Establishment and Maintenance of the Electrical Units

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UNITED STATES DEPARTMENT OF COMMERCE • Charles Sawyer, *Secretary*
NATIONAL BUREAU OF STANDARDS • E. U. Condon, *Director*

Establishment and Maintenance of the Electrical Units

by F. B. Silsbee

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Preface

January 1, 1948, marked the end of an era in the evolution of the science of electrical measurements. On that date the system of so-called "international" electrical units was abandoned, and a new system of measurement, using what are commonly called "absolute" units, was officially instituted. It is the purpose of this Circular to put on record an account of the working of the international system of electrical units, with particular reference to the maintenance of the international units in the 37 years (January 1, 1911, to January 1, 1948) during which the system was in its final form, to point out the trends of development that made them obsolete, to record the official steps by which they were superseded, and to describe briefly the methods used in the measurements that now form the basis for the new absolute units.

In this record many of the illustrative data will be quoted from the records of the National Bureau of Standards, merely because such data were the most readily accessible to the author. It is to be presumed that a similar examination of the records in any of the other national laboratories would show a similar picture.

E. U. Condon, *Director.*

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Abstract

A history is given of the establishment of the "international" system of electrical units, its operation during the interval 1911 to 1947, inclusive, and of the developments that caused it to be superseded. It includes a record of the international comparisons, which indicated that the units of some countries have at times drifted nearly 0.01 percent from the mean, an account of the maintenance procedures used at the National Bureau of Standards, and brief descriptions of the methods currently available for the absolute measurement of resistance and of current, which will be used in the future as a check on the maintenance of the units.

I. Historical

The early workers in electrical measurements set up arbitrary standards of resistance by specifying the use of pieces of wire of a definite material, length, and cross section (or weight), and used the Daniell (zinc-copper) cell as a standard of electromotive force. The work of Gauss (1833) and Weber (1851) showed, however, the possibility of measuring electric and magnetic quantities in terms of mechanical units. In 1861 the British Association for the Advancement of Science established a committee on electrical units and standards [1] [1] with Maxwell as chairman, which for over 50 years played a leading part in the development and coordination of electrical standards. This committee recognized the fundamental value of correlating the electrical and mechanical units and, in 1863, recommended the particular set of decimal multiples of the centimeter-gram-second electromagnetic units that form the "absolute practical" units. In this designation the word "absolute" signifies that the unit is defined directly in terms of the mechanical units by a numerically simple relation. The work "practical' signifies that the unit is (except for the unit of capacitance) of a size that is convenient in practical engineering work. The particular factors chosen are given in the following tabulation.

1 absolute coulomb = 0.1 cgs electromagnetic unit of charge.
1 absolute ampere = 0.1 cgs electromagnetic unit of current.
1 absolute volt = 10^8 cgs electromagnetic units of electromotive force.
1 absolute ohm = 10^9 cgs electromagnetic units of resistance.
1 absolute joule = 10^7 ergs.
1 absolute watt = 10^7 ergs per second.

These factors were given international status by the Paris Electrical Congress of 1881.

Experiments made under the auspices of the British Association Committee, and by others, led to the assigning of numerical values to the resistance of wire standards and to the electromotive force of certain types of standard cells, which at the time were adequately close approximations to the absolute values. Numerous copies of this "B. A. Ohm" were distributed to laboratories in several countries by the committee as a means of securing international consistency.

In the early use of electricity for communication, the principal need for quantitative results was in the field of resistance measurements, but in the 1880's, with the beginning of the application of electric energy to light and power, the need for measurements of other electrical quantities became acute. Numerous power stations, factories for building electric machinery, and electrical laboratories were rapidly being established in many countries. At that time there were no national standardizing laboratories, and the procedures for making accurate absolute measurements were (as now) both difficult and time-consuming. There was, therefore, a very definite need for more convenient and universally accepted

[1] Figures in brackets indicate the literature references at the end of this paper.

procedures by which the electrical units could be reproduced in an isolated laboratory. To satisfy these needs, much experimental work was carried on to develop appropriate reproducible standards, and a number of international electrical congresses were held to promote their acceptance.

As a reproducible standard of resistance, the most promising seemed to be the resistance of a column of pure mercury of specified dimensions at a specified temperature. A pair of such "mercury ohms" is shown in figure 1. Mercury is easily purified and, at room temperature, has a much higher resistivity and lower temperature coefficient than any other pure metal. One such standard—the old Siemens Einheit—had been the resistance at 0° C of a column of mercury 1 m long and 1 sq mm in cross section. An international commission, appointed in accordance with a resolution of the International Congress of Electricians, Paris, 1881, adopted as the "legal ohm" a mercury column having a length of 106 cm and a cross section of 1 sq mm. This unit was never officially "legalized" by any government action, and by the time of the Chicago Congress of 1893 a length of 106.3 cm was recognized as much closer to the correct value.

FIGURE 1. *Mercury ohm tubes.*

Two are shown, each provided with a large spherical bulb at either end. The potential leads are sealed through the bulb walls at the top, and the current leads connect through the filling tubes along the axis. The ends of the main tube are cut to be flush with the inner surfaces of the bulbs, and a small correction is applied to allow for the effective resistances in the bulbs.

As a reproducible standard of current, the work of Lord Rayleigh, Kohlrausch, and others gave promise that high accuracy might be obtained with the silver voltameter, in which the current is measured by the rate at which silver is deposited electrolytically from a silver-nitrate solution on the interior surface of a platinum cup. At a meeting of the British Association in Edinburgh in 1892, a rate of deposition of 0.001118 g per second under specified conditions was adopted as that corresponding to 1 ampere.

A reproducible standard of voltage had been developed by Latimer Clark (1873) [41] in the type of standard cell that bears his name. This cell has electrodes of zinc amalgam and of mercury with an electrolyte of mercurous and zinc sulfates. Its emf is 1.434 volts at 15° C. Somewhat later Weston (1893) [42] introduced the use of cadmium in place of zinc. This change eliminated a number of the difficulties experienced with the Clark cell, and the Weston cell has come into universal use. The positive electrode is mercury and the negative an amalgam containing about 10 percent of cadmium. A paste of mixed mercurous-sulfate and cadmium sulfate crystals is placed over the mercury electrode, and the electrolyte is a solution of cadmium sulfate. Cadmium standard cells are made in two types. In one of these,

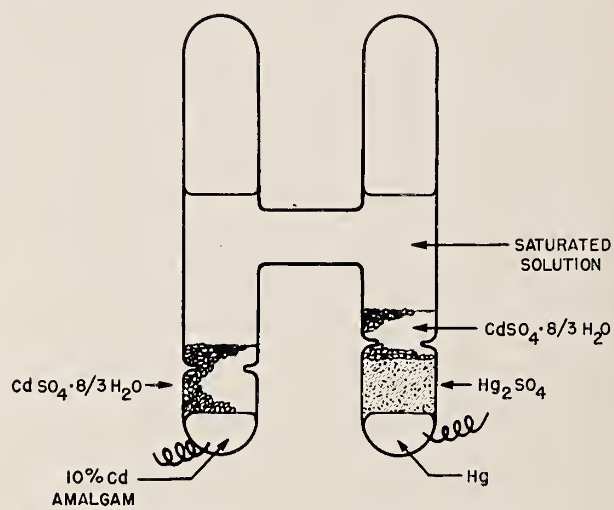

FIGURE 2. *Cross section of a saturated cadmium standard cell.*

The primary reaction in such a cell is
$Cd(\text{2-phase amalgam})+Hg_2SO_4(s)+\frac{8/3}{m-8/3}CdSO_4\ mH_2O(l)=\frac{m}{m-8/3}CdSO_4\ 8/3H_2O(s)+2Hg(l)$.

shown in figure 2, the Cd SO_4 solution is saturated, and surplus crystals of $CdSO_4.8/3H_2O$ are present at any ordinary temperature. Such cells show a very remarkable constancy of emf with time but have a temperature coefficient of about −0.004 percent per degree C. It is this type that is used for all work of high accuracy, such as maintaining or comparing the national units of emf. Often cells of the saturated type are made using 0.05-normal or 0.1-normal sulfuric acid. Such cells are also very permanent but have an emf that is lower by 30 μv and 60 μv, respectively. The second, or unsaturated type, has such a concentration of $CdSO_4$ as to make the temperature coefficient of emf so small as to be negligible for all engineering purposes. This particular concentration corresponds to saturation at 4° C. This unsaturated cell is the type generally preferred in ordinary laboratory work in the United States because of its independence of temperature. It is, however, less constant in emf.

The term "Weston normal cell" is often used to designate any individual cadmium standard cell of the saturated type described above. Such cells may differ from one another in emf by 10 or 20 μv. When written "Weston Normal Cell," the term takes on a slightly different and almost mystical significance as a cell that embodies the essential features, namely, emf and temperature coefficient, shown by the average of an infinite population of Weston normal cells. In the light of measurements reported below, an alternative definition for "The Weston Normal Cell" would be a standard cell the emf E, of which at a temperature of t°C is given in international volts by the equation

$$E=1.018300-0.0000406(t-20) \\ -0.00000095(t-20)^2+0.00000001(t-20)^3.$$

In the literature many instances will be found in which the author has chosen to express the emf of a particular cell or group of cells as differing by a specified amount from the Weston Normal Cell as defined in this way.

The International Electrical Congress held in Chicago in 1893 recognized the fundamental value of the absolute units based on the cgs system of mechanical units and confirmed the decisions of earlier congresses as to the particular integral powers of 10 by which the "practical" units should be related to the cgs units. However, the Chicago congress also recognized the utility of the three reproducible standards and formally recommended the legal adoption of units of both systems as being mutually equivalent.

In accordance with these recommendations the United States Congress passed, on July 12, 1894, Public Bill No. 105, making the practical units, based upon the cgs system and embodied in the reproducible standards, the "legal units of electrical measure in the United States." See Appendix 1.

In the years that followed, national standardizing laboratories (Physikalisch-Technische Reichsanstalt 1887, National Physical Laboratory 1899, National Bureau of Standards 1901), were created in the more highly industrialized nations. The results of work at these laboratories made it clear that, to the higher accuracy then desired, the units of the two sets recommended at Chicago were not equal in magnitude but differed by amounts that were large enough to be measured definitely, and which would, if ignored, cause confusion in future measurements.

Another unfortunate feature of the Chicago recommendations was the specification on independent bases of all three units (the ohm, the ampere, and the volt). In the case of the absolute practical units this is permissible, because an inherent feature of the cgs electromagnetic system of units leads as a theoretical consequence to the relation that an absolute volt is the difference of potential produced between the terminals of an absolute ohm by the presence of an absolute ampere. However, with independent definitions for all three units, Ohm's Law becomes a relation to be experimentally determined, and its expression requires a numerical coefficient, which, in general, will not turn out to be exactly unity. The obvious procedure to avoid such an awkward coefficient is to define only two units independently in terms of separate standards. There was general agreement that one of the two primary units should be the ohm, but opinion was divided as to whether the other should be the ampere or the volt. The discussion [3] waxed violent, one group emphasizing the (apparent) simplicity of the voltameter, while their opponents, pointing out that the unit had to be ultimately maintained by a standard cell, urged the simple process of specifying the construction of a cell and thus saving one experimental step.

After preliminary discussions at international gatherings in St. Louis, 1904, and Berlin, 1905, an International Conference on Electrical Units and Standards was held in London in October 1908. The resolutions drawn up at this conference were in such form (appendix 2) as to distinguish clearly between (a) the "fundamental units," ohm, ampere, etc., which are exact decimal multiples of the cgs electromagnetic units, and (b) a "system of units representing the above and sufficiently near to them to be adopted for the purpose of electrical measurements and as a basis for legislation . . . the International Ohm, the International Ampere, and the International Volt . . . ." The "international" ohm was defined in terms of a mercury column, which was specified in full detail, and the "international" ampere was defined in terms of the silver voltameter, the specifications for which, however, were incomplete. The "international" volt was then defined as "the electrical pressure which, when steadily applied to a conductor whose resistance is one International Ohm, will produce a current of one International Ampere." The volt thus became a derived unit and the standard cell became a secondary standard, the emf of which was to be determined in terms of the two primary international units.

The previous practice of setting up cells as standards was still strong in the minds of the committee so that as a sort of byproduct it stated in its Schedule C, "The Weston Normal Cell may be conveniently employed as a standard of electric pressure . . . ," and gave fairly definite specifications for its construction. A provisional value of 1.0184 volts was assigned, but it was expected that this value would be revised from time to time as a result of future experiments.

differed by only 10 ppm (parts per million), the German unit being the larger. Preliminary results of work then in progress at the National Bureau of Standards [13] were also in agreement, and the committee therefore "recommended to all countries for general use [5] as the international ohm the mean of the values of the units realized at the PTR (Physikalisch-Technische Reichsanstalt) and the NPL (National Physical Laboratory)."

The basis for the ampere was found to be much less satisfactory. In the operation of the silver voltameter one complication arises from the formation at the silver anode of "anode slime" that must be prevented from getting to the cathode where it might cause an error in the weight of the deposit. To avoid such an error a number of arrangements have been used, two of which are shown in figure 3. In the Rayleigh form of

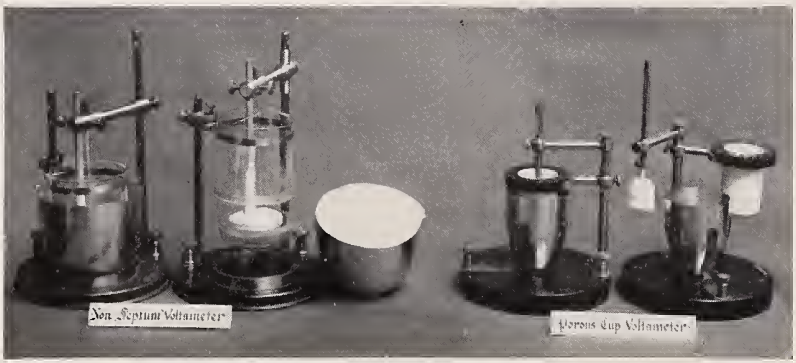

Figure 3. *Two forms of voltameter.*

The nonseptum voltameter is of the Smith form and the porous-cup voltameter is the Richards form. Each form is shown assembled at the left and disassembled at the right.

voltameter the anode is wrapped in filter paper. In the Richards (or porous pot) form a porous, unglazed porcelain pot surrounds the anode and catches the slime while permitting the current to flow in the electrolyte in the pores. In the early Kohlrausch form, a shallow glass cup is placed below the anode to catch the slime, and in the later Smith form, a glass cylinder can be lowered at the completion of the run so as to fit tightly on the upper edge of the cup and prevent any spilling of material when the voltameter is disassembled. A siphon form, in which the two electrodes are in separate vessels, has also been used.

As a sequel to the London Conference, a special International Technical Committee met in Washington at the Bureau of Standards in April and May 1910 to carry out work that the Conference had recommended. The three foreign members [2] of the Committee brought from their respective British, French, and German national laboratories standard resistors and cells that had been evaluated in terms of their national units. They made careful intercomparisons of these coils and cells and those in use at the National Bureau of Standards and also carried out an elaborate series of experiments with silver voltameters of various types. As a basis for the value of the ohm, it happened that both the Reichsanstalt and the National Physical Laboratory had each recently completed an elaborate program of comparisons of the resistance of mercury columns with wire standard resistors [11, 12]. The comparisons of their standards at Washington showed that they

The work of the committee showed clearly that voltameters of various types might give consistently different results. For instance, the deposits from solutions in which filter paper was used were heavier by about 150 ppm. The committee was therefore "of the opinion that the specifications for the silver voltameter should not be completed until further experiments shall be made . . . ". A great deal of work was

[2] The International Technical Committee consisted of Dr. E. B. Rosa (NBS), chairman; Dr. W. Jaeger (PTR); Prof. F. Laporte (LCE); Mr. F. E. Smith (NPL); and Dr. F. A. Wolff (NBS).

done later, particularly at the National Bureau of Standards, [21] in response to this recommendation. A number of sources of error were tracked down and definite operating procedures for the silver voltameter were formulated, but the specifications were never officially adopted.

In spite of the incompleteness of the specifications for the voltameter, however, the committee used the results of the voltameter experiments, together with the values in international ohms assigned to various coils, to derive a value for the international volt and to assign values in terms of this for the emf of the various standard cells used in the work.

A further result of the work of the International Technical Committee was a revision of the value tentatively assigned in 1908 for the emf of the Weston Normal Cell in terms of the International Volt. The committee took as a value representing the Weston Normal Cell the mean of the separate group means of the four groups of cells that had originated in the four different countries, and which had had time to settle down to constant values. A total of 104 cells were included, the number in a group ranging from 15 to 40 cells. The average deviations for the emf of an individual cell from the mean of its group was ± 12 μv, while the groups deviated by ± 5 μv from the mean of the four. The voltameter experiments, excluding the most doubtful results such as those with filter paper present, gave for the final mean the value of 1.0183 international volts.

On the completion of the work of the International Technical Committee [5], each delegate carried back to his respective laboratory its standard coils and standard cells each with its newly assigned value in terms of a common system of units. The system of "international" electrical units was thus successfully launched with universal agreement on the magnitude of the units as of January 1, 1911.

II. Maintenance of Units

1. General

The general procedure followed at the National Bureau of Standards to preserve through the years the value of a primary electrical unit of measurement is to keep under observation a large group, N, of standards of the highest grade. A selected group, n, of these standards is regarded as the primary reference group, and the assumption is made that in the interval between intercomparisons the mean value of all the standards in the primary group, n, has remained unchanged. The intercomparisons are made at intervals, usually once a month for standard cells and seldom exceeding a year for standard resistors. Such comparisons are often preliminary to important checks on the standards of other laboratories.

Following each set of measurements, the value of each of the standards of group n relative to the new mean is compared with its previous value relative to the old mean, and its apparent change is compared with those of the other standards of group n. If these changes are reasonably small and well distributed statistically it is assumed that all is in order. If however one standard shows a change markedly out of line with the others, it is assumed that some unsuspected accident has occurred and the value of this standard is omitted from the mean. In its place is inserted the value of one of the other standards, from the larger group, N, which has shown a reasonable performance during the preceding periods. Thus the final decision as to which standards carry the unit for a given period is made after the data observed at the end of the period have been scrutinized.

After this process has been in operation for a number of periods a new criterion for the rejection from group n of a questionable standard becomes available. A standard that shows only a moderate change during any one interval may, when earlier data are examined, be found to show a progressive drift in one direction and may be rejected for that reason. In such a case two procedures are possible: (1) The value assigned to the mean of the new group may be taken as that which it had at the beginning of the last interval between comparisons; or (2) A new value of the unit can be derived on the basis that the suspected standard had been rejected at the time it first began its drift and that thereafter the unit had been carried by the remainder of the group. The latter process is called "recapturing the unit." Procedure (2) results in a formal admission of an abrupt change in the value of the unit at the time it is "recaptured," because measurements of the same quantity made just before and just after the readjustment will differ by the amount of the adjustment. With procedure (1) the change in the unit is distributed over the period of drift and is not recognizable though still present. Procedure (2), of course, is the more successful in the long run in eliminating the cumulative effects of drifts in one direction. At the National Bureau of Standards, procedure (2) is regularly used in the maintenance of the volt because the tendency of defective standard cells is always toward a drop in emf. In the maintenance of the ohm, procedure (1) has been followed. With either procedure, the intervals are so short and the accuracy of the measurement is so high that any defective standard can be detected and weeded out before its effect is large enough to be

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significant. The use of a fairly large number ($n=10$ or 25) of standards in the primary group contributes very materially to reducing the effect of a drift in any one of them.

