THE FACILITIES AFFORDED BY THE OFFICE OF STANDARD WEIGHTS AND MEASURES FOR THE VERIFICATION OF ELECTRICAL STANDARDS AND ELECTRICAL MEASURING APPARATUS.

THE need of adequate facilities for the official verification of standards and measuring apparatus of all kinds, has long been recognized by American physicists. The Office of Weights and Measures, with its small force, modest equipment and insufficient appropriations, has endeavored to meet any demands imposed upon it within the limits thus set.

The object of this article is to describe what has thus far been accomplished along electrical lines, and in this connection a brief history of the units of reference may not be considered out of place.

The origin of standards of quantity and value dates back as far as the earliest historical records. The transition from the crude measures of antiquity to the systems meeting present requirements has, however, been exceedingly slow, although the growth of commercial intercourse gradually led to the introduction of more precise standards.

The requirements of accuracy were, nevertheless, quite modest until physics began to emerge from its qualitative stage to assume the dignity of an exact science.

The number and complexity of physical quantities at first led to the adoption of more or less arbitrary standards of reference, often based on the physical properties of some definite substance, *e. g.*, the calorie, and as long as the relations between physical quantities remained obscure, such relative standards sufficed. With the development of the science came the recognition of the desirability of a consistent system of units, which was strongly brought to the front, when it became necessary to measure magnetic quantities.

The happy solution of this problem suggested by Gauss and extended to the measurement of electrical and electro-magnetic quantities by Weber, constituted a great advance in the science of Metrology, the units being defined in terms of the mechanical actions to which they give rise. Since all mechanical units can be expressed in terms of three independent fundamental units, such as those of length, mass and time, the magnetic and electrical units of Gauss and Weber are thus expressible in terms of the same fundamental units and are therefore entirely independent of the physical properties of arbitrarily chosen substances. Hence they are called absolute units, their magnitudes depending solely on the choice of the fundamental units.

The units of length and mass selected were usually multiples or sub-multiples of the corresponding metric units, the metric system being the only one meeting the highest scientific and practical requirements and being already in extensive use. While at first uniformity in the selection of the magnitudes of the fundamental units was lacking, the centimeter, gram and second have now been universally adopted, the derived units being known as C. G. S. units.

Practical measurements of electrical resistance were, however, first referred to a variety of arbitrary standards, *e. g.*, the resistance of a given length of copper or iron wire of given diameter, and so long as electrical measurements were confined to the laboratory, the length referred to was usually a few feet, but with the practical applications of electricity to telegraphy and submarine signaling, this length became inconveniently small and was therefore replaced by fathoms, miles, etc. Fortunately none of these units ever gained general acceptance. In 1848 Jacobi pointed out that it would be far preferable to adopt, as a universal standard, the resistance of a certain piece of wire, copies *having the same resistance* being easily constructed.

Jacobi carried this suggestion into practice by sending a piece of copper wire, since known as 'Jacobi's Étalon' to various physicists for that purpose.

In 1860 Werner von Siemens proposed as a standard of resistance, the resistance, at 0°C., of a column of mercury, 1 sq. mm. in cross section and 100 cm. in length.

In 1861 a committee, composed of the most eminent English physicists was appointed by the British Association to consider the question of Standards of Electrical Resistance. Correspondence was opened with the leading foreign physicists and various special investigations of the problems, with which the committee was confronted, were undertaken by its members.

The first question settled was that the unit of resistance should be defined as a multiple by an integral power of 10 of the unit of Weber's absolute system, and that the unit chosen should be of a convenient magnitude. Accordingly, a unit equivalent to 10^9 C. G. S. units was adopted.

This definition fixed the unit, but the evaluation of a resistance in absolute measure requires the construction of especially designed apparatus, having usually a limited range of usefulness; the determination of instrumental constants, most frequently involving tedious mathematical approximations, and in addition, the observations have to be made with the greatest precision. On the other hand, relative measurements require simpler apparatus and less skill in manipulation, besides being, in most cases, far more accurate than absolute measurements. The construction of material standards adjusted to the specified resistance, determined once for all by a series of absolute measurements, was therefore decided upon.

