\, a^3 / n\, M(\text{Si})$$

What does this demonstrate?

The most important outcome is the demonstration that the Josephson and quantum-Hall relations correctly represent macroscopic voltages and resistances – something that had not been demonstrated at this level before.

It is also demonstrates a remarkable level of consistency among the measured values of fundamental constants using a wide variety of methods based on an equally wide variety of equations of physics.

One can conclude that classical and quantum physics in these area are consistent to a few parts in 10^8.
It also gives us confidence that we can redefine the kilogram in terms of this numerical value for *h* without producing a significant step change in the size of the unit of mass.

The 26th CGPM

Considering,

•the essential requirement for an International System of Units (SI) that is uniform and accessible world-wide for international trade, high-technology manufacturing, human health and safety, protection of the environment, global climate studies and the basic science that underpins all these,

•that the SI units must be stable in the long term, internally self-consistent and practically realizable being based on our present theoretical description of nature at the highest level,

•that a revision of the SI to meet these requirements was described in Resolution 1 of the 24th CGPM in 2011, adopted unanimously, that laid out in detail a new way of defining the SI based on a set of seven defining constants, drawn from the fundamental constants of physics and other constants of nature, from which the definitions of the seven base units are deduced,

•that the conditions set by the 24th CGPM, confirmed by the 25th CGPM, before such a revised SI could be adopted have now been met,

The 26th CGPM
Considering,

•the essential requirement for an International System of Units (SI) that is uniform and accessible world-wide for international trade, high-technology manufacturing, human health and safety, protection of the environment, global climate studies and the basic science that underpins all these,

•that the SI units must be stable in the long term, internally self-consistent and practically realizable being based on our present theoretical description of nature at the highest level,

•that a revision of the SI to meet these requirements was described in Resolution 1 of the 24th CGPM in 2011, adopted unanimously, that laid out in detail a new way of defining the SI based on a set of seven defining constants, drawn from the fundamental constants of physics and other constants of nature, from which the definitions of the seven base units are deduced,

•that the conditions set by the 24th CGPM, confirmed by the 25th CGPM, before such a revised SI could be adopted have now been met,

decides

that henceforth the International System of Units, the SI, is the system of units in which:

the unperturbed ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz,
the speed of light in vacuum c is 299 792 458 m/s,
the Planck constant h is 6.626 070 040xx $\times 10^{-34}$ J s,
the elementary charge e is 1.602 176 620 8xx $\times 10^{-19}$ C,
the Boltzmann constant k is 1.380 648 52xx $\times 10^{-23}$ J/K,
the Avogadro constant N_A is 6.022 140 857xx $\times 10^{23}$ mol^{-1},
the luminous efficacy K_{cd} of monochromatic radiation of frequency 540 $\times 10^{12}$Hz is 683 lm/W.

In making this decision, the General Conference notes the consequences as set out in Resolution 1 of the 24th General Conference in respect to the base units of the SI and confirms these in the following Appendices to this Resolution, which have the same force as the Resolution itself.

The General Conference invites the International Committee to produce a new edition of its Brochure *The International System of Units, SI* in which a full description of the SI is given.

Appendix 1 Abrogation of former definitions of the base units:

It follows from the new definition of the SI adopted above and from the new definitions of the base units that

•the definition of the second in force since 1967/68 (13th meeting of the CGPM, Resolution 1) is abrogated,

•the definition of the metre in force since 1983 (17th meeting of the CGPM, Resolution 1), is abrogated,

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

•the definition of the ampere in force since 1948 (9th meeting of the CGPM) based upon the definition proposed by the International Committee (CIPM, 1946, Resolution 2) is abrogated,

•the definition of the kelvin in force since 1967/68 (13th meeting of the CGPM, Resolution 4) is abrogated,

•the definition of the mole in force since 1971 (14th meeting of the CGPM, Resolution 3) is abrogated,

•the definition of the candela in force since 1979 (16th meeting of the CGPM, Resolution 3) is abrogated,

•the conventional values of the Josephson constant K_{J-90} and of the von Klitzing constant R_{K-90} adopted by the International Committee (CIPM, 1988, Recommendations 1 and 2) at the request of the General Conference (18th meeting of the CGPM, 1987, Resolution 6) for the establishment of representations of the volt and the ohm using the Josephson and quantum Hall effects, respectively, are abrogated.

Appendix 2 Status of constants previously used in the former definitions:

It also follows from the new definition of the SI adopted above and from the new definitions of the base units that

- the mass of the international prototype of the kilogram $m(K)$ is equal to 1 kg within a relative standard uncertainty equal to that of the recommended value of h at the time this Resolution was adopted, namely xxxx, and that in the future its value will be determined experimentally,
- that the magnetic constant (permeability of vacuum) μ_0 is equal to $4\pi \times 10^{-7}$ H m^{-1} within a relative standard uncertainty equal to that of the recommended value of the fine-structure constant α at the time this Resolution was adopted, namely xxxx, and that in the future its value will be determined experimentally,
- that the thermodynamic temperature of the triple point of water T_{TPW} is equal to 273.16 K within a relative standard uncertainty closely equal to that of the recommended value of k at the time this Resolution was adopted, namely xxxx, and that in the future its value will be determined experimentally,
- that the molar mass of carbon 12, $M(^{12}\mathrm{C})$, is equal to 0.012 kg mol^{-1} within a relative standard uncertainty equal to that of the recommended value of $N_{\mathrm{A}}h$ at the time this Resolution was adopted, namely xxxx, and that in the future its value will be determined experimentally.