2. Maintenance of the Ohm at the National Bureau of Standards

Following the legalization of the electrical units by Act of Congress in 1894, the Office of Standards, Weights and Measures, then part of the Treasury Department, was authorized in 1897 to appoint a verifier. As fast as the very limited appropriations permitted, standard resistors of various denominations were purchased in Germany and standardized at the Physikalisch-Technische Reichsanstalt. When the National Bureau of Standards was set up, following the passage of its organic act in 1901, it took over this equipment and the personnel that had been operating it. The unit of resistance during this period was therefore that of the German institution. At that time resistance apparatus made in Berlin by the firm of Otto Wolff was recognized as being of the highest quality available, and the Reichsanstalt, the oldest of the national laboratories, was currently active in setting up mercury columns. Resistance standards and other resistance apparatus of Wolff's manufacture were purchased by the Bureau in considerable quantity, submitted to the PTR for standardization in terms of the unit of that institution, and then shipped to Washington to equip the new laboratory.

In 1907 a group of four recently certified 1-ohm resistors of the Reichsanstalt type were received from Berlin. The values of these resistances formed the basis for assigning values to a larger group consisting of ten 1-ohm and seven 0.1-ohm standard resistors. The mean of this group was assumed to remain constant from that time until May 1909, and thus carried the unit forward.

In the meantime, experimental work at Washington had shown that open standards, such as those of the Reichsanstalt type [31], underwent a marked seasonal fluctuation in resistance, which, in the case of some 1,000-ohm resistors, amounted to as much as 200 parts per million in 3 months. This effect, reported by Rosa and Babcock [32], was traced to seasonal variations in atmospheric humidity. The effect is much less with 1-ohm resistors but, to avoid these fluctuations, Rosa [33] designed a new type of standard resistor. In this the insulated manganin coil is enclosed in a hermetically sealed metal container. The container is nearly filled with refined mineral oil, and the terminals are brought out through a hard rubber top. A considerable number of standards of this construction were manufactured both in the instrument shop at the NBS and also by Otto Wolff.

In May 1909, values of resistance were assigned to a group of 1-ohm standards of this new construction, on the basis of the unit that had been carried until then by the seventeen open-type coils. From May 1909 until October 1932 the ohm was maintained at the NBS by a "primary" group of 10 resistors selected from these 1-ohm standard resistors of the Rosa sealed type. The unit thus maintained is that which later came to be designated as the "Ohm—certified NBS".

Comparisons made in 1910, in connection with the work of the International Technical Committee on electrical units, showed that at that time this unit was larger by 2 ppm than the unit then used by the PTR, and larger by 7 ppm than the mean value of the British and the German units. This mean value was adopted by the Committee for purposes of international uniformity and is commonly designated as the "Washington unit". (It is this Washington unit that is represented in figure 8.) The slight difference of 7 ppm was entirely negligible in the practical conduct of ordinary electrical measurements at that time, and therefore the "book values" assigned to the several resistance standards on the earlier basis were not changed.

Between 1909 and 1932, careful comparisons of the relative resistances of the entire group of 1-ohm coils were made at somewhat irregular intervals, averaging 6 months. In computing the results of each intercomparison, it was assumed that the average resistance of 10 selected coils of the highest grade had remained unchanged since the prior intercomparison. On this basis a new value was assigned to each of the coils of the entire group. An examination of the data shows that the average difference (without regard to sign) between the two values thus successively assigned to a resistor was only ± 1.3 microhms, and that in 95 percent of the cases the difference in the successive values was less than ± 3 microhms.

In general, the same resistors were kept in the standard group from year to year unless there was some reason for a change. Also, five of the standards that at one time had been removed from the primary group were later used in it again, so that during the whole period of 23 years twenty standards were involved. During the period, standards were removed from the primary group on 15 occasions. On six of these occasions there was no suspicion of a change or defect in the standard, but the removal was occasioned by the use of the standard for some other purpose, frequently for shipment abroad for use in an international intercomparison. Of the remaining nine removals, one was occasioned by the development of a loose terminal, which obviously caused the hermetic seal to be broken; five were occasioned by an abnormally large increase in the resistance of the coil over its value at the preceding intercomparison. These increases ranged from a minimum of 5 to a maximum of 12 microhms. Three were occasioned by decreases in resistance, the maximum of which was less than nine microhms. Two of the standard resistors remained in the primary group for the entire period, and six resistors were in the group for more than 15 years.

Examination of the data shows that the resistances of five of the resistors drifted at a slow and fairly steady rate over the period while they were in the primary group. The rates of drift of their resistances ranged from a decrease of 1 ppm per year to an increase of 4 ppm per year. One standard that was used for a short period showed a decrease at a rate of 6 ppm per year. The coil that approximated most closely to the mean showed a decrease of 0.3 ppm per year. Several coils showed a drift that changed from an increase of 0.6 ppm per year when first included to a decrease of 2 ppm per year after several years had elapsed.

A comparison of the individual readings made on one of the standards, which showed a nearly linear decrease of 1 ppm per year, with a least square straight line adjusted through these points shows a standard (root mean square) deviation of ± 2.8 ppm. It is probable that the lack of precision in the electrical measurements involved in each intercomparison could have contributed only a very small part of this variation. Most of it probably results from minor secular variations, and perhaps some from uncertainties in the temperature of the standard itself.

Beginning in 1928, Thomas [34] had constructed a number of standard resistors of a new type sometimes referred to as "double-walled." One of them is shown in figure 4. In these the bare manganin wire is annealed in a vacuum at a temperature of 500° C. or above, while wound on a mandrel. It is then slipped on an insulated brass form, spaced with linen thread, tied down, and fastened with shellac, and then baked for about an hour at 80° C. The form is tubular and constitutes the inner wall of a container that is sealed by soldering its end flanges to an outer, slightly larger, tube. Dry air at about atmospheric pressure fills the container, and the leads are brought out through a shellac seal. A group of such resistors showed such excellent behavior that two of them were used in the primary group in October 1930 and a third in April 1932. Beginning in October 1932, the use of the Rosa sealed standards in the primary group was discontinued, and 10 resistors of the Thomas type made with a coil diameter of 6 cm formed the primary group until March 1939.

During this period the average difference observed between successive measurements made at intervals averaging 6 months was only 0.3 microhm, and 80 percent of these differences were less than 0.8 microhm. A least square line adjusted to fit the data over this period of 6 years, for the worst of these resistors, showed an average slope of less than 0.5 microhm per year and a standard deviation from a straight line of only ± 0.4 microhm. It is thus evident that this type of construction produces a standard resistor the relative stability of which is better by an order of magnitude than that of the Rosa type.

In 1933, work was completed on the construction of an additional group of Thomas-type standards of somewhat larger dimensions in which the coil had a diameter of 8 cm, with a correspondingly greater cooling surface. These standards were compared with the smaller double-walled standards between 1932 and 1939, and from March 1939 to the present time a group of 10 of the large Thomas-type standards has been used to carry the unit forward. The average difference observed between successive measurements in individual coils is ± 0.2 microhm, and 95 percent of the differences do not exceed ± 0.5 microhm. The slope of a least-square line passed through the points observed, in the case of the worst of these standards, is 0.1 microhm per year, and the standard deviation of an individual point is 0.1 microhm.

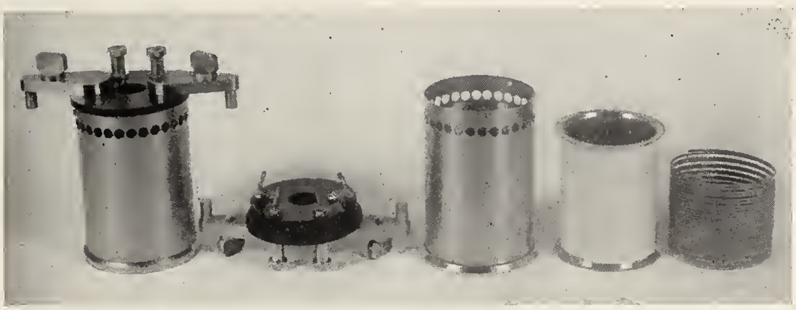

Figure 4. *Double-walled (Thomas type) standard resistor.*

The manganin wire shown at the extreme right is annealed in vacuum. It is tied down on the inner form shown next to it and then sealed between the inner and outer brass cylinders.

One method attempted at the NBS as a means for independently corroborating the maintenance of the ohm was the use of standards formed by wires of pure metals. It would not be expected that such standards would drift at the same rate and in the same direction as those of the metallurgically more complex manganin alloy. In 1933, a platinum and a gold standard were made by winding wires of these metals on insulated brass tubes and enclosing each in a sealed metal container. When in use the container was immersed in an ice bath. Because of the high temperature coefficient of resistance of pure metals, a change of 0.00025 deg C will change the resistance by 1 ppm. This accuracy in temperature seems to be about at the limit to which the ice-point can be reproduced. Measurements at intervals of about a year, between 1933 and 1939, in which these pure metal standards were compared with the small Thomas-type primary group, showed for the gold coil an apparent decrease in its resistance of only 0.13 ppm per year, but the platinum coil showed an apparent increase of nearly 0.7 ppm per year. The standard deviation of either of these rates of drift is ± 0.2 ppm per year. When used in 1947 it was found that the insulation on both of these standards had deteriorated to such an extent that precise measurements could not be made. It is doubtful, therefore, whether much weight should be assigned to the results from the coils of pure metals.

Perhaps the best indication of the constancy of the ohm as maintained in Washington is found in the results of comparisons with the standards of other national laboratories and with the mercury columns set up occasionally by these other institutions. The situation is discussed in section III and summarized by figure 8.

It seems evident from the foregoing data that the apparent constancy of the unit of resistance as maintained between 1909 and 1932, while Rosa-type standards were used, was in considerable measure the result of good luck in the use of standards, some of which increased while others decreased in resistance. The tendency to increase was presumably the result of oxidation or corrosion of the resistance alloy, while the tendency to decrease was perhaps the result of a slow release of strains, or of more obscure metallurgical processes. Of course, the use of a considerable number of standards in the primary group decidedly increased the probability that the group should contain standards drifting in both directions, but even with as many as ten standards in the group the drift in the mean value might well have been much greater than it apparently was. The basis for these self-congratulatory remarks is found, of course, not in the data resulting from intercomparisons within the group but from the international intercomparisons shown in section III, 1, figure 8. Both the German and the British laboratories used a smaller number (four) of standard resistors and apparently were unfortunate in choosing coils that tended to increase in resistance, but their painstaking work with mercury columns enabled them to detect these drifts before they became significant in the industrial field and to make corresponding adjustments in their units. The various determinations of the ohm in absolute units made prior to 1925 are probably not accurate enough to be of much significance in insuring its maintenance but give no indication of any continuous drift. As indicated below, it is probable that from 1939 onward absolute measurements of higher precision may prove to be very valuable for this purpose as well as for the primary establishment of the unit.

The comparisons of the 1-ohm standard resistors have been made since 1918 by use of the high-precision bridge shown in figure 5 [36]. It is used as a Kelvin double bridge and the main ratio arms are of the Waidner-Wolff type [37]. The

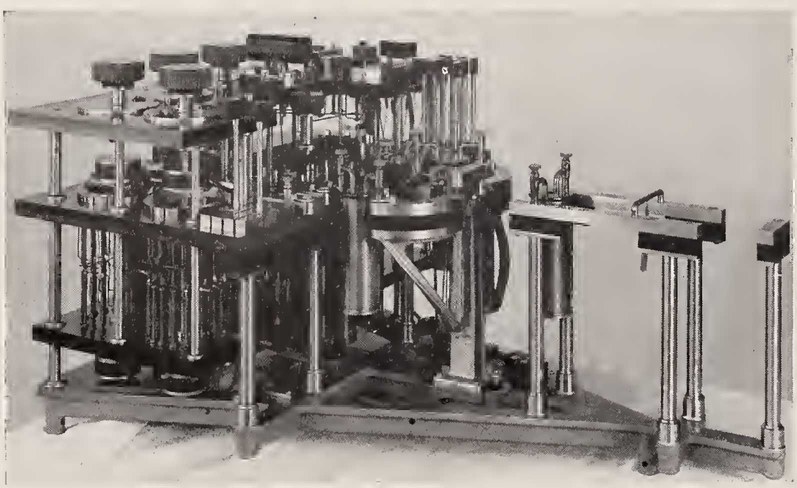

FIGURE 5. *High-precision bridge.*

In use, the whole structure is immersed in a temperature-controlled oil bath to a level above that of the intermediate insulating slab. All resistors and contacts are therefore at a uniform constant temperature. It may be connected as a Wheatstone or as a Kelvin bridge. The nominal ratio may be 1:1 or 10:1. The standards under test are connected through amalgamated contacts.

contacts are only in adjustable shunt circuits of relatively high resistance in parallel with the main resistors, which are connected permanently. The lowest dial corresponds to 1 ppm per step and the galvanometer is sufficiently sensitive to permit of extrapolation to the next significant figure.

3. Maintenance of the Volt at the National Bureau of Standards

The Chicago Electrical Congress of 1893 and the resulting law passed in 1894 had specified 1.434 volts at 15° C as the emf of the Clark cell. A number of Clark cells were made up prior to 1906 at this Bureau using specially purified materials. After correcting for temperature and subtracting 0.0003 volt to allow for the higher purity of the mercurous sulfate used, a value of 1.42110 volts was decided upon as the mean value at 25° C to be assigned to the new Clark cells. Some saturated Weston cadmium cells, made in May 1906, were then compared with the Clark cells, and as a result of the measurements, a mean value of 1.01890 volts at 25° C was derived as the mean of a group of 12 of the Weston cells. This group, with certain losses and replacements, served to carry the unit until the close of the meeting of the International Technical Committee in May 1910.

The experimental work of this committee with silver voltameters of various types fixed the International Ampere. Earlier measurements in England and Germany on mercury columns had served to fix the values of wire standard resistors in terms of the International Ohm. The combination of these units by the committee in its voltameter experiments, which involved the NBS reference cells, led to the conclusion that the volt, as then maintained at the NBS, was smaller by 852 microvolts than the "International Volt" as derived from the International Ohm and the International Ampere. Accordingly, effective January 1, 1911, new values, smaller by this amount, were assigned to all the cells, and the volt and the other electrical units derived from it were changed abruptly on that date by corresponding amounts. This change was announced in Bureau of Standards Circular C29 [4], which contained a brief history of the subject and a summary of the reasons for making the change.

As a byproduct of the work of the International Technical Committee, the Bureau came into possession of a group of 36 cells, which had been included in the large group used to assign a value to the Weston Normal Cell, and which included cells of British and German as well as American origin. Until January 1912, this group was used to maintain the unit of emf, and the mean of these 36 cells was assumed to remain at 1.018300 volts at 20° C. By that time it became evident that some of the cells had drifted rather badly. A smaller group of 19 cells, which had shown steady and nearly equal increases on the new basis, and four of which had been in the reference group in 1908, was therefore used instead to carry the unit forward from 1910 and continued to serve (with two eliminations) as the primary group until 1914. Several changes were then made, and a group of eighteen cells carried on until July 1919 when three were dropped and five added. These 20 cells carried on, with the loss of four, until April 1937 when nine cells of the 0.05-normal acid type, which had been made in December 1932, were added. These 25 cells were in use through 1947.

As an indication of the mutual consistency of the neutral, saturated cadmium cells, data taken between 1919 and 1933 on the primary reference group showed that 18 of these cells had changed relative to their mean by less than 15 μv (microvolts). Nine cells showed a net increase, while the other nine had decreased, the average net change during the 14 years, taken without regard to sign, being ± 5.0 μv. This corresponds to an average drift rate of ± 0.25 μv per year, the greatest mean drift rate being 1 μv per year.

Superposed on these net drifts the cells showed slight fluctuations in emf. Successive values for the same cell measured after the lapse of about a year differed on the average by ± 2 μv. The precision of each comparison as indicated by repeat measurements made a few hours or a few days apart was about ± 0.1 μv, so that these secular fluctuations must be attributed to random changes in the cells. None of the differences between the annual values exceeded 10 μv, and 83 percent of them were less than 4 μv.

In contrast to this behavior of "good" cells, certain cells after showing similar good behavior for many years suddenly begin to drop in emf at a rate of from 3 to 10 μv per year. Since 1919 four such cases have developed and after the "delinquency" of each cell was definitely established by the continuance of its drift, the cell was removed from the primary group. The unit was then "recaptured" by going back to a time before the abnormal drift began and computing forward again on the basis of the remaining cells only. This process resulted in introducing three abrupt increases of 4.6, 0.8, and 1.1, μv, respectively, in the volt on September 19, 1933, April 10, 1937, and September 7, 1944. The changes in the group between January 1912 and July 1919 resulted from shorter-period troubles, which involved three broken cells. These did not involve a shift in the unit.

Of the 16 neutral cells in the group in 1947, 13 had been in the primary group since 1914 and five since 1908. The nine acid cells had been in the group since 1937.

Theoretically, the procedure of maintaining a unit of measurement solely by the use of a large group of standards is subject to the fundamental limitation that a simultaneous progressive drift of all the standards cannot be detected by the intercomparisons and will result in an equally rapid drift of the unit. It is therefore important to seek external corroborative evidence of the constancy of the unit.

One such line of evidence derives from the construction of new groups of cells from freshly prepared batches of pure materials. One example of this is a batch of six cells constructed in 1925 the mean value of which was found to be greater in terms of the 1925 unit by only 12 μv than the mean of the large number of cells set up 15 years earlier by the International Technical Committee. Very similar evidence results from the comparisons shown below (see figure 9 section III, 2) between the British and American volts over a long time. At the British National Physical Laboratory fresh groups of cells are made up every few years and the older groups are discarded at intervals so that their unit has been carried forward by cells that range in age from 1 to 20 years averaging about 6 years. Since 1912 most of the American neutral cells ranged in age from 6 to 41 years, averaging over 20 years. Another difference arises because the British laboratory uses 0.1-normal acid cells, while until 1937 the American cells were all neutral. Yet since 1925 the difference between the two volts has oscillated only over a range of ± 7 μv from a mean difference of 24 μv, the British volt being the larger. The reason for the earlier drift of 18 μv between 1911 and 1925 (that is 1.3 μv/year) is not known.