Investigations were made to determine whether the absolute unit of resistance could be accurately defined in terms of the resistance of a definite portion of a definite substance. Pure metals in the solid and liquid state and alloys were studied with this end in view. On account of the excessive influence on the resistance produced by small quantities of impurities in metals and by small variations in the composition of alloys and on account of the additional difficulty of procuring chemically pure materials, the choice was greatly limited. Moreover solids had to be rejected on account of the marked effect of physical changes produced by drawing, bending, annealing, etc.

Mercury, already recommended by Siemens, was therefore the only material to be further considered. Even this material was rejected, owing to large differences found to exist between coils, supposedly adjusted to agree with different German mercury standards, and the mercury standards constructed by members of the committee.

Having abandoned the above propositions, the alternative remained of constructing material standards adjusted with reference to the absolute unit.

A number of new alloys, in addition to many already in use, were made and investigated. An alloy of 2 parts by weight of silver to 1 part by weight of platinum was finally selected as best meeting all requirements. A special form of resistance standard was also adopted.

In 1863 and 1864 the values of certain coils were determined in absolute units by one of the methods proposed by Weber and from these measurements the B. A. unit was derived. A number of copies were issued gratis by the Association and in addition arrangements were made to furnish others at a moderate price. The B. A. unit soon gained universal acceptance in the English speaking countries, while the Siemens unit still retained its supremacy on the continent.

In 1878 it was shown by Professor Rowland that the B. A. unit differed from its assumed value by more than one per cent. and soon after, this difference was substantiated by a number of other investigators.

In 1881 a call was issued, in connection with the first Paris electrical exhibition, for an international electrical congress for the purpose of adopting definitions of the electrical units to serve as a basis for legislative enactments. Numerous mercury standards had in the meantime been constructed and had been found to agree most satisfactorily with one another; moreover, the results of a considerable proportion of the absolute determinations made had been referred, directly or indirectly, to the Siemens unit. In view of this, the Paris Congress passed a resolution recommending that all absolute determinations in the future be expressed as the resistance of a column of mercury of stated length, 1 sq. mm. in cross section at the temperature of melting ice, and that the C. G. S. electro-magnetic system of units be adopted. The desirability of making new determinations of the ohm was urged.

Three years later the Congress reassembled at Paris and adopted 106 cm. as the length of the specified column of mercury, individual results still differing by as much as $\pm$ .5 per cent. The unit of resistance thus defined was called the legal ohm, but while it was never legalized anywhere, it nevertheless came into extensive use, especially in England and in America.

Absolute methods were gradually improved, sources of error were pointed out, and eliminated as far as possible and accordingly the results of absolute determinations, made by the most radically different methods, became more concordant.

The International Electrical Congress (which met in Chicago in 1893), through its Chamber of Delegates, officially representing all the leading governments, therefore adopted, as the unit of resistance, the mean of all the best determinations, the resistance at 0° C. of a column of mercury 106.3 cm. in length and of uniform cross section having a mass of 14.4521 gm. (equivalent to a cross section of 1 sq. mm., the density of mercury being assumed to be 13.5956). The unit of resistance and the other electrical units defined by the International Congress were legalized in the United States by Act of Congress in 1894, and have also been legalized in the other countries represented.

It was generally supposed that the various governments would sooner or later take up the construction of mercury standards as called for in the definition since each had already been provided by the International Bureau of Weights and Measures with the fundamental standards of mass and length.

The Imperial Physico-Technical Reichsanstalt in Berlin has already begun this task with its characteristic thoroughness. Two one ohm mercurial standards were constructed and later, a third together with a ½ and a two ohm tube. Widely different cross sections were purposely selected to avoid possible sources of error. The calibration and intercomparison of these standards leaves almost nothing to be desired, measurements made by two different methods, both yielding the same results within the limits of experimental error.

Twelve mercury copies were also constructed; these, together with 7 working standards of manganin wire, periodically referred to the primary standards, complete the list.

In England, on the other hand, the B. A. coils have still been retained as primary standards. The legal ohm was defined in that country by the relation, 1 Siemens unit = .9540 B. A. units, and later the International Ohm was defined by the relation, 1 Siemens unit = .95351 B. A. units. According to a comparison made several years ago, 1 Siemens unit, as derived from the Reichsanstalt Standards, is equal to .95341

B. A. units, indicating a change in the coils themselves, or in their assumed relation to the Siemens unit or in both.

Matters have been still further complicated in England by the legalization of the resistance of a coil marked 'Board of Trade Standard verified 1894,' and adjusted with reference to the Cambridge Standards, as the unit of resistance.