Appendix 3 the base units of the SI

It follows from the new definition of the SI adopted above in terms of the seven defining constants, that the base units of the SI are henceforth implicitly defined as follows:

•The second, symbol s, is the SI unit of time. It is implicitly defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine splitting frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1} for periodic phenomena.

•The metre, symbol m, is the SI unit of length. It is implicitly defined by taking the fixed numerical value of the speed of light in vacuum *c* to be 299 792 458 when expressed in the unit m/s, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$.

•The kilogram, symbol kg, is the SI unit of mass. It is implicitly defined by taking the fixed numerical value of the Planck constant *h* to be 6.626 070 040xx $\times 10^{-34}$ 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 $\Delta\nu_{Cs}$.

•The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge *e* to be 1.602 176 620 8xx $\times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{Cs}$.

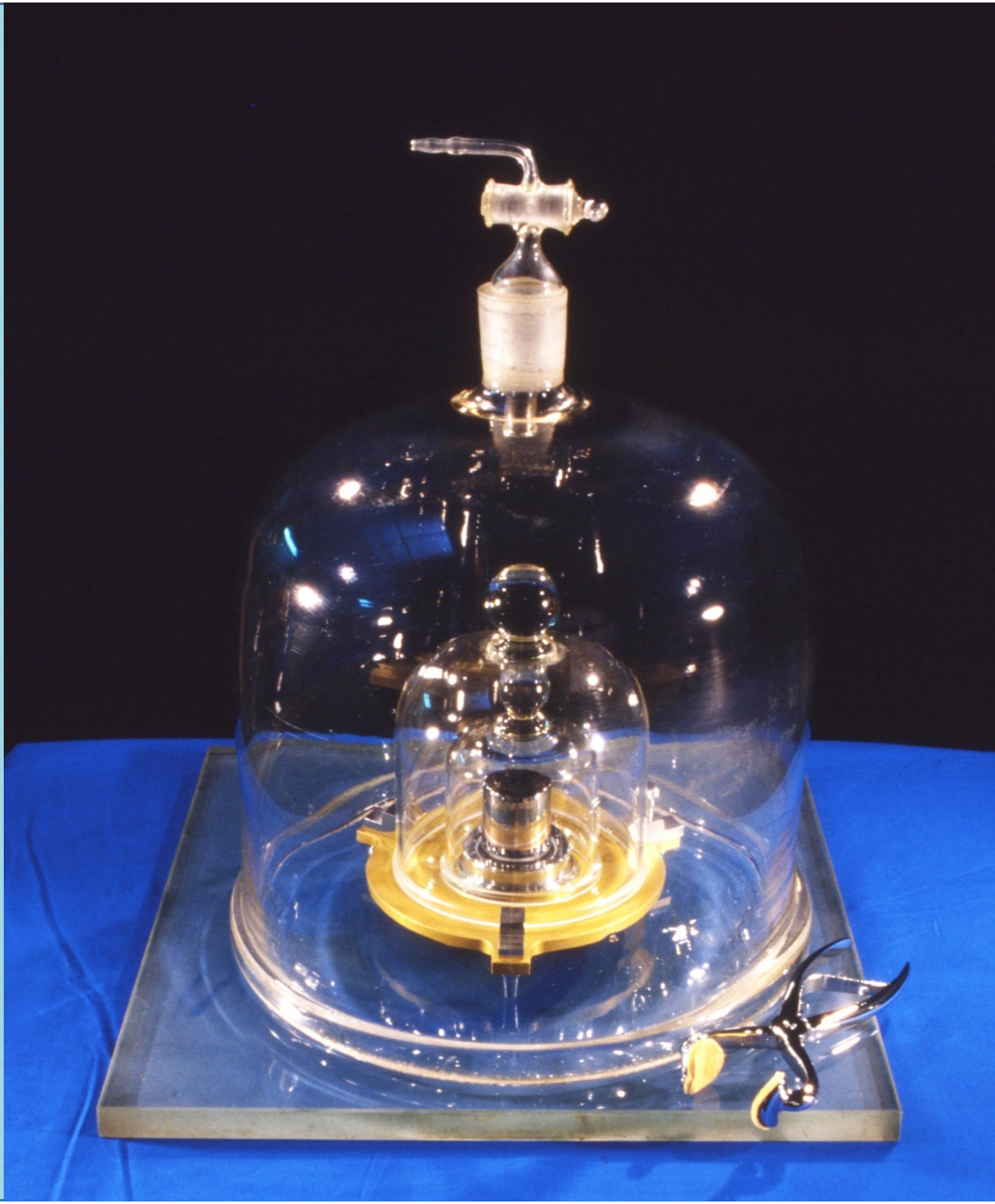
•The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is implicitly defined by taking the fixed numerical value of the Boltzmann constant k to be 1.380 648 52xx $\times 10^{-23}$ when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

•The mole, symbol mol, is the SI 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. It is implicitly defined by taking the fixed numerical value of the Avogadro constant N_A to be 6.022 140 857xx $\times 10^{23}$ when expressed in the unit mol^{-1}.