Another line of evidence lies in the comparison of acid and neutral cells. The emf of a 0.05-normal acid cell is about 30 μv lower than that of a neutral cell, but the tendency for the mercurous sulfate to hydrolyze and for constituents of the glass container to be dissolved by the electrolyte are definitely less. On the other hand, acid cells sometimes develop objectionable gaseous films on the amalgam electrode. Because of these chemical differences, it seems reasonable to expect that if either type of cell showed a characteristic consistent drift in emf its rate would be somewhat different than that for cells of the other type. Over the 7 years from 1937 to 1944, the average of the nine acid cells (0.05 N), which had been made in 1932, increased relative to the 16 old neutral cells, which were at least 24 years old, at a rate of only 0.9 μv per year.

A better check on drift can be obtained by the use of the silver voltameter. Even yet there are no authoritative specifications that enable the voltameter to be used unambiguously as a means for reproducing the international ampere. How-

FIGURE 6. *Primary group of standard cells in oil bath.*

The stirred bath is thermostatically controlled at 28±0.01° C. Connections are made through mercury cups under the oil to the platinum leads sealed through the glass H-tubes.

ever, experiments repeated with a given type under given conditions after the lapse of a number of years are adequate to reproduce the same value of current to a high accuracy. In 1931 a series of measurements using the Smith form of voltameter were carried out at the Reichsanstalt by Vinal [52], Vigoureux [53], and Von Steinwehr [54]. These indicated that the volt as maintained at the National Bureau of Standards was the same in 1931 within 10 ppm as it had been when similar experiments with the Smith form of voltameter were made in 1912 at Washington. Hence the average drift could not have exceeded 0.6 ppm per year.

Figure 6 shows the oil bath that contains the primary group of cells. Its temperature is controlled automatically to 0.01° C. As a precaution against loss of the unit by fire or other catastrophe, two supplementary reference groups of 10 cells each are housed in other buildings. Although these groups are not held at a constant temperature, they have shown little tendency to drift as compared with the primary group.

The intercomparisons of the cells in the primary group are made by opposing the emf of the cell being measured to that of a selected reference cell and measuring the small difference in emf. Because the difference in emf is small, only a moderate percentage accuracy in its determination is required to give very high accuracy in the final result. Since 1933 the instrument used in this work at the NBS has been the Brooks Standard Cell Comparator [43] shown in figure 7. It comprises a specialized form of potentiometer in which the bulk of the emf to be measured is balanced against the IR drop in an adjustable precision resistor but the last two digits of the result are obtained by reading a milliammeter, which measures the current in a small additional resistor in series in the circuit and thus indicates the additional emf developed at its terminals. By an arrangement of slots in the covers of the dials, the instrument serves also as a computing device, one part of which is set to read the known emf of the chosen reference cell, while the other part, when a balance is obtained, indicates directly the emf of the unknown.

The greatest source of error in such measurements is the presence in the circuit of spurious emfs, such as those from thermoelectric action. The principal features in the design and operation of the comparator are devoted to minimizing such emfs. Each division on the milliammeter corresponds to 1 μv, and the galvanometer is sufficiently sensitive to make readings to 0.1 division significant.

4. Maintenance of Units at the International Bureau of Weights and Measures

Additional information on the accuracy with which electrical units can be maintained at a properly equipped laboratory is afforded by the performance of the reference groups of resistors and standard cells kept at the International Bureau. The report by M. Romanowski [58] lists the results of intercomparisons between 1939 and 1946.

Data are given on the four resistors that form the primary group, GO_3, and on five other standard resistors. Romanowski in his report has made an extrapolation on the assumption that the the resistances of these standards were increasing in value by 0.95 ppm per year. As will be shown below, such a drift was probably not real but was a result of the assumption that the mean of the ohms of the six national laboratories had not drifted between 1936 and 1939. If his data are reduced on the alternative assumption that the mean value of GO_3 remained constant over the

FIGURE 7. *Brooks standard-cell comparator.*

The cover and the left-hand milliammeter are adjusted to read the known emf of the reference cell. The main galvanometer (not shown) is balanced by turning the central handle and adjusting the current in the right-hand milliammeter. When a balance is reached, the emf of the unknown cell is read from the digits in the right-hand slot and the right-hand milliammeter.

7-year period, all the standards except the one open-type coil (designated R 2836) show a very excellent performance. The mean difference taken without regard to sign between successive annual values of a given standard relative to GO_3 is only ± 0.4 ppm. For the one open coil it is ± 5.1 ppm, and the net drift of this one coil in the 7 years is $+35.6$ ppm. None of the other coils drifted relative to the mean more than 1.3 ppm in the 7 years. Of the eight good coils three had been made at Teddington, one at Tokyo, one at Philadelphia, and three at Washington. The British coils were sealed in oil, and the others were sealed in gas.

The International Bureau is custodian of a primary group of 47 standard cells made up at various times in six different laboratories. Of this group eight are neutral cells, six are 0.05-normal acid cells, and 33 are 0.1-N acid cells. They are divided into nine subgroups according to their origin and time of manufacture.

The available data on these cells are less uniformly distributed in time than those on the resistors, the five sets of observations being spaced at intervals of 3, 2, 1, and 1 years. If this fact is disregarded, a fair index of the constancy of the cells can still be obtained by averaging, without regard to sign, the differences between successive readings on the same cell. Another measure of quality is the net drift of a cell in 7 years relative to the mean of the whole group. The following table 1 contains the average value of these two indices for the cells of each subgroup.

It will be seen that the constancy of these coils and cells is about the same as that of the primary groups of the NBS, on which more detailed data are given in the two preceding sections. In the case of most of the standards, the performance is amply adequate to meet the current needs in the field of precise measurements and to serve as a reference basis for international comparisons. However, it must be expected that even the small residual drift of such groups will ultimately, over a period of years, accumulate to an excessive error unless some check such as the absolute measurements discussed later is available.

TABLE 1. *Performance of standard cells at International Bureau 1939 to 1946*

Subgroup	Origin	Average difference of successive values (average interval 1.8 years)	Average net drift of individual cells (in 7 years)
		μv	μv
R_1	PTR (Germany)	± 15.2	$+9.0$
E	ETL (Japan)	± 6.5	[a] $+0.1$
M_1	IMS (USSR)	± 5.1	-8.1
C_2	LCE (France)	± 2.7	$+5.4$
S	NBS (USA) neutral.	± 2.1	-3.3
I_B	BIPM (Sevres)	± 1.7	-0.6
I_A	do	± 1.4	$+0.2$
I_1	do	± 1.2	-0.2
S_2	NBS (USA) acid	± 0.8	$+0.8$

[a] The small net drift listed for subgroup E is the difference between an increase of 36.6 μv for one cell and a nearly equal combined decrease in the other four cells of the subgroup.

III. International Comparisons 1911 to 1948

1. Comparisons of the Ohm

Following the meeting in Washington, April 4 to May 25, 1910, of the International Technical Committee, the members of that committee carried back to their respective national laboratories standard resistors to which values had been assigned on the basis of the mean between the British and the German units. This mean value was smaller by 7 ppm than the unit that had been used previously in the United States. This difference was so small that it was felt sufficient to continue the use of the older unit in certifying the values of standard resistors in the United States. This older unit is referred to as the "international ohm (certified NBS)." On the other hand, for purposes of international comparison, the value 7 ppm smaller than the older unit has been used consistently and is commonly referred to as the "Washington unit."

The term "Washington unit" has been used by various foreign laboratories to designate the ohm as maintained in their respective laboratories on the basis of manganin wire coils, the values of which were initially assigned in 1910 following the conclusion of the work of the International Technical Committee. To distinguish between this unit and the units that in later years were determined in certain other national laboratories as a result of later experimental realizations of the mercury ohm, these latter units have been commonly designated as "international ohms" of the respective countries.

In the years immediately following 1910, comparisons of the units used in different countries were made only sporadically. When an American scientist crossed the Atlantic for some other purpose, he was frequently persuaded to carry standard resistors and standard cells from one national laboratory to another, but it was not until the International Bureau of Weights and Measures was authorized to enter the field of electrical measurements that systematic international comparisons were begun. In a comparison between two laboratories, coils are first carefully measured in terms of the unit of their country of origin. They are then taken to the second laboratory where they are measured in terms of the unit of that laboratory and are watched (preferably for some months) to be sure that no changes have been stimulated by the transportation. They are then carried back to the first laboratory and again measured. If any differences are obtained between the first and last measurements it is assumed that the change is a result of a gradual drift, and an intermediate value is assigned by linear interpolation to represent the value in terms of the units of the first laboratory at the time when the measurements in the second laboratory were made. The difference between this value and the value measured in the second laboratory then constitutes a measure of the difference in the units of the two countries involved. The amount of the drift is, of course, an indication of the reliability of the intercomparison and has ranged from changes of less than 1 ppm, in some instances, to values as high as 80 ppm in cases where the coils have been carried to many intermediate laboratories and ultimately half around the world.

Although, according to the decision of the London Conference in 1908, the mercury column was by definition the ultimate standard of resistance, in actual practice relatively little use has been made of it. At the National Bureau of Standards mercury ohm tubes were set up and careful measurements made in 1911 and 1912 [13]. The results were found to agree with the Washington unit within the experimental error estimated for the work with the mercury columns, and therefore no adjustment was made in the American unit.

At the National Physical Laboratory, Smith in 1912 [14] and Hartshorn [15] in 1924 made careful determinations with mercury columns and found their Washington unit to be greater than that derived from the mercury column by 16 ppm and by 41 ppm, respectively, on the two occasions. In view of this, in the international comparisons of 1931, the National Physical Laboratory decided to abandon the Washington unit which it had used until then and to use a unit smaller by 30 ppm.

Between 1923 and 1925 Von Steinwehr and Schultze [16] at the Reichanstalt carried out extensive determinations with mercury columns. As a result, in the comparisons with the Japanese standards brought to them in 1927 by Professor Jimbo, and in the comparisons with British and American standards in 1931 and thereafter, they used a new unit smaller by 33 ppm than the Washington unit that they had used previously. The results of the work with mercury columns in the three laboratories are indicated by the isolated points marked "Hg" in figure 8.

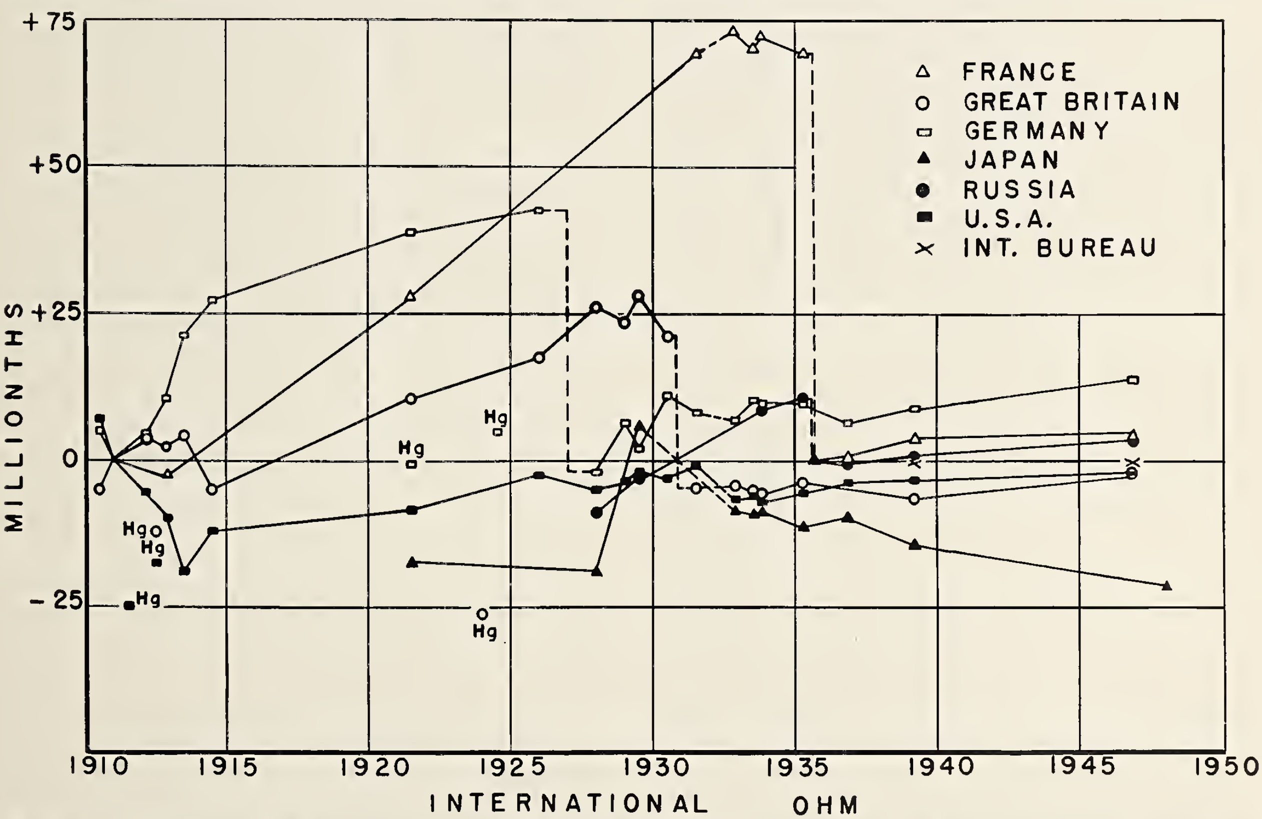

FIGURE 8. *Differences from the adjusted mean of the values of the International Ohm, as maintained by various national laboratories, 1911 to 1948.*

Points marked "Hg" indicate the results of measurements on mercury columns.

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Between 1932 and 1939 frequent and systematic intercomparisons were made by the staff of the International Bureau of Weights and Measures to determine the relative values of the units maintained in a number of countries. Standards from France, Germany, Great Britain, Japan, Russia, and the United States of America were used in almost all of these intercomparisons.

Following World War II comparisons at the International Bureau were resumed. Although the standards from the various countries could not be assembled in Paris simultaneously, by the middle of 1948 data had been obtained on the units of all six countries.

The results of these intercomparisons are shown in figure 8. These data are, for the most part, taken from the proceedings of the International Committee on Weights and Measures [51]. In this figure, for various epochs, the relative values of the ohm as recognized by the various countries have been plotted to a very open scale. Many of the apparent small changes in value of the national units may well be the result of errors introduced by the hazards of transportation. It is probable that the actual uncertainty of the electrical measurements by which any two standard resistors are intercompared is usually less than 1 ppm, and therefore not appreciable in the figure.

It should be kept in mind that, in the very nature of the case, the location of the point indicating the value of the unit of a given country at a later time can be related to the position of the corresponding point at an earlier date only by making some arbitrary assumption as to the constancy of some unit between the two dates. Therefore, too much significance should not be given to the slope of the lines, which, in the diagram, have been arbitrarily drawn to connect successive points. In the plotting of figure 8, for convenience, three different conventional procedures have been used to relate the data at successive epochs, as follows.

From 1910 to 1932 only data derived from measurements at the NPL, PTR, and NBS were used to carry forward a common base from epoch to epoch. This convention was chosen because data from other laboratories were very fragmentary. The mean of the three values of the Washington unit as maintained during this period at the three laboratories has been assumed to have drifted upwards at the rate of 1.1×10^{-6} per year. The justification for this somewhat arbitrary assumption is as follows. In 1931 the NPL, as a result of earlier measurements on mercury columns, decided that its Washington unit had increased by 30 ppm in the course of the 21 years since the unit was established at Washington. This corresponds to a drift of 1.4×10^{-6} per year. Similarly, the PTR, in 1927, decided that its Washington unit had drifted upwards by 33 ppm in the preceding 17 years, or at a rate of 1.9×10^{-6} per year. The NBS has seen no reason to change its unit, and it is assumed that its rate of drift was 0. The mean of these three drift rates is the 1.1×10^{-6} assumed above.

Between 1932 and 1939 the work of MM. Pérard and Romanowski at the International Bureau provides a much better basis to give continuity between successive intercomparisons. In 1935 the Advisory Committee on Electricity recommended that there be taken as the mean international ohm the mean obtained that year of the units of Germany, Great Britain, Japan, Russia, and the United States of America. The French unit, which had been used in this and in some earlier intercomparisons, was recognized as being out of line with the others. Therefore it was not included, and the Laboratoire Central d'Electricité (LCE) decided to adjust its unit by decreasing it by 69.5 ppm to coincide with the new mean. The Russian laboratory also readjusted its unit by reducing it by 10.6 ppm. This latter readjustment, however, was made after the international mean value for 1935 had been fixed. In plotting figure 8, this 1935 mean value has been used as a reference corresponding to 0 on the scale of ordinates. In other words, it has been assumed to be the same as the mean value chosen in 1910 as a result of the intercomparisons at Washington. In projecting the 1935 mean value forward or backward in time it has been assumed that the mean of the units of all six countries remained unchanged. In plotting the points for December 1932 and July 1933, when data on the Russian unit were not available, it was assumed that the ratio of the Russian unit to the mean of the other five nations was the same as in November 1933.

It will be noted that this procedure of equating the mean international ohm of 1935 with the mean Washington unit of 1910, when combined with the rate of drift postulated during the earlier years, gives a very satisfactory correlation between the 1931 data on the older basis and the 1932 data on the newer basis. This correlation would seem to justify the apparently arbitrary assumption of drift used in plotting the earlier data.

When the international comparisons of the ohm were resumed, following World War II, a question arose as to the proper basis for carrying forward the mean international ohm from 1933 to 1947. The problem was unfortunately complicated by a strange coincidence that illustrates the importance of having some absolute standard as a fundamental basis for preserving units of measurement. The staff of the International Bureau had originally assumed that the Mean International Ohm was the same in 1939 as it had been in 1936. On this assumption it appeared that the resistances of the coils in their reference group GO_3 were increasing at the rate of 0.95 ppm per year. An extrapolation of this rate over the war period would predict an accumulated increase of 6.6 ppm by 1946. The comparisons in 1946 between GO_3 and some American standards showed only a very slight increase (0.9 ppm) in the American unit relative to GO_3. If this were combined with the predicted drift in GO_3 it would imply an increase of $6.6+0.9=7.5$ ppm in the American unit. Strangely enough, comparisons in 1946 between British and American standards indicated that the provisional value of the British ohm was then 19.3 ppm smaller than the American ohm, although in 1939 it had been only 3.3 ppm smaller. A splitting of the difference in this shift would imply an increase of 8 ppm in the American unit and an equal decrease in the British. In spite of the apparent agreement between these two figures 7.5 and 8 ppm, such an increase in the American ohm seemed improbable in view of the high quality of the standards in the American group. The National Physical Laboratory therefore made further comparisons of its reference group with other British standards of high quality and found a number of divergencies which led them to "recapture" their unit by using as a basis for its maintenance other coils of probably better stability. On this final basis the British ohm in 1946 was larger than the provisional value by 18.2 ppm. If as an alternative basis the international reference group GO_3 is assumed to have remained constant from 1939 to 1946, it follows that the British and the American ohm have increased by only 4.8 and 0.9 ppm, respectively [57]. This latter basis has therefore been accepted by all concerned and was used in plotting the 1947 value in figure 8.