A still more radical suggestion was made in that country several years ago, by Professor A. Viriamu Jones and Professor W. E. Ayrton, that each government adopt a Lorenz apparatus from which to derive by absolute measurements the unit of resistance. The practical substitution of an absolute method with its disadvantages as pointed out above, for a purely relative one seems to be taking a step or indeed several steps backward, but may be taken as indicating the lack of confidence in the permanency of the B. A. coils.

After the legalization of the International Electrical Units it became the imperative duty of our government to provide facilities for the official verification of electrical standards and electrical measuring apparatus, especially in view of the continually increasing importance of the applications of electrical energy to the industral arts. This function obviously devolved upon the Office of Standard Weights and Measures, already equipped for the verification of standards of length, mass, capacity, etc.

Owing, however, to the limited force and to the still more limited appropriations available for the purchase of apparatus, practically nothing could be done until July 1, 1897, when the appointment of a verifier was authorized, but unfortunately progress has frequently been interrupted for long periods by the pressure of routine work.

It was determined from the outset that it should be the aim of the Office to provide facilities for measurements to any degree of accuracy likely to be set even by the most exacting demands of modern science. The first steps taken by the Office consisted in working out a general plan and providing the most needed apparatus and facilities.

STANDARDS OF RESISTANCE.

To avoid the delay which would naturally arise from the construction of primary mercury standards, it was decided to refer all measurements of electrical resistance to the mean value of a number of wire coils, known in terms of the best existing mercury standards. The general excellence of coils of the Reichsanstalt type, the extremely small temperature coefficients and thermo-electromotive power with respect to copper of manganin and the permanency of coils of that material as shown by long continued observations at the Reichsanstalt, decided in favor of standards of the above description.

Four unit coils were purchased and were standardized at the Reichsanstalt where they were kept under observation for about one month, during which period they decreased in value by about .0015%. This, according to the maker, is the normal behavior of the material which undergoes, after the artificial aging, a small decrease in resistance followed by a slow increase. In addition to these coils the Office possesses two other coils of the same type purchased several years ago. Periodic intercomparisons between the old coils and the new ones will be made so that any relative changes will be made manifest, the two hardly having the same rate of change. Two new manganin coils have been ordered and are also to be referred to the German Standards. On their receipt, they will furnish us positive evidence in regard to any changes which may have taken place in the preliminary standards adopted. The approximate corrections at any time can then be determined by simple interpolation.

To fix this standard, the construction of a number of mercury copies will also be taken up. The construction of primary mercury standards, which is of fundamental importance, not only from a scientific standpoint but also on account of the legal questions which will surely arise, will be undertaken as soon as time permits.

The Office has acquired in addition to the unit coils, standards of the following denominations:

1	2	Ohm
1	5	"
4	10	"
4	100	"
3	1,000	"
2	10,000	"
2	100,000	"
3	0.1	"
3	0.01	"
3	0.001	"
3	0.0001	"

The temperature coefficients of these coils were first carefully determined, then the coils of the same denomination were intercompared and the observations reduced to differences at 20° C.

The next step consisted in determining the resistance of the multiples and submultiples in terms of the unit. Thus, two unit coils placed in series by means of a connecting link of known resistance were compared with the two ohm coil. The five and ten ohm coils were similarly evaluated in terms of the unit. From the known ratio of a 10 ohm coil to one of the units, the step can be made to the 100 ohm coils by means of a second ten ohm coil also known in terms of the unit. Similarly the values of the coils of still higher value were determined and those of the sub-multiples of the unit, by a slightly modified method.

THE METHOD OF COMPARISON ADOPTED.

The practice in this country and in England has been overwhelmingly in favor of the Carey Foster method, but the construction of the Reichsanstalt standards, with their terminals 16 cm. apart, makes the use of the Carey Foster Bridge almost out of the question. The design of a suitable bridge capable of comparing coils of this type with those having a different distance between the terminals, introduces still further complications. Moreover, in the Carey Foster method, additional resistances are introduced in the mercury cups of the commutator which are only eliminated in a perfect mechanical construction. Besides the resistances connecting the coils to the commutator, unless equal, are *not* eliminated. While the Carey Foster method is at first glance superior in being a zero method, the Wheatstone Kelvin Bridge, more simple and far less expensive in construction, excels the former especially where the intercomparison of low resistance standards is concerned, provided the coils to be compared are first made nearly equal by means of a shunt of known value applied to the greater. The value of the shunt need not even be known to a high degree of accuracy in case of fairly well adjusted coils.