•The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is implicitly defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or kg^{-1} m^{-2} s^3 cd sr, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

- The mole, symbol mol, is the SI 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. It is implicitly defined by taking the fixed numerical value of the Avogadro constant N_A to be 6.022 140 857xx $\times 10^{23}$ when expressed in the unit mol^{-1}.

- The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is implicitly defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or kg^{-1} m^{-2} s^3 cd sr, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.



Where in fact do we get the best numerical values of the constants?

REVIEWS OF MODERN PHYSICS, VOLUME 84, OCTOBER–DECEMBER 2012

CODATA recommended values of the fundamental physical constants: 2010*

Peter J. Mohr,† Barry N. Taylor,‡ and David B. Newell§

National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8420, USA

(published 13 November 2012)

This paper gives the 2010 self-consistent set of values of the basic constants and conversion factors of physics and chemistry recommended by the Committee on Data for Science and Technology (CODATA) for international use. The 2010 adjustment takes into account the data considered in the 2006 adjustment as well as the data that became available from 1 January 2007, after the closing date of that adjustment, until 31 December 2010, the closing date of the new adjustment. Further, it describes in detail the adjustment of the values of the constants, including the selection of the final set of input data based on the results of least-squares analyses. The 2010 set replaces the previously recommended 2006 CODATA set and may also be found on the World Wide Web at physics.nist.gov/constants.

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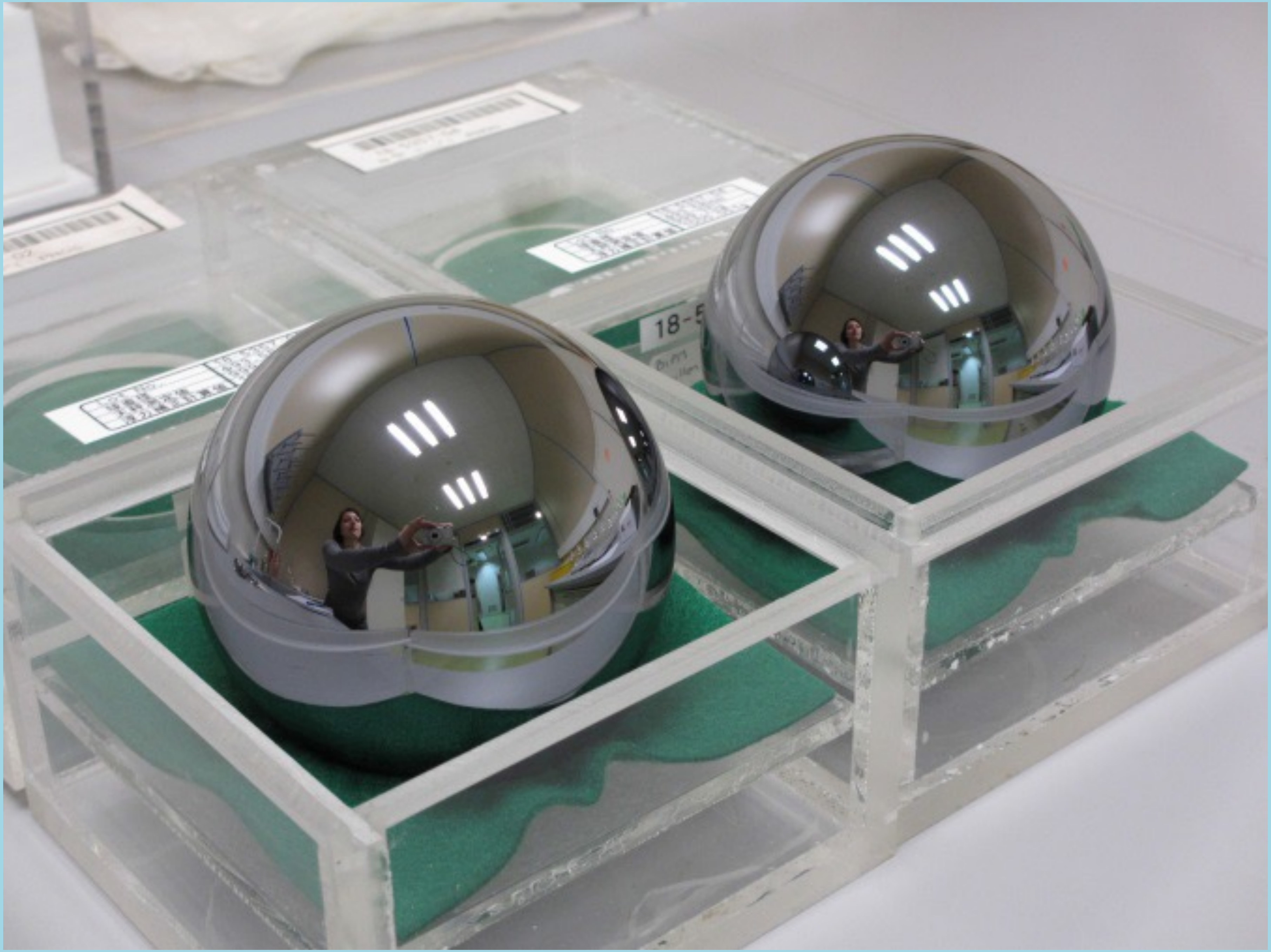
TABLE XL. An abbreviated list of the CODATA recommended values of the fundamental constants of physics and chemistry based on the 2010 adjustment.