2. Comparisons of the Volt

In general the procedures used in the maintenance and in the intercomparisons of the volt at the various national laboratories have been similar to those used for the ohm. For many years the comparisons were rather sporadic, and they have been interrupted by the two World Wars. With the entry of the International Bureau of Weights and Measures into the field of electrical measurements, the intercomparisons became much more frequent and systematic. The records of many of the earlier intercomparisons, as well as of the later ones, will be found in the Procès Verbaux of the International Committee for Weights & Measures and in their various Annexes.

The standard cell is a much more delicate device than a standard resistor, and therefore more susceptible to changes during shipment. Consequently, in general, groups of from 4 to 10 such cells have been used for important intercomparisons. For these precise comparisons, as well as for maintaining the value of the unit in the national laboratories, cells of the "saturated" type are used. This practice introduces some difficult problems of temperature control. The temperature coefficient of such cells is about 40 ppm per deg C, which is several times as large as that of a manganin resistor. Also, it is the net difference of the separate temperature coefficients of the potentials developed at each of the electrodes. Each of these half-cells has a temperature coefficient of over 300 ppm per deg C but the two are of opposite sign. Consequently, temperature gradients in the enclosing oil bath may introduce serious error. Most national laboratories maintain their standard cells at about 20° C, while some foreign laboratories make measurements at temperatures as low as 16° C, but the climate at Washington requires that the bath be held at 28° C if condensation of moisture is to be avoided. The situation is further complicated because the temperature coefficient of a standard cell varies somewhat with its age and perhaps with its acidity.

As one indication of the probable precision of such international comparisons, it may be noted that in 1929 six comparisons were reported, each based on a different group of cells. The standard deviation from the mean value of the six observed differences between the units at the NPL and the NBS was 4 ppm. Among these comparisons were those involving Russian and Japanese cells, which had been transported long distances, and which had been handled many times in different laboratories. In seven different years, comparisons between the same two laboratories were made by using more than one group of cells. A second measure of the accuracy of these comparisons is obtained by noting for each of these seven years the highest and the lowest value of the observed ratio of the units of the two countries. The difference between each pair of extreme values indicates the uncertainty for that year. The average difference for the seven years was 9 ppm. In contrast with such differences that appear when transportation of cells is involved are the results of work done in 1931 [53] at the Reichsanstalt, when a group of eight British cells was compared with a group of 10 American cells on eight different days. The observations were scattered over an interval of 5 weeks, but the cells were not moved between measurements. On only two of the eight days did the difference in the units reported by the two groups differ by 1 ppm from the mean value of 30 ppm; on one day the difference was 29, and on another, it was 32.

The results of the various comparisons of the volt through the period from 1911 to 1948 are shown in figure 9. In this figure, the plotted points show at a given epoch the relative values of the volt as maintained by the various national laboratories. The correlations between the values at one epoch, and those at another, have been made on the basis of the following somewhat arbitrary assumptions. From 1911 to 1932, inclusive, it has been assumed that the mean value of the units at the NPL and NBS was constant, and this mean is made the axis of abscissas. The

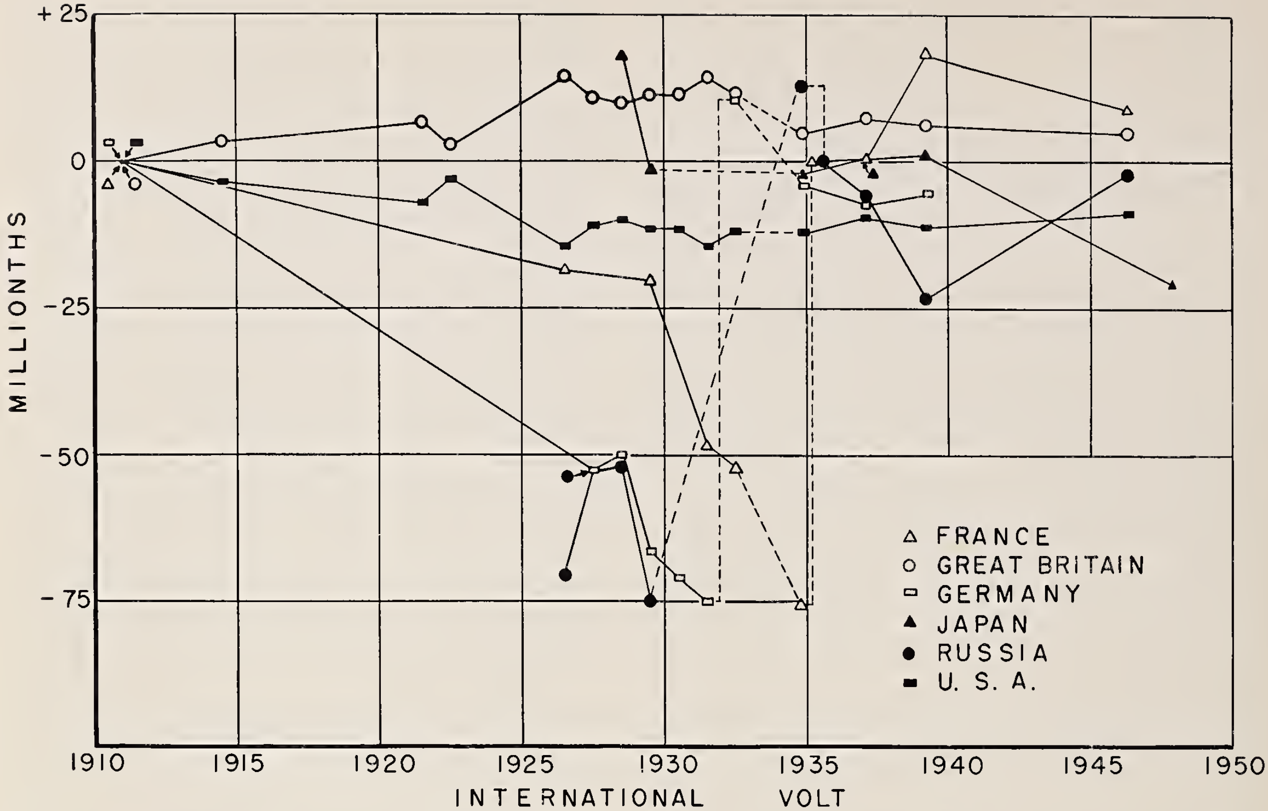

Figure 9. *Differences from the mean of the values of the International Volt, as maintained by various national laboratories, 1911 to 1948.*

reason that data from the PTR were not included is, first, that during the early years relatively few comparisons were made with the German laboratory, and, second, that in 1931, the PTR recognized that its standard had drifted by 82 ppm. It would be difficult to decide when the major part of this drift occurred and to make a reasonable correction for it in the graph. After 1934, the data in figure 9 have been plotted on the assumption that the "Mean International Volt", V_m, as defined in 1935, by the Consultative Committee on Electricity [56], has remained constant. During World War II, this is equivalent to assuming that the large group of standard cells maintained at the International Bureau and originating in various laboratories has also remained constant in emf.

In 1931 it became evident that there was an increasing discrepancy between the unit as maintained at the PTR, and that at the British and American laboratories. Consequently, at the invitation of the Reichsanstalt, arrangements were made to have an international committee carry out experiments with the silver voltameter, and, thus, to reestablish the international volt. P. Vigoureux of the NPL and G. W. Vinal of the NBS took to Berlin standard cells and standard resistors, the values of which had been carefully determined at their respective laboratories. In Berlin, these standards were compared with those of the PTR and an extensive series of silver deposits were made using several types of voltameters. The results have been reported by all three laboratories [52, 53, 54.] Following this work the PTR increased its unit by 82 ppm.

The large change in the Russian unit between 1929 and 1934 was presumably the result of extensive work with the silver voltameter reported by Kolossov [22].

Comparisons at the International Bureau began in 1932 [55] with measurements on standard cells from four countries, and in December 1934 data were obtained for cells from all six national laboratories. The LCE, finding its unit to be out of line with the others, increased its volt by 76 ppm in 1935. The Consultative Committee on Electricity suggested [56], in view of the very small differences between the units of the other five laboratories and the mean of the units, that each should, if possible, adopt this mean value as its unit and thus obtain an immediate international unification. However, only the Russian laboratory followed this suggestion and reduced its volt by 13 ppm. In the intercomparisons of 1937 and

1939, the International Bureau has carried forward the mean value of V_m as defined prior to the change in the Russian unit by assuming the mean of the six national units to be the same (that is, $1-2.1\times10^{-6}$) as it was in 1935, after the Russian adjustment.

Between July 1945 and May 1948, standard cells were received at the International Bureau from five of the six national laboratories (The Reichsanstalt did not submit any). The results are plotted in figure 9 on the basis that the mean emf of the reference group GV_2 of 47 cells at the International Bureau has remained constant.

IV. Developments 1911 to 1948

1. Enlargement of Scope of International Committee on Weights and Measures

The London Conference of 1908 envisaged, as shown by its schedule D (appendix 2), the ultimate establishment, by the governments interested, of a permanent International Commission for Electrical Standards. Pending such action, its president, Lord Rayleigh, appointed an interim scientific committee of 15 members. The only action of this committee seems to have been to select the delegates who constituted the special International Technical Committee, which carried on the experimental work in Washington in 1910, and to officially promulgate its results. The work of the technical committee was so satisfactory that during the next few years little need was felt for further improvement in the situation. In 1914 World War I started and rendered international cooperative action, in other than military matters, quite impractical.

Following the war, there was a wave of interest in new international cooperative organizations, and older organizations began to renew their activities. One of the oldest international scientific organizations is that set up in 1875 by the treaty commonly designated The Convention of the Meter. This provided for the establishment of a permanent International Bureau of Weights and Measures, which is located on a plot of ground set aside as international territory in the Parc de St. Cloud at Sevres, near Paris. The functions of that Bureau included the custody and preservation of the metric standards of length and mass and comparison of the several national standards with the international prototypes. The work of the Bureau is supervised by an International Committee of 18 scientists, appointed by reason of their individual competence in the field of measurements, but with the proviso that only one member shall be appointed from any one nation. This Committee normally meets at the Bureau every 2 years to review the work of the Bureau and lay out its future program. At intervals, normally of 6 years, a General Conference on Weights and Measures, to which all nations signatory to the Convention of the Meter may send delegates, meets to review the work of the Committee and of the Bureau and to give official authority to their actions. The Conference is a diplomatic rather than a scientific body, and many of the delegates come from the embassies of the various countries.

At the 1920 meeting of the International Committee for Weights and Measures, after the close of the war, the American and Belgian members suggested that the scope of the International Bureau of Weights and Measures might well be enlarged to include the electrical units and the determination of important physical constants.

The proposition was formally presented at the Sixth General Conference on Weights and Measures (1921) [6]. There was evidently a very real advantage to be gained in keeping under the control of a single international body as many fields of exact measurement as possible, because, thereby, duplications of effort and conflicts of authority would be minimized. On the other hand, the large amounts of expensive equipment and specially trained personnel required to make real advances in the science of precise electrical measurement seemed to be beyond the very meager financial resources that the various signatory nations had hitherto been willing to contribute to the International Bureau. The British delegates in particular opposed any major enlargement of the laboratory facilities of the Bureau such as would be needed for an independent primary establishment of the units and pointed out that such a procedure would duplicate services already available in the national laboratories. However, all felt that the International Committee could perform a very valuable function by coordinating the work of the national laboratories, comparing the units established by them, and giving official status to properly weighted mean values.

The Sixth Conference finally voted unanimously to amend the Convention of the Meter (Appendix 3) so as to give to the International Committee and Bureau authority for the "establishment and conservation of the standards for the electrical units . . .". This action of the General Conference was duly ratified by the United States Senate in 1923.

With the assumption of its new duties it seemed to the International Committee that it should secure (1) the cooperation of experts in the field of electrical measurements and (2) a closer and more official connection with the national standardizing laboratories where the primary electrical measurements were being developed. To achieve these objects it recommended the formation of an Advisory Committee on Electricity that should advise the International Committee on questions relating to electrical standards and systems of measurement. This recommendation was approved by the Seventh General Conference held in 1927. The Advisory Committee on Electricity is limited to 10 members, including a representative appointed by each of the national laboratories designated by the International Committee, and also specialists named by the Committee. The chairman of the Advisory Committee is elected by the International Committee from among the membership of the latter.

The national laboratories designated were the National Physical Laboratory of Great Britain, the Laboratoire Central d'électricité at Paris, the Physikalisch-Technische Reichsanstalt of Germany, the Central Chamber of Weights and Measures of the USSR, the Electrotechnical Laboratory of the Department of Communications of Japan, and the National Bureau of Standards of the United States. Two individual specialists, Prof. L. Lombardi, Director of the Electrotechnical Laboratory of the Royal School for Engineers, Rome, and M. Ch.-Ed. Guillaume, Director of the International Bureau, were appointed in 1928.

At its meeting in 1929, the International Committee asked the Advisory Committee to consider also problems related to photometric measurements and standards, and specialists in photometry were invited to attend the meetings. At this time the committee was often referred to as the "Advisory Committee on Electricity and Photometry." However, in view of the differences between the two fields of work, a separate Advisory Committee on Photometry organized along parallel lines was authorized by the International Committee at its 1935 meeting.

The increase in the scope of work of the International Bureau required increased laboratory space, and in November 1928 the International Education Board contributed 900,000 francs and the French government released an additional small strip of land that made it possible to add sufficient laboratory space to house the electrical apparatus. Another assistant was added to the staff in 1929 to carry the additional work.

2. Trend Toward Absolute Units

In the decades following the London Conference of 1908, the developments of science and of the electrical art materially changed the situation that had led to the establishment of the system of international units. The genius of Lord Rayleigh, who served as President of the Conference, may have enabled him to foresee these trends, for even when he was in the act of establishing the international system by formally putting to a vote the resolution on the mercury ohm, he could not refrain from saying, "Before putting the resolution, I should like to say a word or two. I have no doubt this proposition will commend itself to a large majority of the Conference, but in my own mind I feel some doubt as to whether the introduction of the mercury column is not what we call a fifth wheel to the coach . . . to define it (the ohm) as the resistance of a column of mercury seems to me—I will not say illogical, but hardly in accord with the precision that absolute measurements made now obtain . . . I only wish to liberate my conscience by these few remarks . . . I will put the resolution to the Conference, that The International Ohm shall be defined as the resistance of a specified column of mercury. . . ."

A number of factors cooperated in the ensuing years to demonstrate the wisdom of Lord Rayleigh. One of these was the fact that the need for standards that were conveniently reproducible vanished with the growth of testing service by the national laboratories. A standard cell or resistor could be shipped from San Francisco to Washington, tested, and returned with a tiny fraction of the time and expense involved in setting up a voltameter or mercury column experiment. Laboratories in the smaller countries could obtain similar service from the large national laboratories or, more recently, from the International Bureau.

A second factor in the diminishing utility of the international units was the discovery of isotopes. Mercury has seven isotopes, of which five occur in considerable amounts, and which have masses covering a range of 2 percent. Silver has two isotopes of almost equal abundance, which differ in mass by about 2 percent. The volume resistivity of mercury is presumably nearly the same for all isotopes, but the Chicago Congress, in an endeavor to make the definition more precise, changed the earlier specification for a column 1 sq mm in cross section by specifying a column having a mass of 14.4521 g. With this definition a change in isotopic composition would be expected to make a change in the resistance of the column proportional to the change in density. This difficulty is probably more academic than real because specimens of mercury from widely different sources have been found to have very closely the same density.

The difficulty from the silver isotopes is less academic, because the process of electrolysis may well introduce an appreciable change in isotopic composition. In fact, electrolysis is the most common process for concentrating the heavy isotope of hydrogen. If, in the deposit, the ratio of the light to the heavy isotope content is greater by 1 percent than it is in the solution, the deposit will be 100 ppm lighter than if no separation had occurred. Moreover the extensive work from 1911 to 1914 with the silver voltameter revealed still other complications such as effects from colloidal silver, spurious inclusions in the deposit, etc., which could cause appreciable errors in work of the highest accuracy.

At first sight it might appear that the conventional choice of a fixed number, namely 0.00111800 grams of deposit per international coulomb, to define the unit of electric charge would have a theoretical advantage by eliminating one experimental step in the determination of the Faraday. This physical constant would then be given by $F=A/0.00111800$, where A is the atomic weight of the silver deposited. For the standard atomic weight 107.880, F is 96,494 international coulombs per gram equivalent, and the only experimental determination involved is that of the atomic weight. However, in the numerous theoretical uses of the Faraday, as in the determination of Avogadro's number, it is combined with other physical constants at least some of which involve the electromagnetic forces on elementary charges, which in turn are expressible primarily in absolute units. The "international Faraday" is therefore useful only when the ratio of the international to the absolute coulomb is also known. Moreover, the complications from inclusions, colloidal silver and possible isotopic separation constitute serious sources of error when the silver voltameter is used to determine the Faraday. On the other hand, they drop out when a single particular type of voltameter operating under closely controlled conditions is used to reproduce the same average current in a repeat experiment even after the lapse of many years.

The third and perhaps most important factor was the tremendous increase in the scope of application of electrical methods of measurement in many fields of science and engineering and the simultaneous increase in the accuracy required. Electrical methods are used to measure temperatures, pressures, strains, acidity, concentrations, and a myriad of other physical and chemical quantities. In some of these, particularly in the measurement of energy and in the calibration of calorimeters, the desired precision has long been so high that corrections had to be be applied for the difference between the international and the absolute units. Electrical effects are fundamental in the experiments by which a large number of basic physical constants such as the Faraday, electronic charge, mechanical equivalent of heat, Bohr magneton, and Zeeman displacement constant are measured. It soon became evident that the bother and confusion already experienced in the field of thermochemistry would soon become serious in many other fields if the independently fined international units continued in use.

3. Official Actions Leading to the Adoption of the Absolute Units

The possibility of shifting back to the absolute system of units had doubless been in the minds of many scientists for a long time, and indications of it are evident in some of the discussions in 1921 regarding the extension of the authority of the International Committee. Perhaps the first official action in this direction was a set of resolutions formulated by the Committee on Instruments and Measurements of the American Institute of Electrical Engineers and formally adopted June 27, 1928, by its Board of Directors. This (see appendix 4) pointed out the unsatisfactory aspects of the situation then existing and urged the national laboratories to undertake the additional researches necessary to make it feasible to legalize the absolute units.

At the same time Dr. G. K. Burgess, then Director of the National Bureau of Standards and its representative on the international Advisory Committee, called together an American Advisory Committee on Electrical Units and Standards. The membership included representatives of the National Academy of Sciences, American Institute of Electrical Engineers, the American Physical Society, the National Electric Light Association, the Association of Edison Illuminating Companies, the National Electrical Manufacturers Association, and the American Telephone and Telegraph Company. In 1930, two members, representing the Illuminating Engineers Society and the Optical Society of America, were added when photometric questions were under consideration. This advisory committee met first in Washington on June 16, 1928, and discussed the functions that it was desirable to have the International Bureau undertake in connection with the electrical units, and the consensus was as follows:

(1) A central secretariat to arrange for systematic exchange of standards and compilation of results of intercomparisons thus made among the national laboratories.