The coils are connected to one another by copper forgings 1.5 cm. thick and 2 cm. wide, having therefore a resistance of about 0.6 micro-ohm per cm. of length, their terminals resting in mercury cups. To permit the comparison of coils differing widely from the standards, provisions have been made to enable one of the coils compared, to be placed in parallel with an accurately known coil by means of a second pair of mercury cups.

The sources of error characteristic of the direct deflection method are due to the following causes:

(1) Variation of E. M. F. of test battery.

(2) Variation of galvanometer sensibility, due either to the variation of proportionality between deflection and current, or to a change in the actual sensibility.

These only affect the deflection corresponding to the unbalanced *differences* in the ratios of the coils intercompared so that even if the errors in interpolation should be relatively large, the error in the ratio will be exceedingly small. With the ratios adjusted by means of shunts to within $\frac{100}{1000000}$ of equality an error of 1%, 5 to 10 times that actually existing, would produce an error of one part in 1,000,000 in the calculated ratio of the coils compared.

The Wheatstone-Kelvin bridge entirely eliminates the resistance of the parts connecting the lower mercury cups of these coils by means of shunting a second ratio coil across the resistance to be eliminated, the battery contact being transferred to its middle point. The inequality of the two halves of the ratio coil is eliminated by its reversal. The remaining sources of error are possible variable contact resistances in the mercury cups and possible differences in the insulation resistances between them. The bottoms of the cups are accurately surfaced and these sources of error are shown to have no importance by interchanging the positions of the two coils compared. Thermo-electromotive forces are eliminated by battery reversal. The heating effect of the test current was shown to be quite negligible, less than $\frac{1}{100000000}$ for a current of .03 ampere for one ohm manganin coils, since a current of 1 ampere through such a coil produces a heating of the coil above the temperature of the petroleum bath in which the comparisons are made, of approximately 1° C.

A specimen of the results which may be obtained under rather unfavorable conditions is given below. Four one ohm coils were intercompared in the 6 possible combinations, 6 additional measurements being made with the left and right coils interchanged with the following results:

L R	Observed Differences.	Cal. Diff.	Residuals Obs.-Cal.
1402—1403	$= -3.8 \times 10^{-6}$ ohm	—3.8	0.0
R L			—0.1
1402—1403	= —3.9		
L R			
1402—1404	= —4.6	—3.7	—0.9
R L			
1402—1404	= —2.8		+0.9
L R			
1402—1405	= —0.8	—0.8	0.0
R L			
1402—1405	= —1.0		—0.2
L R			
1403—1404	= +0.2	—0.2	+0.4
R L			
1403—1404	= —0.6		—0.4
L R			
1403—1405	= +3.4	+3.0	+0.4
R L			
1403—1405	= +2.5		—0.5
L R			
1404—1405	= +3.4	+3.2	+0.2
R L			
1404—1405	= +3.0		—0.2

Since resistance comparisons can be made to such a very high order of accuracy, to within $\frac{1}{500}$% at least, even in the case of properly designed .0001 ohm standards, all interested may assure themselves that every effort will be made by the Office to provide itself with primary standards of reference meeting the highest scientific requirements.

STANDARDS OF ELECTRO-MOTIVE FORCE.

The unit of electro-motive force, the volt, is legally defined as $\frac{1000}{1434}$ of the electromotive force of a Clark Standard cell at 15° C.

The official standards of electro-motive force for a government should obviously be, as far as possible, independent of any error due to impurities of the chemicals used. A large number of cells were set up with the purest commercially obtainable materials, from a number of independent sources. The work of purifying these materials by special methods was begun. Cells have also been set up with some of the purified materials, though much still remains to be done.