Quantity	Symbol	Numerical value	Unit	Relative std. uncert. u_r
Speed of light in vacuum	c, c_0	299 792 458	$\mathrm{m\,s^{-1}}$	Exact
Magnetic constant	μ_0	$4\pi \times 10^{-7}$	$\mathrm{N\,A^{-2}}$	
		$= 12.566\,370\,614\ldots \times 10^{-7}$	$\mathrm{N\,A^{-2}}$	Exact
Electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817\ldots \times 10^{-12}$	$\mathrm{F\,m^{-1}}$	Exact
Newtonian constant of gravitation	G	$6.673\,84(80) \times 10^{-11}$	$\mathrm{m^3\,kg^{-1}\,s^{-2}}$	1.2×10^{-4}
Planck constant	h	$6.626\,069\,57(29) \times 10^{-34}$	$\mathrm{J\,s}$ $m^2 kg s^{-1}$	4.4×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,726(47) \times 10^{-34}$	$\mathrm{J\,s}$	4.4×10^{-8}
Elementary charge	e	$1.602\,176\,565(35) \times 10^{-19}$	C	2.2×10^{-8}
Magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,758(46) \times 10^{-15}$	Wb	2.2×10^{-8}
Conductance quantum $2e^2/h$	G_0	$7.748\,091\,7346(25) \times 10^{-5}$	S	3.2×10^{-10}
Electron mass	m_e	$9.109\,382\,91(40) \times 10^{-31}$	kg	4.4×10^{-8}
Proton mass	m_p	$1.672\,621\,777(74) \times 10^{-27}$	kg	4.4×10^{-8}
Proton-electron mass ratio	m_p/m_e	1836.152 672 45(75)		4.1×10^{-10}
Fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5698(24) \times 10^{-3}$		3.2×10^{-10}
inverse fine-structure constant	α^{-1}	137.035 999 074(44)		3.2×10^{-10}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	10 973 731.568 539(55)	$\mathrm{m^{-1}}$	5.0×10^{-12}
Avogadro constant	N_A, L	$6.022\,141\,29(27) \times 10^{23}$	$\mathrm{mol^{-1}}$	4.4×10^{-8}
Faraday constant $N_A e$	F	96 485.3365(21)	$\mathrm{C\,mol^{-1}}$	2.2×10^{-8}
Molar gas constant	R	8.314 4621(75)	$\mathrm{J\,mol^{-1}\,K^{-1}}$	9.1×10^{-7}
Boltzmann constant R/N_A	k	$1.380\,6488(13) \times 10^{-23}$	$\mathrm{J\,K^{-1}}$	9.1×10^{-7}
Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3 c^2$	σ	$5.670\,373(21) \times 10^{-8}$	$\mathrm{W\,m^{-2}\,K^{-4}}$	3.6×10^{-6}
		Non-SI units accepted for use with the SI		
Electron volt (e/C) J	eV	$1.602\,176\,565(35) \times 10^{-19}$	J	2.2×10^{-8}
(Unified) atomic mass unit $\frac{1}{12}m(^{12}\mathrm{C})$	u	$1.660\,538\,921(73) \times 10^{-27}$	kg	4.4×10^{-8}