(2) A laboratory to which concrete standards representing the results obtained in the different countries may be brought for precise comparisons.

(3) A repository for international reference and working standards with the necessary equipment so that other standards may be compared with these standards on request.

The committee then voted the following resolution:

> That in the opinion of this Committee, in view of improvements which are being made in absolute measurements, electrical standards should in future be based upon the absolute system of units.

At almost the same time Dr. D. W. Dye, who represented the National Physical Laboratory on the international Advisory Committee, laid the same questions before the Electrical Units and Standards Committee of the NPL.[3] The opinions of this committee as to the desirable functions of the International Bureau were very closely concordant with those of the American Advisory Committee. They also regarded it "as of the utmost importance that the use of the absolute units should be introduced at the earliest possible moment. * * * It is felt that this change can be made now (1928), but that the difficulties involved will increase with each year of delay."

The German position at this time, as set forth in a memorandum by Dr. von Steinwehr, was much less favorable to the proposed change. While admitting the theoretical advantages of the absolute system, they emphasized the inconveniences that they feared would develop in practice during the transition. They proposed that much additional work should be carried out first to determine the ratios of the international to the absolute units. After these ratios were definitely established, they would then urge that the definitions in absolute terms be used as the basis for defining the units, but that the established ratios should then be applied so as to keep the magnitudes of the units actually used at the same values as the current international ones.

On the other hand, a similar committee of Italian scientists under the chairmanship of Prof. L. Lombardi favored the ultimate transition to absolute units, although they felt that considerable further experimental work in absolute measurements should be done first. Professor D. Konovalov of the Central Chamber of Weights and Measures, USSR, sent in proposals that had been approved by a group representing several central scientific and technical institutions in Russia. These proposals were closely parallel to those of the American and British members. Similar responses came from analogous committees of the Société Française des Electriciens and from the Japanese Electrotechnical Laboratory.

In view of this preponderance of opinion, the Advisory Committee, on June 8, 1929, adopted a resolution translated as follows:

> In view of the great importance of unifying the systems of electrical measurement upon a basis free from arbitrary characteristics, the absolute system, derived from the centimeter-gram-second system, should replace the international system of units for all measurements in science and industry.

This was officially approved by the International Committee at its 1929 meeting and widely publicized.

As might have been expected, a few individuals disagreed with the proposed change in units, and felt that the change in the ohm would involve excessive inconveniences in laboratory work. G. A. Campbell, in a paper entitled, "A definitive system of units," which he presented at a meeting in Chicago on June 24, 1933, of the Committee for Symbols, Units, and Nomenclature (SUN Committee) of the International Union of Pure and Applied Physics, suggested that the ohm be fixed by a material standard resistor and that all other electrical units be derived from this and from the meter, the kilogram, and the second. On this basis, the "permeability of space," μ_v, would become a derived quantity to be determined by experiment and would have a value of about 0.9995×10^{-7} henry per meter. According to this plan the prototype ohm was to be preserved at the International Bureau in the same manner as the meter and the kilogram. It would follow that if this standard resistor should drift in time as did those whose values are shown in figure 8, the experimentally determined value of μ_v would also be found experimentally to drift and to have different values at different epochs. This proposal was formally rejected by the SUN Committee.

A similar suggestion was proposed by Prof.-Ing G. Giorgi and endorsed by F. Emde and by A. Sommerfeld. A great deal of confusion has arisen because the name Giorgi thus became attached to a second system of units, which was, in effect, almost a special case of an earlier system of units that he had proposed. As early as 1901 Giorgi [2] had made the constructive suggestion that the incomplete "practical absolute" system of eight electrical units (coulomb, ampere, volt, ohm, henry, farad, joule, watt) could be extended into a complete system that would include mechanical and magnetic units as well. By the artifice of assigning to μ_v the value 10^{-7} in place of the value 1, which is chosen in the centimeter-gram-second electromagnetic system, Giorgi found that the meter, the kilogram, and the second became automatically the mechanical units in his new complete system, and it is therefore usually called the "MKS System". The unit of force in this system has a magnitude of 10^5 dynes and the name "newton" has been proposed for it. This valuable suggestion has met with growing but rather belated approval.

In 1935 the International Electrotechnical Commission meeting at Scheveningen gave its formal approval to this MKS system, recommended its general use for engineering purposes, and suggested that it be called the "MKS-Giorgi" system. In engineering uses, the distinction between the international units and the absolute units is negligible and was probably not given any consideration by the IEC. Theoretically, if the absolute units are used everything will be inherently consistent. On the other hand, with the suggestion of Campbell or the later suggestion of Giorgi, which was not approved by the IEC, the joule and watt would have retained their absolute values, the ohm would by definition have kept its inter-

[3] The members of this Committee were Sir Richard Glazebrook, Chairman, Sir William Bragg, Dr. D. W. Dye, Dr. Alexander Russell, Sir Arthur Schuster, Dr. F. E. Smith, and Sir Joseph Petavel.

national value, and the ampere and the volt would have had neither their absolute nor their international values, but would have been respectively less and greater than their absolute values by the square root of the factor by which the international ohm is greater than the absolute ohm. Later, at its meeting in Torquay in 1938, the IEC explicitly showed its preference for the absolute system by recommending ". . . as the connecting link between the electrical and mechanical units the permeability of free space with the value $\mu_v=10^{-7}$ in the unrationalized system or $\mu_v=4\pi.10^{-7}$ in the rationalized system."

The alternative suggestions of Campbell and of Giorgi were duly considered by the International Committee, but at its meeting in 1935 the decision to shift to the absolute units was reaffirmed.

It should be emphasized that the action of the International Committee for Weights and Measures in authorizing the change from the international to the absolute electrical units has no bearing whatever on the question also now under discussion as to the relative merits of the MKS and cgs systems. The absolute ohm, ampere, and volt may be regarded equally well either (1) as units of the absolute MKS system (either rationalized or unrationalized), or (2) as convenient decimal multiples of the corresponding units of the cgs system. Moreover, the action of the IEC in specifically assigning a value to μ_r as the link between electrical and mechanical units should not be interpreted as giving any particular fundamental significance to permeability. The IEC Committee on Electric and Magnetic Magnitudes and Units (EMMU) explicitly stated "The Committee recognizes that any one of the following practical units, ohm, ampere, volt, henry, farad, coulomb, weber already in use may equally serve as the fourth fundamental unit, because it is possible to derive each unit and its dimensions from any four others mutually independent."

At the Eighth General Conference on Weights and Measures, meeting in 1933, the change to the absolute units was definitely confirmed (see appendix 5). The Conference delegated to the International Committee full authority to fix the ratios of the new to the old units and to set the date for their adoption. It was hoped that the change might be made in 1935.

However, absolute measurements of high accuracy are very time-consuming, and although work was pushed vigorously at several national laboratories, it became evident that reliable values of adequate accuracy for the ratios of the absolute to the international units could not be obtained so quickly. At the 1935 meeting, the International Committee [8] postponed the date of adoption to January 1, 1940, asked the Advisory Committee to meet early in 1939 to fix the ratios, and announced that only experimental work reported before the end of 1938 would be considered in fixing the values. It published provisional values for the ratios expressed to parts in 10,000 based on

1 international ohm=1.0005 absolute ohms.
1 international volt=1.0004 absolute volts.

The Advisory Committee met in June 1939, and the several members reported the status of the work in their respective laboratories on determining the ratios of the international to the absolute units. The German, Japanese, and Russian laboratories had not yet completed their programs. However, the Committee felt that the good agreement between the British and American data, and the increasing inconvenience that the transition would entail if too long postponed justified adhering to the proposed date of January 1, 1940. Resolutions were drawn up transmitting this opinion to the International Committee, fixing provisionally the ratios to be announced, and offering suggested wordings for exact theoretical definitions of the new absolute units, which could if desired be incorporated in the legislation that might be enacted by the several adherent nations to put the new units into full effect.

The meeting of the International Committee has been scheduled for September 1939, but the outbreak of World War II brought all activity in this field to a standstill.

Following a brief preliminary session in November 1945, the International Committee met in plenary session in October 1946.[4] A poll of the laboratories represented on the Advisory Committee on Electricity showed that, with the exception of the Reichsanstalt, all still concurred in the opinion expressed by the Committee in 1939 that the transition to the new units should be made promptly. The Germans still would have preferred to postpone the change until they could verify by their own experiments the correctness of the new units. It was evident however that their flight from Berlin to Weida to escape the bombings must have deranged the laboratory to such an extent that they would not be in position to make an effective contribution for a very long time. Accordingly the International Committee formally voted resolutions (see appendix 6) based on the recommendations made in 1939 by the Advisory Committee. These (1) set the date January 1, 1948, for the change; (2) fixed the ratios

1 mean international ohm=1.00049 absolute ohms.
1 mean international volt=1.00034 absolute volts.

as those governing the change on that date; and (3) gave official formulations of definitions for the new units.

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[4] The membership of the International Committee at this time was: L. de Broglie (France); G. Cassinis (Italy); M. Châtelain (USSR); E. C. Crittenden (USA); M. Dehalu (Belgium); W. J. de Haas (Holland); E. S. Johansen (Denmark); C. Kargatchin (Yugoslavia); W. Kösters (Germany); H. Nagaoka (Japan); Z. Rauszer (Poland); M. Ros (Switzerland); J. E. Sears (Great Britain); M. Siegbahn (Sweden); C. Statescu (Rumania); A. Pérard.

This action was given ex post facto approval by the Ninth General Conference when it met in October 1948.

Conformance with this formal action of the International Committee was of course desirable on the part of the United States as a signatory nation. Accordingly the National Bureau of Standards proceeded to prepare for the impending change. Bureau Circular C459, "Announcement of change in electrical and photometric units", was published in May 1947 and given wide circulation. Excerpts appeared in most of the technical magazines concerned, and oral announcements were made at various scientific meetings. During 1947 all certificates issued by the Bureau giving precise electrical values contained a supplementary statement of what the values were going to be in the new units. Similarly, during 1948 such certificates contained not only the values in the new units but also a supplementary statement of what the values would have been in terms of the old units.

Because of the differences, shown in figures 8 and 9, between the mean international units as defined by the intercomparisons at the International Bureau and the Washington units as maintained at the National Bureau of Standards, the ratios of the units as certified by the NBS prior to January 1, 1949 to the absolute units used after that date are as given in the tabulation below. (It should be noted that the U. S. "Washington ohm" was 7 ppm smaller than the ohm as certified for use in the USA).

1 international ohm	=1.000495 absolute ohms.
1 international volt	=1.000330 absolute volts.
1 international ampere	=0.999835 absolute ampere.
1 international coulomb	=0.999835 absolute coulomb.
1 international henry	=1.000495 absolute henries.
1 international farad	=0.999505 absolute farad.
1 international watt	=1.000165 absolute watts.
1 international joule	=1.000165 absolute joules.

The legal status of the new units in the United States is, of course, exactly the same as that of the older ones because the law of 1894 (appendix 1) mentions both sets of units on an equivalent basis. However, in order to remove the ambiguities of the old act, and also to provide a statutory basis for photometric units that have hitherto been based merely on the common consent of those interested, new legislation has been proposed. Substantially identical bills, HR4113 and S1850 were introduced in the United States Congress in July 1947 and December 1947, respectively, but died with the expiration of the 80th Congress in December 1948. Bill S441 (see appendix 7) was introduced in the 81st Congress in January 1949.

V. Absolute Measurements

1. General

The many interactions between electrical and mechanical phenomena have offered a considerable variety of possible methods for deriving electrical quantities from mechanical measurements [61, 62, 63]. However, experience has shown that relatively few of these give prospects of yielding an accuracy as high as a few parts in 100,000.

One such relation is that between the inductance of a circuit and its geometrical size and shape. Many formulas [69] have been worked out for such relations. By constructing an inductor of simple shape in such a way that all its significant dimensions can be measured with sufficient accuracy, and by ensuring that all materials used in its construction or located in its neighborhood are nonmagnetic, a standard is obtained, the inductance of which can be computed in absolute henries. For results of high accuracy, extreme care and attention to detail are required in the construction of the inductor. The mechanical measurements involve a tedious multiplicity of measurements of diameter and length of various parts of the structure, all of which must be of the highest accuracy. An example of the effort to avoid systematic errors is the use by one group at the NBS of end-length standards only, while the workers using another method used line standards only.

As a second step, the inductance can be used in one of several forms of measuring circuit at a known frequency to determine the value in absolute ohms of the resistance of a resistor. Because of the fact that resistors rather than inductors are commonly used for the maintenance of the unit, most experimenters have combined the two steps so that the final result of their experiment is the determination of the value of a resistance in absolute units. Hence such experiments are referred to as absolute-ohm determinations, although the absolute henry is really the first product.

It might appear that this single electrical determination of the ohm should suffice because the ampere can theoretically be defined as the current that dissipates energy at the rate of 1 watt when flowing in a resistance of 1 ohm, and the watt is purely a mechanical unit. In practice, however, the mechanical measurement of energy or power with high accuracy is difficult. It has been found preferable to make use of a second type of absolute measurement in which the current in a pair of coils develops a mechanical force of attraction or repulsion between them. The force, F_x, in the x direction developed in such a circuit by a current, I, is given by

$$F_x=I^2 \frac{dM}{dX},$$

where dM/dX is the rate of increase of the mutual inductance between the fixed and the moving coils as the dimension is increased. By arranging the coils so that F_x is vertical, it may be measured by balancing it against the gravitational force, Mg, on a mass, M. The force is then readily obtained and the major problem is the computation of dM/dX from the known proportions of the circuit. Such an apparatus is commonly called a "current balance."

Because of the transitory nature of an electric current, the customary procedure is to connect in series with the coils of the balance a resistor of resistance, R. The voltage drop, IR, in this resistor is opposed to the emf, E, of a standard cell. When the current, I, is held at such a value that IR balances E and at the same time the mass, M, of the weight has been adjusted to balance the electrodynamic force, the relation

$$E=R\sqrt{mg/\frac{dM}{dx}}$$

holds. If R is known in absolute ohms, E can be computed in absolute volts. An experiment of this type is usually called a determination of the ampere in absolute measure, although the final result is the determination of the emf of a standard cell.

2. Absolute Measurement of Resistance

In recent years, four distinct methods of comparable and very high accuracy for the absolute measurement of resistance have been used in the national standardizing laboratories of Great Britain and of the United States. The following paragraphs give a brief description of each.

An early method employs the "Lorenz apparatus," [64], which has been used successfully several times at the National Physical Laboratory. Figure 10 shows a schematic cross section of the apparatus. D and D' are disks mounted on the rotating shaft, S. Brushes b and b' make contact with the periphery of the disks. Each pair of fixed coils, for example, C_1 and C_2, or C_3 and C_4 may be considered the primary windings of a mutual inductor, M, of the Campbell type, the secondary of which is formed by the periphery of a slip-ring carried on a disk. When there is a current I in the coils, the magnetic flux linking the periphery of one ring is $\phi=MI$. When the shaft, S, is rotated, each conducting path ($b\ d\ d'\ b'$) from a point on the periphery of one ring through the disk and shaft to a corresponding point on the periphery of the other ring will cut the total flux embraced by the peripheries of the two rings, and this flux is given by $\phi+\phi'=(M+M')\,I$. The emf generated between the brushes is therefore proportional to the current and to the speed of rotation.

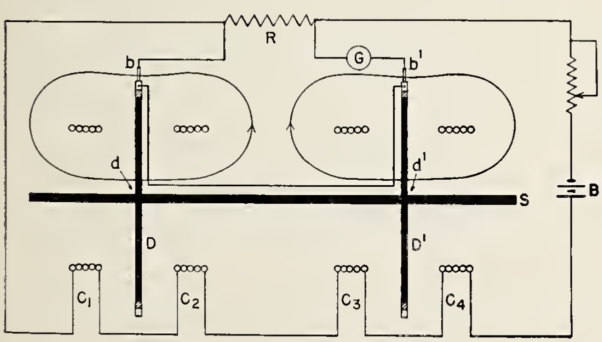

Figure 10. *Lorenz apparatus.*

This schematic cross section shows how the IR drop in the resistor, R, which is being measured, is balanced against the emf, induced between the brushes $b\ b^1$ of the homopolar generator. The generator field is formed by the coils $C_1C_2C_3C_4$, coaxial with the shaft and connected in series with R, while its armature winding is a conductor such as bdd^1b^1 connecting the two slip rings carried by disks D and D^1.

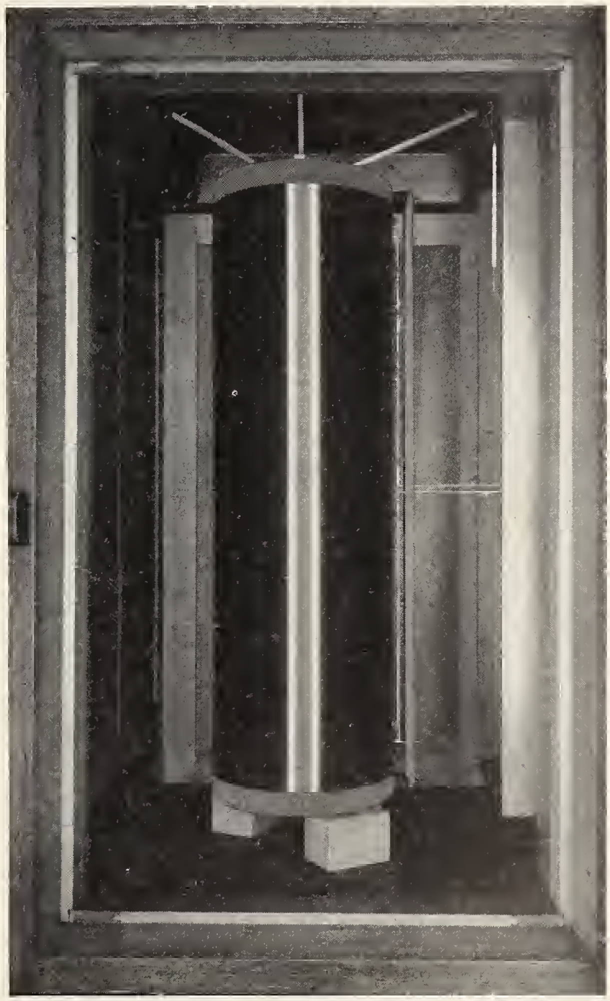

Figure 11. *Self-inductor wound in lapped helical groove in pyrex glass form.*

The coil has 1,000 turns, is about 35 cm in diameter and 100 cm long. Its inductance is 103 mh. The enclosing cabinet for temperature control is made of wood and glass with no metal fastenings.

This emf is balanced against the IR drop of the same current through the resistor, R, which is being measured. When a balance is obtained, $R=n\ (M+M)'$. Here R is in ohms if n is the speed in revolutions per second and M and M' are in henries.

One method used at the NBS by Curtis, Moon, and Sparks [65] was to construct a large self inductor of copper wire wound in a carefully lapped groove on the outer cylindrical surface of a form of pyrex glass or of fused quartz. The inductor on the pyrex form is shown in figure 11. The computation of the inductance of such a coil is made by the formulas developed by Snow. Figure 12 shows the circuits used in the electrical

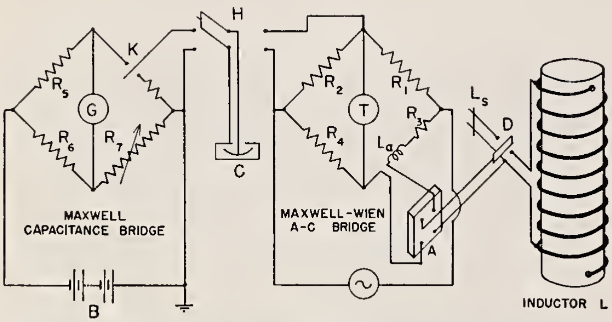

Figure 12. *Schematic diagram of circuits used by Curtis, Moon, and Sparks for the absolute measurement of resistance.*

experiment by which, in two stages, the measurement is made in terms of inductance and time. The first stage consists in an experiment at a frequency of 24 c/s using a Maxwell-Wien bridge to establish with high precision the relation between the values of the inductor, L, a large air capacitor, C, and two resistance arms, R_1 and R_4. The switch, D, serves to give a base reading in which a link of small and computable inductance, L_s, is substituted for the large inductor. The capacitor, C, is then connected into a Maxwell absolute capacitance bridge circuit in which its value is determined in terms of the resistances R_5, R_6, and R_7 and the number (100) of charges and discharges per second produced by the contactor, K. Additional comparisons among the resistors serve to express the final results in terms of the resistance of any one of them. In all, four different inductors wound on forms of different materials and dimensions have been used in this work.

The Campbell method used by Hartshorn and Astbury [66] at the British National Physical Laboratory involves the construction of a mutual inductor of the Campbell type [67]. A schematic cross section of such an inductor is shown in figure 13. This type of mutual inductor has the

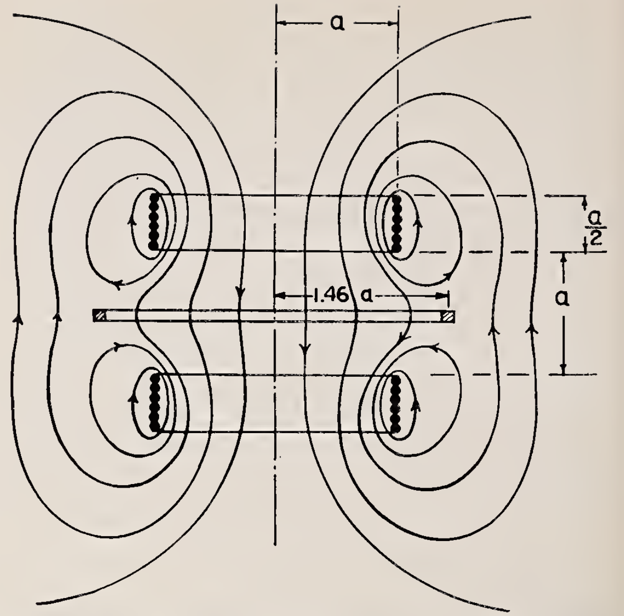

Figure 13. *Schematic cross section of Campbell mutual inductor.*

For a primary winding in two sections of the proportions shown, the magnetic field is almost zero in the annular space occupied by the secondary coil. Hence an error in the measured dimensions or location of the secondary coil will have little effect on the calculated mutual inductance.

advantage that the secondary circuit is located in an annular space in which the magnetic field is very weak. Hence the location of the secondary turns need be known with an accuracy less by about three orders of magnitude than the accuracy that is required in the location of the primary turns. This annular region of weak magnetic field results from the presence of the gap between the upper and lower halves of the primary winding as indicated. The mutual inductance is calculated from the dimensions of the coils.

The inductances of two working mutual inductors, M_1 and M_2, are then compared successively with that of the single computable inductor of the Campbell type, of the same nominal value, by directly opposing the secondary emf's to that of the standard when the primary coils are carrying a suitable current at a frequency of about 10 c/s. The circuit shown in figure 14 is then used with a frequency of about 100 c/s to compare the inductances with the resistances r and R. Here R indicates the resistance of the entire circuit formed by the secondary coil of M_1 and the primary coil of M_2, together with the auxiliary resistor, S. When a balance exists the constants of the circuit satisfy the relations:

$$\omega^2 M_1 M_2 = Rr$$

$$M_1 S = (L_1 + L_2) r$$

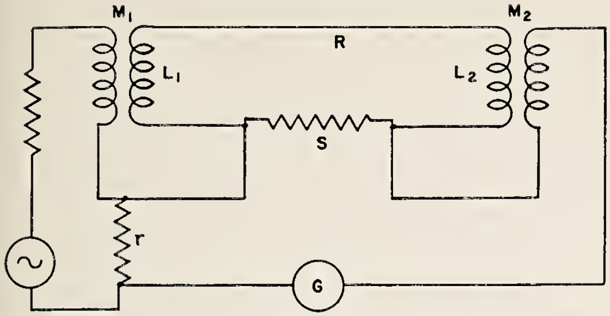

FIGURE 14. *Campbell method for the absolute measurement of resistance.*

The values of the two mutual inductors are derived by comparison with a computable standard inductor. The secondary emf of M_2 is nearly equal in magnitude and opposite in phase to the drop of the primary current in r.

The first of these equations, together with the measured ratio of R to r, gives a value for R (or r) in terms of M and ω.

FIGURE 15. *Modified Campbell inductor used in Wenner method.*

Here Dr. F. Wenner is shown measuring the average pitch of a section of the primary winding. For the electrical measurements the coil is removed from this steel comparator frame and mounted with its secondary in a nonmetallic housing.

A second method used at the NBS is the Wenner method [68], which combines certain desirable features of several of the preceding methods. The mutual inductor, the primary of which is shown in figure 15, is a modification of the Campbell type with two gaps in the primary winding so placed as to produce two annuli of zero field. By proper design, the resulting annular space within which the field is very small and in which the secondary winding is to be located can be made relatively large. The circuit used is shown in figure 16. A direct current flowing through the four-terminal resistance, R, which is being measured (here shown with an adjustable shunt, S_h, across its potential terminals) also flows in the primary winding, P, of the mutual inductor M, but is reversed in direction cyclically by the commutator, C_p. The emf induced in the secondary of the mutual inductor is rectified by the commutator, C_s, and opposed through the galvanometer, G, to the IR drop in the resistor, R. The two commutators are mechanically alined with such relative phases that the secondary connections are reversed after the primary current has had time to settle to a steady value. The current flowing in the secondary at the time of secondary commutation is negligibly small. When a balance is obtained the resistance is given by the equation

$$R=4\ nM\ I_r/I_a,$$

where n is the frequency of commutation in cycles per second, I_a is the average current through the resistor, R, and I_r is the current flowing in the primary of the inductor at the moment the secondary connections are reversed. The primary current is supplied from two storage batteries and the circuit is so adjusted that battery, B_1, supplies energy as far as the commutator, C_P, while battery, B_2, supplies the energy needed for the rest of the circuit. With this adjustment the voltage between points a and c is always zero, and no change in the current occurs when commutator C_P makes its connection between a and c at the beginning of the process of commutation. The resistance network, R_G, associated with battery, B_2, is connected to a series of contact segments similar to the commutator of a d-c motor, and these contacts are mechanically driven by the same shaft as that which drives the primary and secondary commutators. The resistances in the network are so chosen that the wave form of the primary current approximates a trapezoid, whereas the wave form of the secondary voltage consists of a sequence of approximately square-topped pulses. The magneto generator, J, inserts into the galvanometer circuit an alternating emf, the average value of which is strictly zero, which serves to maintain an approximate balance of the emf's throughout the cycle. The inductors, K_s and K_p, serve to greatly reduce the fluctuations in current in the two circuits.

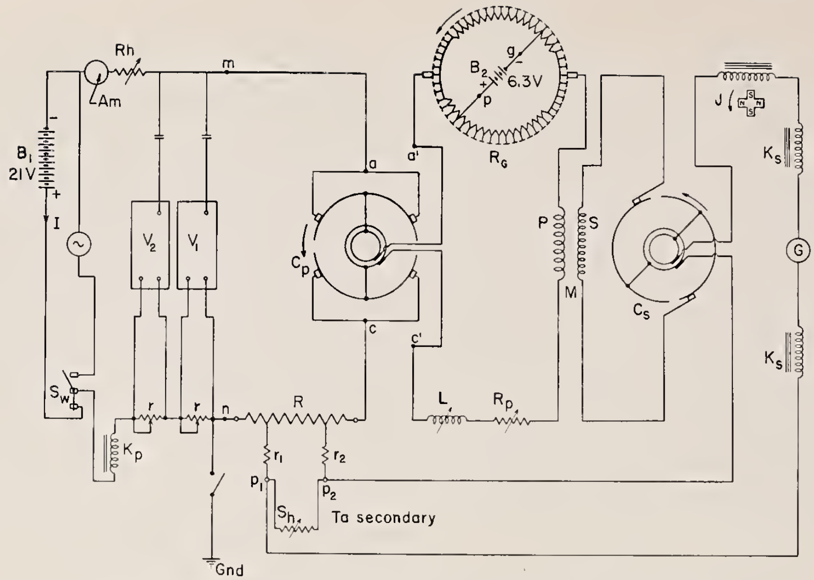

FIGURE 16. *Schematic circuit diagram for the Wenner method.*

Resistor R is measured in terms of mutual inductor M, and frequency of reversal of primary and secondary commutators C_p and C_s. Electronic amplifier V_1 and V_2 hold the current in R constant, while that in P reverses cyclically.

Two electronic amplifiers, V_1 and V_2, of the phase-inverter type that have a "gain" of 1:1, give further regulation and reduce any cyclic and irregular fluctuations in the potential across a and c by a factor of 400. The current in the resistor, R, is thus kept constant to better than 1 ppm throughout the cycle. At the time of each secondary commutation, the resistor is directly in series with the primary winding of the mutual inductor. Therefore I_r equals I_a to a high accuracy, and

$$R=4\ nM.$$

This method has been found so convenient to operate that it is planned to keep the apparatus in commission continuously and to measure the resistance of the 1-ohm standards in the primary group at intervals of not longer than 1 year. A continued agreement with earlier values will be a very strong indication that neither the resistance standards nor the mutual inductor has drifted in value. The chance that two such different structures should show simultaneous and equal drift in the same direction is very small. If discrepancies develop, the laborious process of measuring the mechanical dimensions of the inductor will have to be repeated. It is hoped that this will not be necessary more often than once every 10 or 20 years.

Table 2 summarizes results obtained by these four methods for the absolute measurement of resistance and shows that the agreement is highly satisfactory in spite of the very considerable differences between the methods. It therefore seems probable that the systematic errors have been largely eliminated from all of them.

TABLE 2. *Absolute measurements of resistance*

Date	Authors	Method	Value [1]
1937	Vigoureux	Lorenz	1. 000 499
1937	Hartshorn and Astbury.	Campbell	1. 000 505
1936-38	Curtis, Moon, and Sparks.	Self-inductor.	1. 000 472
1948	Thomas, Peterson, Cooter, and Kotter.	Wenner	1. 000 484
	Mean		1. 000 490

[1] Number of absolute ohms in 1 mean international ohm.

Many sources of error are common to all of the methods, although they would be expected to appear to a very different extent in different methods. One of these is the uncertainty in the dimensions and the uniformity of the windings. Perhaps the best inductors are those of Curtis, Moon, and Sparks, but even in these the outside diameter of the helix has a maximum variation of 4 microns, although the variations in pitch correspond to axial irregularities certainly less than a few tenths of a micron. Errors may arise from the change in dimensions resulting from the temperature rise caused by the heating effect of the current if the current used in the measurement is increased to obtain higher sensitivity. Still another source of error is the uncertainty in the permeability of the form on which the inductor is wound and the effects from magnetic material in the neighborhood. For instance, to avoid such effects at the NBS, the end of the building assigned for absolute measurements was constructed with bronze plumbing, reinforcing rods of special nonmagnetic steel, lead window weights, etc.

The frequency used in the main balance in the second method, or in the Maxwell bridge in the third method, and the speed of rotation of the generator or commutator shafts in the other two methods must be measured to the full accuracy desired in the final result. This, however, has not constituted a serious limitation because the average speed over a considerable time can readily be determined to high accuracy by comparison with circuits timed by crystal oscillators. A more subtle source of error may be the uncertainty in the location of the current within the cross section of the primary winding. If the material were homogeneous one would expect the center of gravity of the current distribution to lie somewhat inside the center of the wire because of the shorter circumference of the inner edge of each turn. The problem is complicated, however, because in the process of winding, parts of the material are strained even beyond their elastic limits, and these strains may cause small changes in the resistivity, which in turn will affect the distribution of current. Such errors, are, of course, greater when the cross section of wire is made large to permit the use of large currents.

Other sources of error applicable to particular methods that may be mentioned are: Imperfect integration of the current by the galvanometer used in the Maxwell bridge; changes in the resistance of the intermediate circuit of the Campbell method as a result of heating of the copper coils that form part of this circuit; the low voltage developed in the Lorenz apparatus, which makes thermoelectric and contact trouble at the brushes rather significant, and the possibility of residual emf in the secondary of the inductor at the time of commutation of the secondary circuit in the Wenner method.

In spite of all these possible errors, the great effort expended on these methods has led to results which, as shown in table 2, differ by only a very few parts in 100,000.

3. Absolute Measurement of Current

The only methods [70, 71, 72] used in recent times for the absolute measurement of current with high precision involve a current balance somewhat like that shown schematically in figure 17. The current to be measured is passed in series

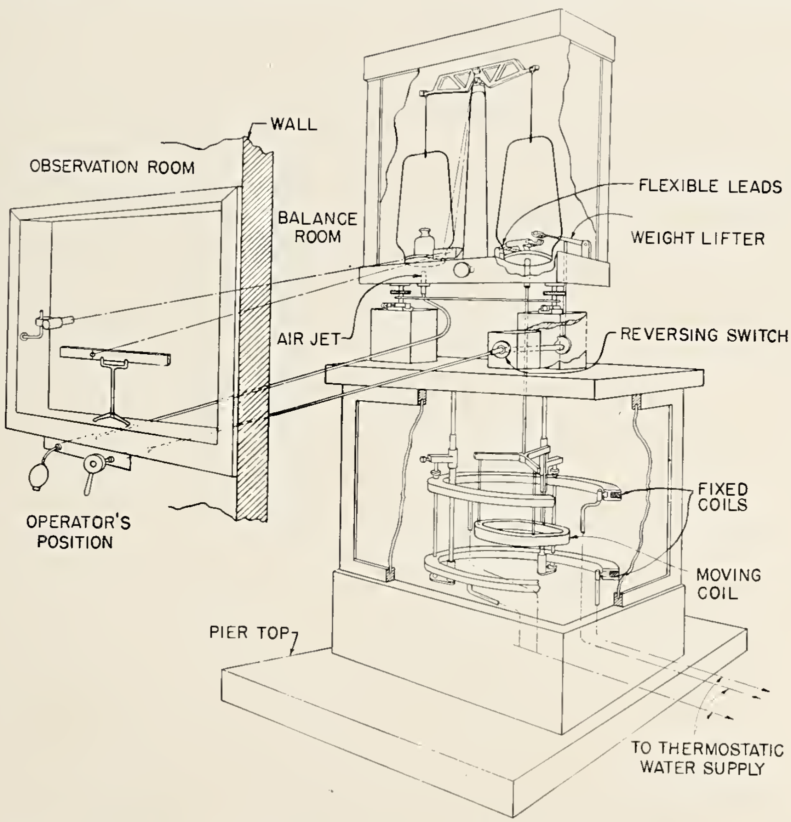

Figure 17. *Schematic drawing of Rayleigh current balance.*

With the weight lifted, the direction of currents is such that the moving coil is attracted by the lower and repelled by the upper fixed coil. When the switch is reversed, the weight is lowered on to the balance pan and the electrodynamic forces are in the opposite direction.

through the two fixed coils and the moving coil. The direction of the windings is such that the magnetomotive forces of the two fixed coils are in opposition so that they conspire to force the moving coil in the same direction. The current balance at the NBS uses coils the cross section of which is small relative to their radius and is commonly designated as of the Rayleigh type. At the NPL all three coils are wound with single-layer windings that have considerable axial length, and the balance is designated as the Ayrton-Jones type. The NPL balance has two sets of coils, one moving coil being supported from either end of the balance. This has the advantage of doubling the force and of giving some compensation between the disturbing forces due to convection currents arising from the heating developed by the current in the moving coils. In operation, the rest point of the balance is observed before and after reversal of current in the fixed coils. A compensating mass of known weight, nearly equal to the change in electromagnetic force, is also added during one observation and removed during the other.

The formulas for computing the force in terms of current are complicated, but in the Rayleigh form involve principally the ratio of the effective radii of the fixed and moving coils. It has been found possible to measure this ratio of the effective radii by an electrical method with a higher precision than can be obtained by purely mechanical measurements. This is done with the circuit shown in figure 18. The two coils concerned are mounted concentrically with their planes in the magnetic meridian and are energized with currents of such magnitude that the net magnetic field at the common center of the coils is zero. This condition is indicated by a sensitive magnetometer at the center. When the magnetometer shows no deflection as a result of a reversal of both currents, the ratio of the radii is equal to the ratio of the currents. The ratio of the currents is then equal to the ratio of the resistances, R_1 and R_2, when the galvanometer, G, also shows a balance.

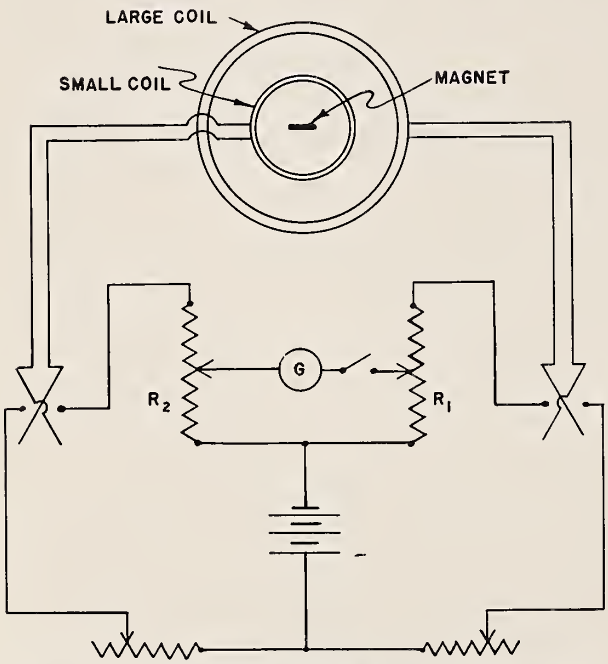

Figure 18. *Circuit for measuring ratio of effective radii of current-balance coils.*

If the currents are adjusted to have equal and opposite effects on the small magnet, their ratio is equal to that of the effective radii of the coils. If the galvanometer is also balanced, this ratio is equal to that of the resistance R_1 to R_2.