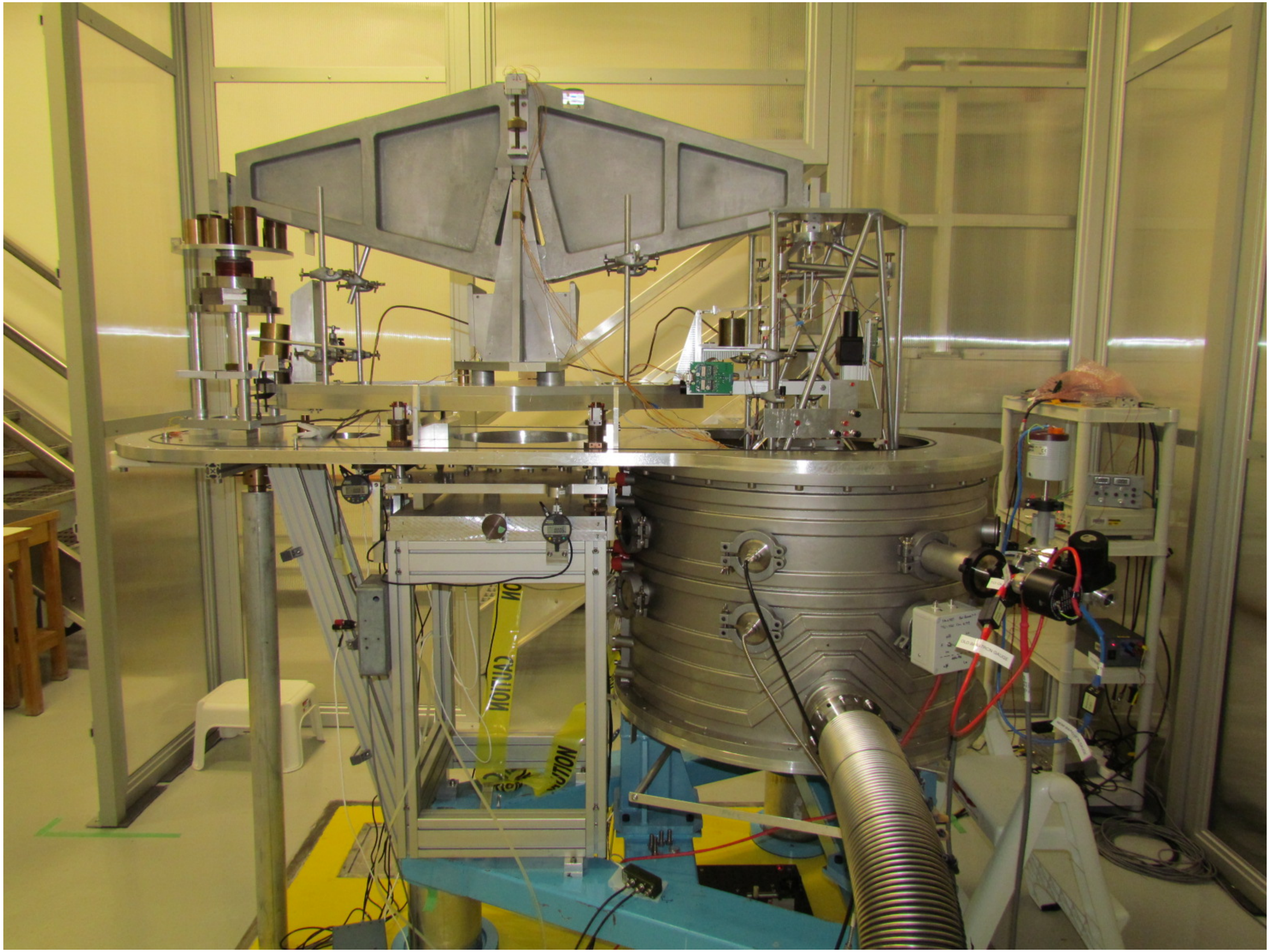

K1
8(41)
7
32
47



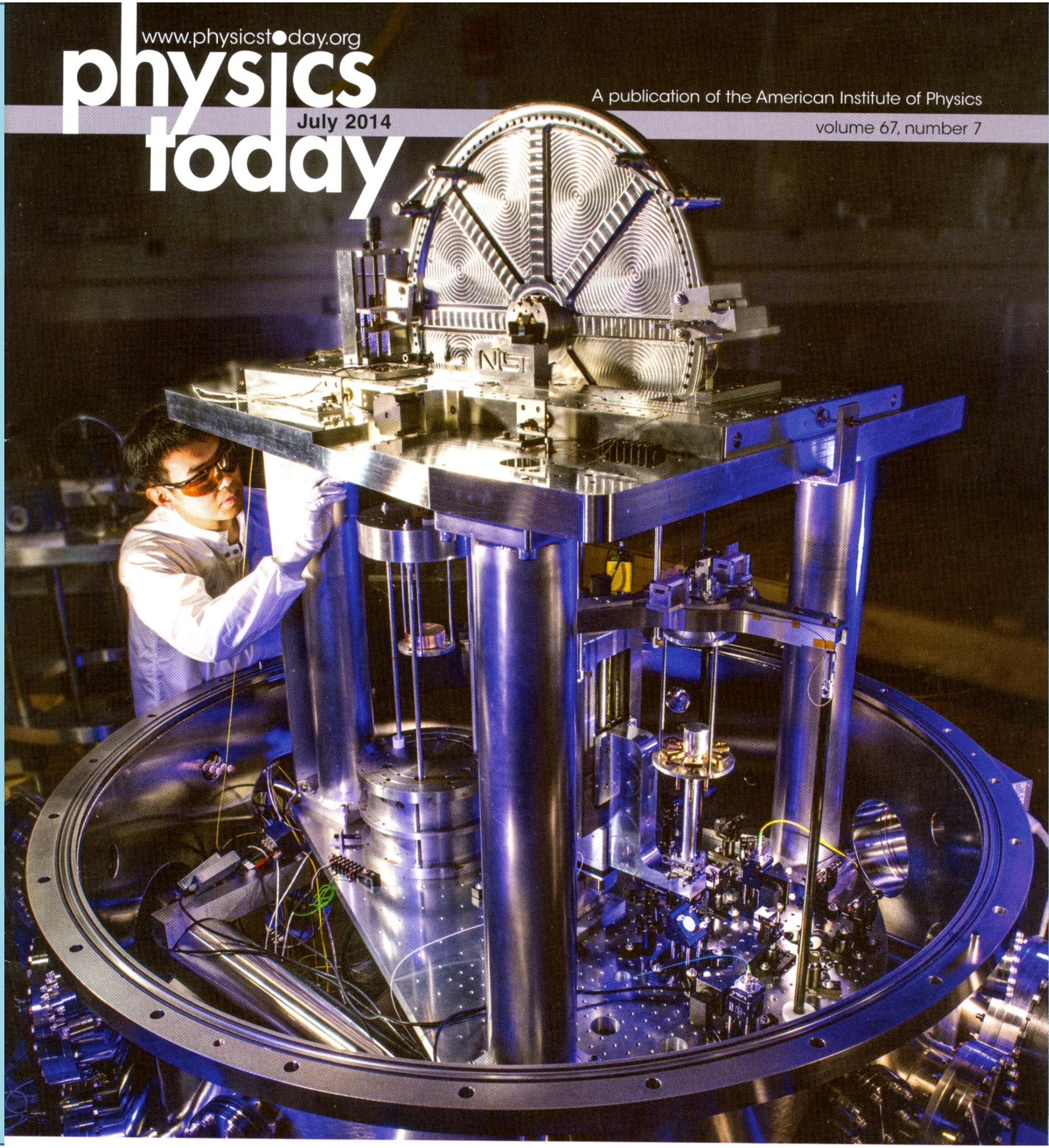

EL-FLOW
Bronkhorst
HIGH-TECH
FLOW

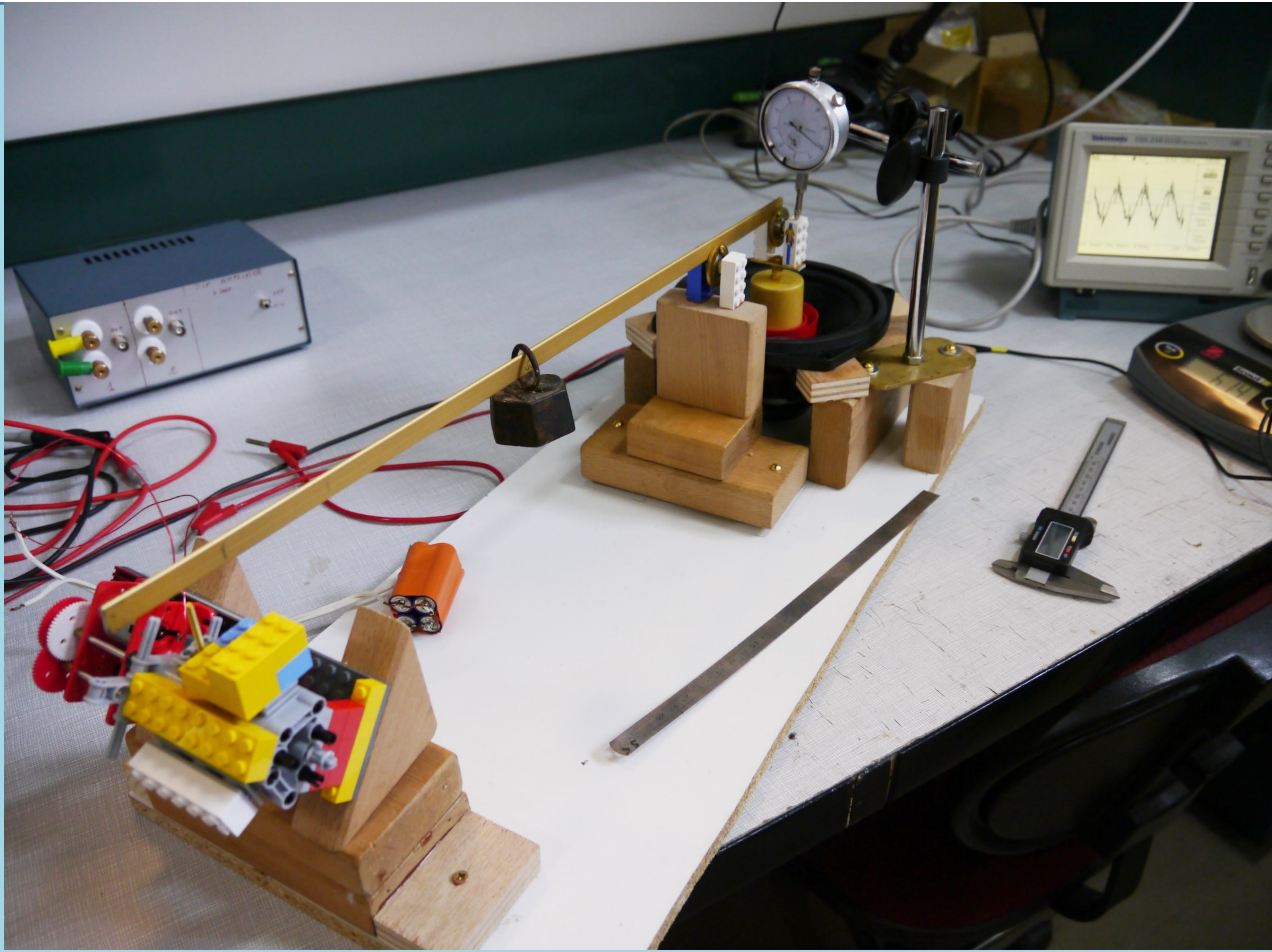
silicon spheres weighing about 1 kg containing about $215\ 253\ 842 \times 10^{17}$ atoms