The principal limitation in the absolute measurement of current seems to be in the uncertainty in the location of the coils, and it has seemed better to sacrifice the greater mechanical forces that can be obtained by using multilayer coils of round insulated wire and to use instead single layer solenoids of bare wire or coils wound of metallic ribbon to form a coil of many layers but of one turn per layer. Aluminum ribbon insulated by an anodizing process has been found convenient for such coils.

Figure 19 shows the combination of a helical moving coil with a pair of spiral fixed coils as mounted at the NBS. A comparison of the results obtained when different coil combinations are in use is shown in table 3. The values listed in this table are the amounts in ppm by which the absolute ampere, as derived by the use of various combinations of fixed and moving coils in the current balance at the NBS, exceeds the NBS international ampere as certified in the United States. It will be seen that when the larger (25-cm diam) moving coil was used with the smaller (40-cm diam) of the fixed coils, the difference, 26 ppm, was 145 ppm smaller than the value, 171 ppm, observed when the ribbon-wound (25-cm diam) moving coil was used with the fixed single-layer solenoids (46-cm diam). These systematic difference are definitely larger than the random errors of observation and are still unexplained.

Table 3. *Results with different coils in current balance*

Moving coil	Fixed coils			
	Wire, small	Wire, large	Spiral	Helical
	ppm	*ppm*	*ppm*	*ppm*
Wire, large	26	110	----	----
Wire, small	69	97	----	----
Spiral	96	129	163	171
Helical	118	136	165	165

A further uncertainty arises from possible errors in the value, g, used for the acceleration of gravity in computing the gravitational force on a known

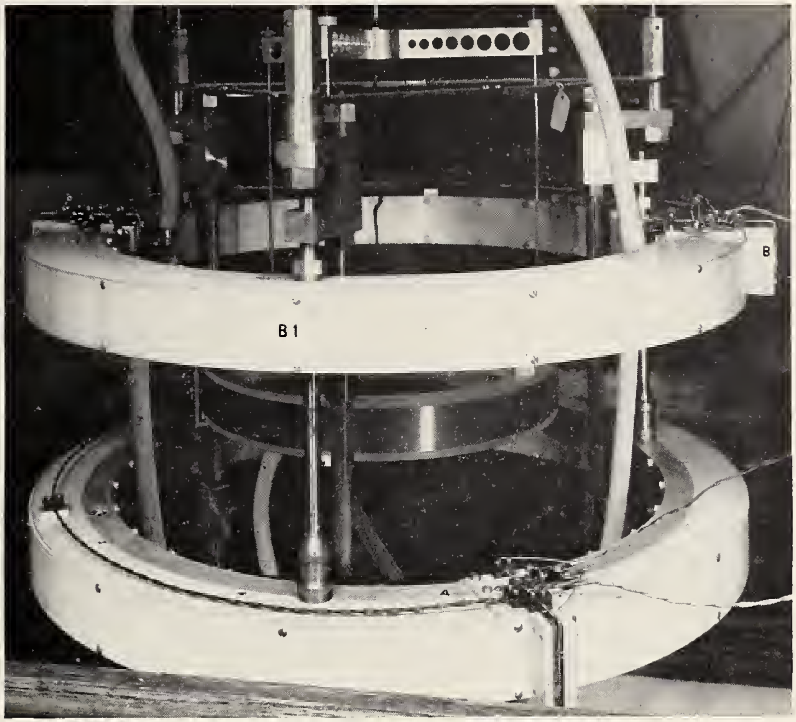

FIGURE 19. *Coils of current balance.*

Here the two spiral fixed coils are wound of anodized aluminum strip on the outside of the water jacket and enclosed in a protective case. The moving coil is a single-layer helix wound in a lapped groove in the glass form, and suspended by three rods from the perforated spider, which in turn hangs from one end of the balance.

mass. The values reported from earlier work and given in table 4 are based on the 1906 Potsdam determination. In the light of more recent measurements [75], it appears that the best value of g is probably less by 15 ppm than that derived from Potsdam.

The results of the best recent absolute measurements of current are summarized in table 4. [62].

TABLE 4. *Absolute measurement of current*

Date	Authors	Method	Value [a]
1936	Vigoureux	Ayrton-Jones.	0. 999 863
1939	Curtis, Curtis, and Critchfield.	Rayleigh	0. 999. 860
1942	Curtis, Driscoll, and Critchfield.	Combination	0. 999 856
	Mean		0. 999 860

[a] Number of absolute amperes in 1 mean international ampere, using values of gravity derived from the Potsdam determination.

On the basis of these results, the International Committee chose the reduced value 0.99985 for the value of the mean international ampere in absolute amperes. Hence the international ampere as certified by the National Bureau of Standards is 0.999835 absolute ampere.

It is evident from table 3, however, that the certainty of the final result is not as high as might be concluded from the (perhaps fortuitous) agreement of the independent values listed in table 4.

There is an evident need for the development of some radically different method for measuring current in absolute amperes that will not be subject to the same types of systematic error. The Pellat balance [73] in which the current in two coils placed with their axes at right angles produces a mechanical torque, seems to offer such a possibility. The construction of such a balance was begun at the NBS some time ago, and the mathematical formulas needed in its use have been worked out by Snow [74]. It is hoped that this project can be resumed in the near future.

VI. Summary

The preceding record has shown that for the 37 years from 1911 to 1947, inclusive, the national standardizing laboratories, with valuable coordinating service from the International Bureau of Weights and Measures, succeeded in maintaining throughout the civilized world a system of electrical units that did not vary in time among any of the six participating nations by more than 0.01 of 1 percent. The units in the United States apparently never departed from the desired ideal by more than 20 ppm.

The ideal pursued during these years was the system of international electrical units, formulated by the London Conference of 1908, and experimentally realized by the Technical Committee in Washington in 1910. The basic definitions in terms of mercury columns and silver deposits were brought into play apparently on only four occasions: To readjust the British ohm in 1927, the German ohm and the volt in 1932, and the Russian volt in 1930, when each of these nations changed its unit to offset the effect of cumulative drift in the standards it had been using to maintain the unit. The fact that such drifts did accumulate makes it clear that in the future as in the past some fixed definitions must be set up by which the standards can be checked periodically. The results of absolute measurements by a variety of methods have shown that such absolute measurements can be used to serve as a check against cumulative drift with an accuracy at least as great as that attainable in the discarded international standards.

The change of January 1, 1948, involved both a change in the size of each unit by the factor shown on page 22 and a change in the type of experiment by which, at fairly long intervals, checks will be made by one or another of the national laboratories to detect any incipient progressive drifts in its standards. The older procedures for maintaining the ohm and the volt by groups of standard resistors and cells of the highest quality will continue unchanged. The biennial intercomparisons at the International Bureau are being resumed and will serve both to detect relative drifts between the standards of different countries and to maintain accurate values for the standards deposited at Sèvres, which in turn serve as primary standards for the laboratories of countries that do not have national laboratories of their own.

It is to be expected that the International Advisory Committee on Electricity will meet only at fairly long intervals as additional experimental realizations of the absolute units become available, or if an undue drift in the value of one or more nation's unit relative to the mean indicates a need for consideration by the International Committee on Weights and Measures. Any readjustment of values resulting from such situations will presumably be very small.

However, the adoption of the new ideal, which is inherently consistent with the mechanical units, has automatically eliminated all future need of correcting precise scientific data to allow for the artificial distinction between the international and the absolute units. Future absolute measurements can be depended upon to keep the units as maintained amply close to the ideal, because with adequate attention they may be expected to increase in accuracy in parallel with any possible future increases in the accuracy of the scientific measurements that they are to correlate.

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VIII. Appendix 1

U. S. Law of 1894, 53d Congress, 28 Stat., Ch. 131, p. 102

(Public—No. 105)

An Act To define and establish the units of electrical measure

Be it enacted by the Senate and House of Representatives of the United States of American in Congress assembled, That from and after the passage of this Act the legal units of electrical measure in the United States shall be as follows:

First. The unit of resistance shall be what is known as the international ohm, which is substantially equal to one thousand million units of resistance of the centimeter-gram-second system of electro-magnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice fourteen and four thousand five hundred and twenty-one ten-thousandths grams in mass, of a constant cross-sectional area, and of the length of one hundred and six and three tenths centimeters.

Second. The unit of current shall be what is known as the international ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electro-magnetic units, and is the practical equivalent of the unvarying current, which, when passed through a solution of nitrate of silver in water in accordance with standard specifications, deposits silver at the rate of one thousand one hundred and eighteen millionths of a gram per second.

Third. The unit of electro-motive force shall be what is known as the international volt, which is the electro-motive force, that steadily applied to a conductor whose resistance is one international ohm, will produce a current of an international ampere, and is practically equivalent to one thousand fourteen hundred and thirty-fourths of the electro-motive force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of fifteen degrees centigrade, and prepared in the manner, described in the standard specifications.

Fourth. The unit of quantity shall be what is known as the international coulomb, which is the quantity of electricity transferred by a current of one international ampere in one second.

Fifth. The unit of capacity shall be what is known as the international farad, which is the capacity of a condenser charged to a potential of one international volt by one international coulomb of electricity.

Sixth. The unit of work shall be the Joule, which is equal to ten million units of work in the centimeter-gram-second system, and which is practically equivalent to the energy expended in one second by an international ampere in an international ohm.

Seventh. The unit of power shall be the Watt, which is equal to ten million units of power in the centimeter-gram-second system, and which is practically equivalent to the work done at the rate of one Joule per second.

Eighth. The unit of induction shall be the Henry, which is the induction in a circuit when the electro-motive force induced in this circuit is one international volt while the inducing current varies at the rate of one Ampere per second.

Sec. 2. That it shall be the duty of the National Academy of Sciences to prescribe and publish, as soon as possible after the passage of this Act, such specifications of details as shall be necessary for the practical application of the definitions of the ampere and volt hereinbefore given, and such specifications shall be the standard specifications herein mentioned.

IX. Appendix 2

International Conference on Electrical Units and Standards, 1908

REPORT

The Conference on Electrical Units and Standards for which invitations were issued by the British Government, was opened by President of the Board of Trade, the Right Hon. Winston S. Churchill, M. P., on Monday, 12th October 1908, at Burlington House, London, S. W.

Delegates were present from twenty-two countries, and also from the following British Dependencies, namely, Australia, Canada, India and the Crown Colonies.

It was decided by the Conference that a vote each should be allowed to Australia, Canada and India, but a vote was not claimed or allowed for the Crown Colonies.

The total number of delegates to the Conference was forty-six, and their names are set out in Schedule A to this Report.

The officers of the Conference were;

President

The Right Hon. Lord Rayleigh, O. M., President of the Royal Society.

Vice-Presidents

Professor S. A. Arrhenius.	M. Lippmann
Dr. N. Egoroff.	Dr. S. W. Stratton.
Dr. Viktor Edler von Lang.	Dr. E. Warburg.

Secretaries

Mr. M. J. Collins.	Mr. C. W. S. Crawley.
Mr. W. Duddell, F. R. S.	Mr. F. E. Smith.

The Conference elected a Technical Committee to draft specifications and to consider any matter which might be referred to the Committee and to report to the Conference.

The Conference and its Technical Committee each held five sittings.

As a result of its deliberation the Conference adopted the resolutions and specifications attached to this report and set out in Schedule B, and requested the Delegates to lay them before their respective Governments with a view to obtaining uniformity in the legislation with regard to Electrical Units and Standards.

The Conference recommend the use of the Weston Normal Cell as a convenient means of measuring both electromotive force and current when set up under the conditions specified in Schedule C.

In cases in which it is not desired to set up the Standards provided in the resolutions Schedule B, the Conference recommends the following as working methods for the realisation of the International Ohm, the Ampere, and the Volt.

1. For the International Ohm.
   The use of copies, constructed of suitable material and of suitable form and verified from time to time, of the International Ohm, its multiples and sub-multiples.
2. For the International Ampere.
   (a) The measurement of current by the aid of a current balance standardized by comparison with a silver voltameter;
   or (b) The use of a Weston Normal Cell whose electromotive force has been determined in terms of the International Ohm and International Ampere, and of a resistance of known value in International Ohms.
3. For the International Volt.
   (a) A comparison with the difference of electric potential between the ends of a coil of resistance of known value in International Ohms, when carrying a current of known value in International Amperes;
   or (b) The use of a Weston Normal Cell whose electromotive force has been determined in terms of the International Ohm and the International Ampere.

The duties of specifying more particularly the conditions under which these methods are to be applied has been assigned to the Permanent Commission, and pending its appointment to the Scientific Committee to be nominated by the President (see Schedule D), who will issue a series of Notes as Appendix to this Report.

The Conference has considered the methods that should be recommended to the Governments for securing uniform administration in relation to Electrical Units and Standards, and expresses the opinion that the best method of securing uniformity for the future would be by the establishment of an International Electrical Laboratory with the duties of keeping and maintaining International Electrical Standards. This Laboratory to be equipped entirely independently of any National Laboratory.

The Conference further recommends that action be taken in accordance with the scheme set out in Schedule D.

Signed at London on 21st October, 1908.

By the Delegates of the Countries above written.

For the United States of America:	S. W. Stratton.
	Henry S. Carhart.
	Edward B. Rosa.
For Austria:	Victor Von Lang.
	Ludwig Kusminsky.
For Belgium:	P. Clément.
For Brazil:	Leopold J. Weiss.
For Chile:	Victor Eastman.
For Colombia:	Jorge Roa.
For Denmark and Sweden:	Svante Arrhenius.
For Ecuador:	C. Nevares.
For France:	G. Lippmann.
	J. Réne Benoît.
	T. De Nerville.
For Germany:	E. Warburg.
	W. Jaeger.
	St. Lindeck.
For Great Britain:	Rayleigh.
	J. Gavey.
	R. T. Glazebrook.
	W. A. J. O'Meara.
	A. P. Trotter.
	J. J. Thomson.
For Guatemala:	Francisco de Arce.
For Hungary:	Harsányi Desiré.
	Vater Joisef
For Italy:	Antonio Ròiti.
For Japan:	Osuke Asano.
	Shigeru Kondo.
For Mexico:	Alfonso Castelló.
For Netherlands:	Dr. H. Haga.
For Paraguay:	Max. F. Croskey.
For Russia:	N. Egoroff.
	L. Swentorzetzky.
For Spain:	Jose Ma. de Madariaga.
	A. Montenegro.
For Switzerland:	Dr. H. F. Weber.
	P. Chappuis.
	Jean Landry.
For Australia:	C. W. Darley.
	Threlfall.
For Canada:	Ormond Higman.
For Crown Colonies:	P. Cardew.
For India:	M. G. Simpson.
	M. J. Collins.
In the presence of:	W. Duddell.
	C. W. S. Crawley.
	F. E. Smith.
	Secretaries.

Schedule B

RESOLUTIONS

1. The Conference agrees that as heretofore the magnitudes of the fundamental electric units shall be determined on the electro-magnetic system of measurement with reference to the centimetre as the unit of length, the gramme as the unit of mass and the second as the unit of time.

These fundamental units are (1) the Ohm, the unit of electric resistance which has the value of 1,000,000,000 in terms of the centimetre and second; (2) the Ampere, the unit of electric current which has the value of one-tenth (0.1) in terms of the centimetre, gramme, and second; (3) the Volt, the unit of electromotive force which has the value 100,000,000 in terms of the centimetre, the gramme, and the second; (4) the Watt, the Unit of Power which has the value 10,000,000 in terms of the centimetre, the gramme, and the second.

II. As a system of units representing the above and sufficiently near to them to be adopted for the purpose of electrical measurements and as a basis for legislation, the Conference recommends the adoption of the International Ohm, the International Ampere, and the International Volt defined according to the following definitions:

III. The Ohm is the first Primary Unit.

IV. The International Ohm is defined as the resistance of a specified column of mercury.

V. The International Ohm is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grammes in mass, of a constant cross sectional area and of a length of 106.300 centimetres.

To determine the resistance of a column of mercury in terms of the International Ohm, the procedure to be followed shall be that set out in Specification I attached to these Resolutions.

VI. The Ampere is the second Primary Unit.

VII. The International Ampere is the unvarying electric current which, when passed through a solution of nitrate of silver in water, in accordance with Specification II attached to these Resolutions, deposits silver at the rate of 0.00111800 of a gramme per second.

VIII. The International Volt is the electrical pressure which, when steadily applied to a conductor whose resistance is one International Ohm, will produce a current of one International Ampere.

IX. The International Watt is the energy expended per second by an unvarying electric current of one International Ampere under an electric pressure of one International Volt.

Specification I.

Specification Relating to Mercury Standards of Resistance

The glass tubes used for mercury standards of resistance must be made of a glass such that the dimensions may remain as constant as possible. The tubes must be well annealed and straight. The bore must be as nearly as possible uniform and circular, and the area of cross-section of the bore must be approximately one square millimetre. The mercury must have a resistance of approximately one ohm.

Each of the tubes must be accurately calibrated. The correction to be applied to allow for the area of the cross-section of the bore not being exactly the same at all parts of the tube must not exceed 5 parts in 10,000.

The mercury filling the tube must be considered as bounded by plane surfaces placed in contact with the ends of the tube.

The length of the axis of the tube, the mass of mercury the tube contains, and the electrical resistance of the mercury are to be determined at a temperature as near to 0° C, as possible. The measurements are to be corrected to 0° C.

For the purpose of the electrical measurements, end vessels carrying connections for the current and potential terminals are to be fitted to the tube. These end vessels are to be spherical in shape (of a diameter of approximately four centimetres) and should have cylindrical pieces attached to make connections with the tubes. The outside edge of each end of the tube is to be coincident with the inner surface of the corresponding spherical end vessel. The leads which make contact with the mercury are to be of thin platinum wire fused into glass. The point of entry of the current lead and the end of the tube are to be at opposite ends of a diameter of the bulb; the potential lead is to be midway between these two points. All the leads must be so thin that no error in the resistance is introduced through conduction of heat to the mercury. The filling of the tube with mercury for the purpose of the resistance measurements must be carried out under the same conditions as the filling for the determination of the mass.

The resistance which has to be added to the resistance of the tube to allow for the effect of the end vessels is to be calculated by the formula,

$$A=\frac{0.80}{1063\pi}\left(\frac{1}{r_1}+\frac{1}{r_2}\right) \text{ ohm},$$

where r_1 and r_2 are the radii in millimetres of the end sections of the bore of the tube.

The mean of the calculated resistances of at least five tubes shall be taken to determine the value of the unit of resistance.

For the purpose of the comparison of resistances with a mercury tube the measurements shall be made with at least three separate fillings of the tube.