Photo BIPM



NIST watt balance Mk II





The first Lego Kibble balance, 92 rue Brancas Sèvres

The first Lego Kibble balance on show at the Royal Society Summer Exhibition July 2014, with the team: Terry Quinn, Lucas Quinn and Richard Davis.

A simple watt balance for the absolute determination of mass

Terry Quinn, Lucas Quinn and Richard Davis

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Abstract
A watt balance is an electromechanical device that allows a mass to be determined in terms of measurable electrical and mechanical quantities, themselves traceable to the fundamental constants of physics. International plans are well advanced to redefine the unit of mass, the kilogram, in terms of a fixed numerical value for the Planck constant. A watt balance is one of the devices now being used to measure the Planck constant, but after redefinition will be used to make practical realizations of the kilogram. In this paper we describe a simple 'homemade' watt balance working at the level of about 10% which demonstrates the principle with a view to demystifying the proposed new definition of the kilogram to be based on the Planck constant.

Introduction

A significant overhaul of the present International System of Units (SI) [1] is expected to be implemented within the next five years with the aim of achieving a system of units based on the constants of nature. The biggest change will concern the unit of mass, the kilogram, which will no longer be defined by the mass of a single artefact standard, but instead will be defined in terms of a fixed numerical value for the Planck constant. The ampere, kelvin and mole will be defined by specifying exact numerical values for the elementary charge, e, the Boltzmann constant, k_B, and the Avogadro constant N_A, respectively. The present definitions of the unit of time, the second, and the unit of length, the metre, will remain essentially unchanged. The second will still be defined by specifying the exact numerical value of the frequency in hertz which is exploited by the caesium 'atomic clock' and the metre will still be defined by specifying the exact numerical value of the speed of light in metres per second. Note that at present the kilogram is the only unit based on an artefact and that it also affects the definitions of the ampere (which includes the specification of a force) and the mole (which refers to a mass of 1 kg).

An essential prerequisite to the new SI [2] is that these four constants must be measured experimentally in the present SI. The exact numerical values specified in the new SI will be chosen to be consistent with the present experimental values, thereby ensuring a seamless transition from the present to the new SI.

This paper describes how the new definition of the kilogram can be implemented by taking advantage of electromagnetic phenomena. As mentioned above, the current definition of the kilogram affects the ampere and the mole. It is therefore not surprising that a second method for implementing the new kilogram definition is also being pursued, based on counting the atoms in a single crystal [3]. These methods are complementary.

Note. Our watt balance has been selected as an exhibit at the 2013 Royal Society Summer Science Exhibition.

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doi:10.1088/0031-9120/48/5/601

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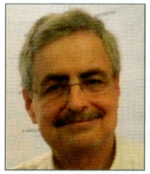
Terry Quinn is emeritus director of the BIPM and a fellow of the Royal Society. He was much involved in international metrology over many years.

Lucas Quinn is Terry Quinn's grandson, aged 11 years and an expert in Lego construction.