Specification II

Specification Relating to the Deposition of Silver

The electrolyte shall consist of a solution of from 15 to 20 parts by weight of silver nitrate in 100 parts of distilled water. The solution must only be used once, and only for so long that not more than 30 percent of the silver in the solution is deposited.

The anode shall be of silver, and the kathode of platinum. The current density at the anode shall not exceed 1/5 ampere per square centimetre and at the kathode 1/15 ampere per square centimetre.

Not less than 100 cubic centimetres of electrolyte shall be used in a voltameter.

Care must be taken that no particles which may become mechanically detached from the anode shall reach the kathode.

Before weighing, any traces of solution adhering to the kathode must be removed, and the kathode dried.

Schedule C

Weston Normal Cell

The Weston Normal Cell may be conveniently employed as a standard of electric pressure for the measurement both of E. M. F. and of current, and when set up in accordance with the following Specification, may be taken, provisionally,* as having, at a temperature of 20° C., an E. M. F. of 1.0184 volts.

Specification Relating to the Weston Normal Cell

The Weston Normal Cell is a voltaic cell which has a saturated aqueous solution of cadmium sulphate ($CdSO_4$ 8/3 H_2O) as its electrolyte.

The electrolyte must be neutral to Congo Red.

The positive electrode of the cell is mercury.

The negative electrode of the cell is cadmium amalgam consisting of 12.5 parts by weight of cadmium in 100 parts of amalgam.

The depolariser, which is placed in contact with the positive electrode, is a paste made by mixing mercurous sulphate with powdered crystals of cadmium sulphate and a saturated aqueous solution of cadmium sulphate.

The different methods of preparing the mercurous sulphate paste are described in the notes.† One of the methods there specified must be carried out.

* See duties of the Scientific Committee, Schedule D.

†Notes on methods pursued at various standardising laboratories will be issued by the Scientific Committee or the Permanent Commission, as an Appendix to this Report.

For setting up the cell, the H form is the most suitable. The leads passing through the glass to the electrodes must be of platinum wire, which must not be allowed to come into contact with the electrolyte. The amalgam is placed in one limb, the mercury in the other.

The depolariser is placed above the mercury and a layer of cadmium sulphate crystals is introduced into each limb. The entire cell is filled with a saturated solution of cadmium sulphate and then hermetically sealed.

The following formula is recommended for the E. M. F. of the cell in terms of the temperature between the limits 0° C. & 40° C.

$$E_t=E_{20}-0.0000406(t-20^\circ) \\ -0.00000095\ (t-20^\circ)^2+0.00000001(t-20^\circ)^3$$

Schedule D

1. The Conference recommends that the various Governments interested establish a permanent International Commission for Electrical Standards.

2. Pending the appointment of the Permanent International Commission the Conference recommends(1) that the President, Lord Rayleigh, nominate for appointment by the Conference a scientific Committee of fifteen to advise as to the organisation of the Permanent Commission, to formulate a plan for and to direct such work as may be necesary in connection with the maintenance of standards, fixing of values (2), intercomparison of Standards and to complete the work of the Conference(3). Vacancies on the Committee to be filled by co-optation.

3. That Laboratories equipped with facilities for precise electrical measurements and investigations should be asked to cooperate with this Committee and to carry out, if possible, such work as it may desire.

4. The Committee should take the proper steps forthwith for establishing the Permanent Commission, and are empowered to arrange for the meeting of the next Conference on Electrical Units and Standards, and the time and place of such meeting should this action appear to them to be desirable.

5. The Committee or the Permanent International Commission shall consider the question of enlarging the functions of the International Commission on Weights and Measures, with a view to determining if it is possible or desirable to combine future Conferences on Electrical Units and Standards with the International Commission on Weights and Measures, in place of holding in the future Conferences on Electrical Units and Standards. At the same time it is the opinion of the Conference that the Permanent Commission should be retained as a distinct body, which should meet at different places in succession.

(1) In accordance with the above, Lord Rayleigh has nominated the following Committee, which has been approved by the Conference, viz.:

Dr. Osuke Asano.	Prof. G. Lippmann.
M. R. Benoit.	Prof. A. Röiti.
Dr. N. Egoroff.	Prof. E. B. Rosa.
Prof. Eric Gérard.	Prof. S. W. Stratton.
Dr. R. T. Glazebrook.	Mr. A. P. Trotter.
Dr. H. Haga.	Prof. E. Warburg.
D. L. Kusminsky.	Prof. Fr. Weber.
Prof. St. Lindeck.	

(2) This will include the reconsideration from time to time of the E. M. F. of the Weston Normal Cell.

(3) With this object the Committee are authorised to issue as an Appendix to the Report of the Conference Notes detailing the methods which have been adopted in the Standardising Laboratories of the various countries to realise the International Ohm and the International Ampere, and to set up the Weston Normal Cell.

X. Appendix 3.

Metric Convention. Article 7, as amended 1921

ART. 7. After the committee shall have proceeded with the work of coordinating the measures relative to electric units and when the general conference shall have so decided by a unanimous vote, the bureau will have charge of the establishment and keeping of the standards of the electric units and their test copies and also of comparing with those standards, the national or other standards of precision.

The bureau is also charged with the duty of making the determinations relative to physical constants, a more accurate knowledge of which may be useful in increasing precision and further insuring uniformity in the provinces to which the above-mentioned units belong (article 6 and first paragraph of article 7).

It is finally charged with the duty of coordinating similar determinations effected in other institutions.

XI. Appendix 4.

Resolutions Adopted by the Board of Directors, American Institute of Electrical Engineers, at its Meeting in Denver, Colorado, June 27, 1928

Whereas, there is conclusive evidence that there are discrepancies between the statutorily established international electrical units (ohm, ampere, and volt) and the fundamental ohm, ampere and volt which the international units were intended to represent, these discrepancies in the case of the ohm and the volt amounting to approximately one-twentieth of one per cent; and

Whereas, differences of this magnitude are objectionably large in comparison with the precision required and now being attained in the construction and use of standards fundamental to all electrical measurements; therefore be it

Resolved, that the American Institute of Electrical Engineers hereby urges the Bureau of Standards and foreign national standardizing laboratories to undertake, as soon as possible, the additional researches necessary in order that legislation to reduce these discrepancies to within acceptable limits may be enacted in the near future.

And *whereas*, the present electrical units are defined by statute in terms of material standards, namely, the mercury ohm and the silver voltameter, which it is now known only approximately represent the absolute ohm and ampere and which experience has shown to have serious limitations, and

Whereas, such progress has been made in recent years in the art of making absolute electrical measurements in terms of the fundamental units of length, mass, time and space permeability that the accuracy and reproducibility of a system of electrical units realized by such absolute measurements would seem to be adequate for commercial, industrial and scientific purposes; and

Whereas, the legalization of the absolute ohm and ampere and the units derived from them (these units to be realized by the national standardizing laboratories) would avert the recurring proposals for revision of the values of the legalized units, and would establish the electrical units on a permanent legal basis; therefor be it

Resolved, that the American Institute of Electrical Engineers hereby urges the Bureau of Standards and foreign national standardizing laboratories to undertake as soon as possible, the additional researches necessary in order that the absolute ohm and absolute ampere based on the centimeter-gram-second electromagnetic system, with the absolute volt, watt and other units derived from them, may be legalized in place of the international ohm and ampere and their derived units.

Resolved, further, that in order to avoid the confusion which would result from an interim use of new empirical units based on corrected values of the international units, the international electrical units should be continued in effect without any readjustment of values until such time as the practicability of legalizing the above-mentioned absolute units shall have been determined.

Resolved, further, that copies of these resolutions be communicated to the various national standardizing laboratories and other interested bodies, by the Standards Committee.

XII. Appendix 5.

Translation of Resolution No. 10 adopted October 6, 1933, by the 8th General Conference on Weights and Measures

Resolution No. 10. Substitution of the absolute electrical units for the units called "international".

In accord with the first resolution relative to the electrical units proposed by the Advisory Committee and approved by the International Committee on Weights and Measures;

The Conference approves the principle of the substitution of the absolute system of electrical units for the international system;

Considering, however, that a number of national laboratories have not yet completed the measurements necessary to relate the international units to the absolute units;

It decides to postpone to the year 1935 the provisional fixing of the ratio between each international unit and the corresponding absolute unit;

For this purpose it gives to the International Committee the necessary authority to fix at that time and without waiting for another Conference, these ratios as well as the date of adoption of the new units.

XIII. Appendix 6.

Translation of Resolutions adopted October 29, 1946 by the International Committee on Weights and Measures

RESOLUTIONS

Concerning the Change in Electrical Units

RESOLUTION 1

The International Committee on Weights and Measures meeting officially for the first time since 1937, adopts in principle the resolutions which were submitted to it by the Advisory Committee on Electricity in June, 1939. To adapt these resolutions to the current situation, which has resulted from the developments and scientific progress accomplished since 1939, it decides that:

1) The date for putting in effect the absolute units shall be January 1, 1948.

2) The relations for passing between the mean international units and the absolute units are:

1 mean international ohm = 1.00049 absolute ohm.
1 mean international volt = 1.00034 absolute volt.

The precision of the two relations given above will permit laboratories and industries to express all electrical quantities in terms of the new units, without introducing in this conversion an error exceeding two units in the last place. This error is hardly larger than that estimated as being the accuracy obtained in the national laboratories for their absolute measurements.

RESOLUTION 2

1) *Definitive Substitution of Absolute Electrical Units for the International System.*—In virtue of authority which was conferred on it by the General Conference on Weights and Measures in 1933, the International Committee on Weights and Measures announces at this time its decision that the substitution of the system of practical absolute electrical units for the international system shall be put into effect beginning January 1, 1948.

The present resolutions constitute the "new announcement" which the Circular Letter of January 1, 1940, signed by the President and Secretary of the International Committee on Weights and Measures, requested the various countries to await, before proceeding with any change in units.

2) *Historic Continuity of the System.*—The first definition of the practical absolute system of electrical units adopted by the Committee was enunciated by the London Conference of 1908 in the following manner:

(Here follows Schedule B of the London Conference, see Appendix 2.)

3) *General Considerations.*—The definitions of the absolute electrical and magnetic units rest on the generally recognized electromagnetic laws, which lead to a system of inter-dependent relations among the various quantities which are to be measured. Consequently the units can be defined in various ways, according to the starting point chosen.

In order to formulate legal decisions which are concerned solely with the size of the units and not with the processes experimentally employed for their realization in accordance with the theory on which they are based, it is convenient to have a set of definitions, adequate for this purpose, expressed in as simple and easily understood language as is possible.

In response to questions which have been addressed to it concerning a text intended to serve as a guide for the wording of legislation, the Committee recommends consequently the adoption of the sequence of definitions given in paragraph 4. The Magnitudes of the units: ohm, ampere, volt and watt, thus defined, are identical with those which were adopted at the London Conference of 1908.

The procedure to be followed for the establishment and the conservation of the standards of reference required for certain chosen units is indicated in paragraphs 6 and 8, which are likewise equally intended to serve as a guide for legislation.

4) *Theoretical Magnitudes of the Units.*—A. DEFINITION OF MECHANICAL UNITS USED IN THE FOLLOWING TEXT:

I. Unit of Force—The unit of force (in the system M. K. S. (meter, kilogram, second)) is the force which gives to a mass of 1 kilogram an acceleration of 1 meter per second per second.(1)

II. The Joule (unit of energy or work).—The joule is the work done when the point of application of the M. K. S. unit of force is displaced a distance of 1 meter in the direction of the force.

III. The Watt (unit of power).—The watt is the power which gives rise to the production of energy at the rate of 1 joule per second.

B. DEFINITION OF THE ELECTRICAL UNITS. The Committee offers the following proposals defining the theoretical magnitudes of the electrical units.

IV. The Ampere (unit of electric current).—The ampere is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular sections, and placed 1 meter apart in a vacuum, will produce between these conductors a force equal to 2×10^{-7} M. K. S. unit of force per meter of length.

V. The Volt (unit of difference of potential and of electromotive force).—The volt is the difference of electric potential 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.

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

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

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

IX. The 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 a rate of 1 ampere per second.

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

5) *Object of These Definitions.*—The definitions given in paragraph 4) are intended solely to fix the magnitude of the units and not the methods to be followed for their practical realization. This realization is effected in accord with the well-known laws of electro-magnetism. For example, the definition of the ampere represents only a particular case of the general formula expressing the forces which are developed between conductors carrying electric currents, chosen for the simplicity of its verbal expression. It serves to fix the constants in the general formula which has to be used for the realization of the unit.

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(1) It has been proposed to give the name "newton" to the M. K. S. unit of force.

The foregoing text refers to the M. K. S. system. It is naturally possible to translate it into another system (C. G. S., M. T. S., etc.) by appropriate modification by powers of ten.

6) *Material Standards.*—For practical comparisons the electrical units are represented by material standards for the ohm and the volt to which are assigned appropriate values expressed in absolute units. The standards for the ohm at the present time take the form of resistance coils and those for the volt of voltaic cells (Weston cells for example.)

7) *International Standards of Reference.*—The values which are to be assigned to the standards of reference maintained at the International Bureau of Weights and Measures will be fixed from time to time by the International Committee, on the recommendation of the Advisory Committee on Electricity, in accord with the results of comparisons made between these standards and the national standards the values of which will have been determined directly by absolute measurements.

8) *National Standards of Reference.*—The values to be assigned to the national standards of reference will be determined in accordance with the results of comparisons made with the standards of reference of the International Bureau.

9) *Ratio Between the Absolute Units and the Units of the International Systems.*—These ratios are indicated in Resolution 1 above.

For the standards of each nation, or of particular laboratories, it will be necessary to take account, not only of the values indicated above for the ratios between the "mean international units" Ω_M, A_M, and V_M (which have been accepted by the International Committee) and the absolute units, but also of the difference between the units of the international system maintained by each laboratory and the corresponding "mean international units."

RECOMMENDATION

For the purpose of avoiding confusion as far as possible the Committee advises that, during the period of transition, the adjective "international" (abbreviation: "int.") be applied to the names of the electrical units for the units formerly in use and the adjective "absolute" (abbreviation: "abs.") for the units which the Committee has decided to adopt.

Annex to Resolution 1

In anticipation of the meeting of the International Committee in October, 1946, the International Bureau of Weights and Measures sent a circular letter to a number of national laboratories requesting their opinion on the question of the absolute electrical units. The replies received showed that on the whole the opinion was clearly favorable to the immediate adoption of these units.

The National Bureau of Standards transmitted to the International Committee a formal recommendation requesting that the date of introduction of the absolute units in practical use should be fixed as January 1, 1948.

Moreover, this laboratory has made a very exhaustive study including an objective and impartial discussion of all the experimental work carried out in the majority of the large scientific institutions of the world. The result of this study together with the results of later work done at the National Bureau of Standards is such that it seems proper to consider that the 5th decimal place has been obtained in the measurement of the ratios between the international and the absolute units. The ratios proposed by the National Bureau of Standards are therefore:

1 mean international ohm = 1.00049 absolute ohms.
1 mean international ampere = 0.99985 absolute ampere.
1 mean international volt = 1.00034 absolute volts.

the 6th decimal being zero.

The National Physical Laboratory declared itself in accord with the proposals of the National Bureau of Standards and merely remarked that it would be preferable not to give the results of the standardization to more than five decimal places and to reserve strictly the use of the 6th decimal to the work of coordination between the national laboratories and their relations with the International Bureau of Weights and Measures.

It is on the basis of the above documents and on the consensus of the replies received from members of the Advisory Committee on electricity, that the International Committee has adopted Resolution 1.

The difference in opinion shown by the Physikalisch-Technische Reichsanstalt has not appeared such as to justify a further delay in the introduction of the absolute units which are so much desired by the electrical workers in the majority of the nations. By force of circumstances, the Physikalisch-Technische Reichsanstalt has not been able to participate in the recent discussions and its objection appears to be the result of a certain doubt on the part of its physicists as to the accuracy which one should attribute to the ratios that appear in Resolution 1. The reply of the Physikalisch-Technische Reichsanstalt expresses the fear that the results stated by the Committee may have too provisional a character and may have to be corrected in the future.

The International Committee points out that in any event the values for the ratios appearing in its Resolution 1 will be applied only on the present occasion. Any work on the absolute units will lead to slight future adjustment of the values assigned to the national standards and to those of the International Bureau. The concept of a ratio between the absolute units and the international units will itself lose all interest in the future with the disappearance of the latter.

XIV. Appendix 7

81st Congress, 1st Session.

S. 441

In the Senate of the United States January 13, 1949

Mr. Johnson of Colorado (by request) introduced the following bill; which was read twice and referred to the Committee on Interstate and Foreign Commerce.

A BILL

To redefine the units and establish the standards of electrical and photometric measurements.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That from and after the date this Act is approved, the legal units of electrical and photometric measurement in the United States of America shall be those defined and established as provided in the following sections.

Sec. 2. The unit of electrical resistance shall be the ohm, which is equal to one thousand million units of resistance of the centimeter-gram-second system of electromagnetic units.

Sec. 3. The unit of electric current shall be the ampere, which is one-tenth of the unit of current of the centimeter-gram-second system of electromagnetic units.

Sec. 4. The unit of electromotive force and of electric potential shall be the volt, which is the electromotive force that, steadily applied to a conductor whose resistance is one ohm, will produce a current of one ampere.

Sec. 5. The unit of electric quantity shall be the coulomb, which is the quantity of electricity transferred by a current of one ampere in one second.

Sec. 6. The unit of electrical capacitance shall be the farad, which is the capacitance of a capacitor that is charged to a potential of one volt by one coulomb of electricity.

Sec. 7. The unit of electrical inductance shall be the henry, which is the inductance in a circuit such that an electromotive force of one volt is induced in the circuit by variation of an inducing current at the rate of one ampere per second.

Sec. 8. The unit of power shall be the watt, which is equal to ten million units of power in the centimeter-gram-second system, and which is the power required to cause an unvarying current of one ampere to flow between points differing in potential by one volt.

Sec. 9. The units of energy shall be (a) the joule, which is equivalent to the energy supplied by a power of one watt operating for one second, and (b) the kilowatt-hour, which is equivalent to the energy supplied by a power of one thousand watts operating for one hour.

Sec. 10. The unit of intensity of light shall be the candle, which is one-sixtieth of the intensity of one square centimeter of a perfect radiator, known as a "black body", when operated at the temperature of freezing platinum.

Sec. 11. The unit of flux of light shall be the lumen, which is the flux in a unit of solid angle from a source of which the intensity is one candle.

Sec. 12. It shall be the duty of the National Bureau of Standards to establish the values of the primary electric and photometric units in absolute measure, and the legal values for these units shall be those represented by, or derived from, national reference standards maintained by the National Bureau of Standards.

Sec. 13. The Act of July 12, 1894 (Public Law Numbered 105, Fifty-third Congress), entitled "An Act to define and establish the units of electrical measure", is hereby repealed.

Washington, March 1, 1949