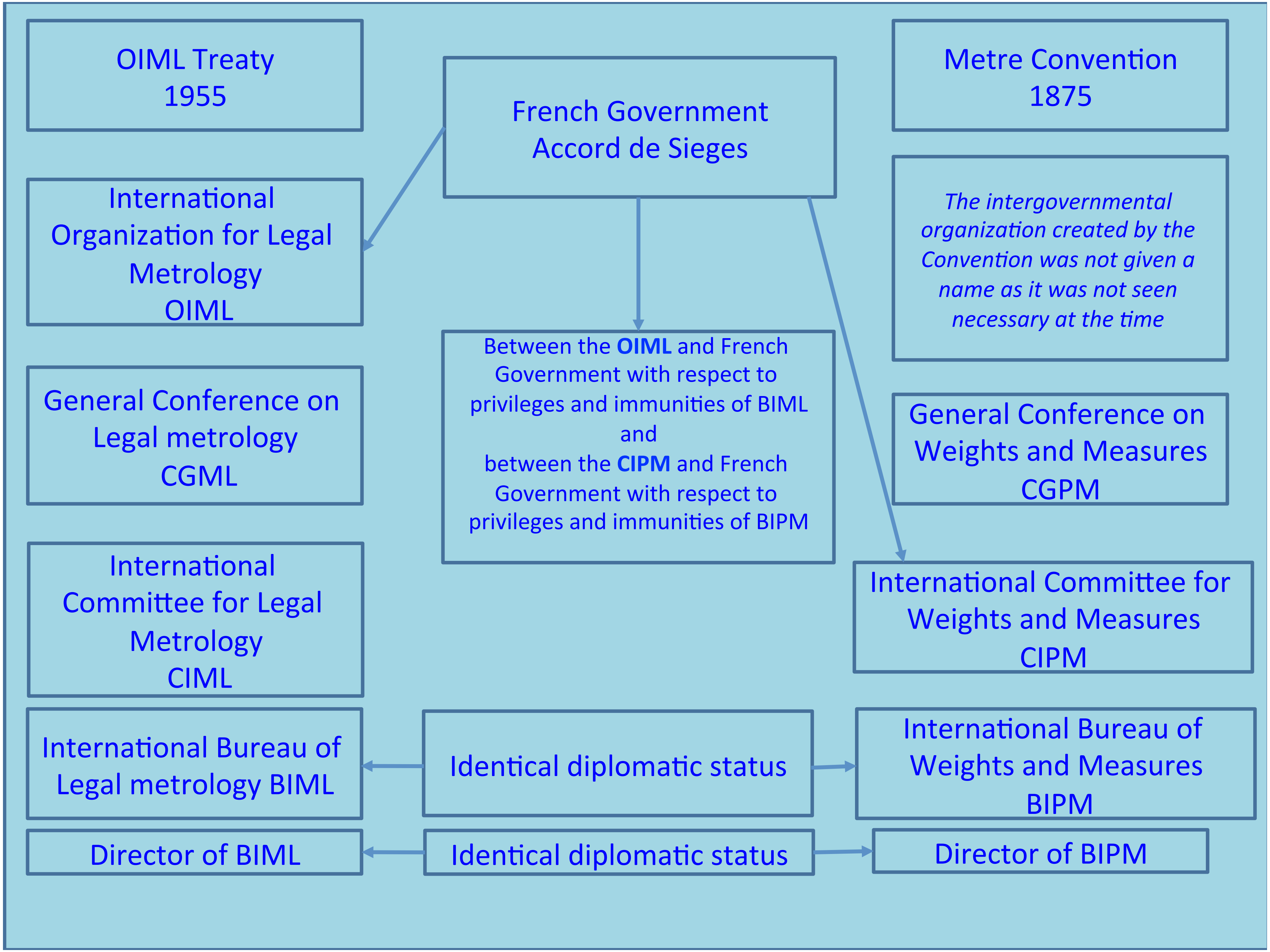


Richard Davis is emeritus principal research physicist of the BIPM, a fellow of the American Physical Society, and former director of the Mass Department of the BIPM.

The site and buildings of the BIPM in 2002

Located at: 48° 49' 46" N, 2° 13' 13" E

Image BIPM


OIML Treaty 1955
French Government Accord de Sieges
Metre Convention 1875
International Organization for Legal Metrology OIML
The intergovernmental organization created by the Convention was not given a name as it was not seen necessary at the time
Between the OIML and French Government with respect to privileges and immunities of BIML and between the CIPM and French Government with respect to privileges and immunities of BIPM
General Conference on Legal metrology CGML
General Conference on Weights and Measures CGPM
International Committee for Legal Metrology CIML
International Committee for Weights and Measures CIPM
International Bureau of Legal metrology BIML
Identical diplomatic status
International Bureau of Weights and Measures BIPM
Director of BIML
Identical diplomatic status
Director of BIPM

Article XXIII of the OIML Treaty relative to the formal status of the International Bureau of Legal Metrology BIML:

"The Governments of Member states declare that the Bureau shall be recognized as of public utility, that it shall have legal status and that, generally speaking, it shall benefit from the privileges and facilities commonly granted to intergovernmental bodies under the laws in force in each of the member States."

The BIPM is an international scientific institute recognized in France as of public utility, with legal personality and with the privileges and immunities commonly granted to intergovernmental bodies under the laws of France according to the Accord de Siege between the French Government and the CIPM

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