The intercomparisons so far made indicate a most satisfactory agreement of all the cells on hand, well within $\pm\frac{1}{200}\%$. The mean electro-motive force of the three dozen or more cells furnishes therefore a standard of reference which may be relied on within this limit. In addition to the Clark cells, a number of Cadmium cells, having considerable advantages over Clark cells, have been set up, but owing to lack of time no comparisons have as yet been made. New cells of both types are to be added from time to time, and intercompared with the old ones to determine whether any observable changes have taken place.

The relation which the E. M. F. of the Clark cell bears to that of the Cadmium cell will also be periodically determined, furnishing an additional check on the constancy of the standards of both types.

With an accurately calibrated potentiometer, and reliable standards of electromotive force the office is thus prepared to undertake the verification of direct current volt-meters and millivolt-meters.

MEASUREMENT OF ELECTRIC CURRENTS.

A grave mistake was made by the International Congress in concretely defining all three of the principal electrical units, the ohm, volt and ampere, which are necessarily connected by the fixed relation $C = \frac{E}{R}$. Hence only two of the definitions are independent, the chances being infinitesimal that the three definitions satisfy the relation between them on account of the relatively large errors in the absolute determinations on which they are based. Indeed, it already seems that the volt, as defined in terms of the Clark cell is in error by almost .1%.

Since the standards of resistance and electromotive force, as specified by the International Congress, are certainly reproducible within $\frac{1}{100}\%$, the unit of current intensity, defined as the current which will flow through a conductor of unit resistance, there being unit difference of potential between its terminals, would be fixed within the same limits of error.

Instead, it is defined in terms of the electro-chemical equivalent of silver. The voltametric measurement of a current is limited by the size of the apparatus available and is besides impossible under ordinary circumstances with the above accuracy.

Lord Rayleigh is of the opinion that his determination of the electro-chemical equivalent of silver may be in error by as much as $\frac{1}{10}\%$.

Retaining for the present the legal definitions of the ohm and volt, currents may be consistently measured by the fall in potential or potentiometer method, in terms of the specified standards of reference.

It is proposed to base all direct current measurements on these principles. With suitable low resistance standards for the measurement of heavy currents and with the set of Clark cells already on hand, the Office is prepared to undertake the verification of direct current ammeters within the limits practically set by the current generating apparatus on hand.

To summarize, the Office is therefore practically equipped for the verification of following classes of apparatus, viz:

Resistance Standards.—Coil of the following denominations: 1, 2, 5, 10, 100, 1000, 10,000 ohms.

Low Resistance Standards for current measurements of the following denominations: 0.1, 0.01, 0.001 and 0.0001 ohms.

Resistance boxes.

Potentiometers.

Ratio coils.

Standards of Electro-motive Force.—Clark standard cells and other standard cells.

Direct Current Measuring Apparatus. Millivoltmeters and voltmeters up to 150 volts.

Ammeters up to 50 amperes.

For the verification of direct current measuring apparatus of even moderate range, the present facilities of the Office are entirely inadequate, although now-a-days potential differences up to 20,000 volts and currents of 20,000 amperes are met with in actual practice.

Provision must also be made for the calibration of Wattmeters and Energy meters.

The verification of alternating current measuring apparatus requires further facilities, and in view of the ever increasing importance of alternating current systems, such facilities should be provided without delay.

The verification of Condensers and Self Induction Standards also merits attention.

Another question, practically related to electrical measurements, is the photometry of arc and incandescent lamps.

Preliminary steps have already been taken by the American Institute of Electrical Engineers, looking forward to the coöperation of the office in the official verification of incandescent lamps as secondary photometric standards to enable even the moderate consumer to procure reliable standards at a reasonable rate.

The measurement of high and low temperatures will also be taken up, a knowledge of the exact thermal conditions under which certain industrial operations are conducted being of the utmost practical consequence.

There are two most reliable electrical methods based respectively on the variations of electrical resistance and of thermo-electromotive force with the temperature. Hence, with standards of electromotive force and resistance available, this subject is brought within easy reach.

No claim of originality is made in what has been accomplished. The magnificent work of the Physico-technical Reichsanstalt at Berlin with its staff of scientific and technical assistants and in its almost unlimited resources has been of the greatest help. It has set such a high standard of excellence that it will require years for similar bureaus, which will surely be organized by other governments, to attain.

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U. S. Office of Standard Weights and Measures.

THE ESTABLISHMENT OF A NATIONAL UNIVERSITY.*

The sub-committee appointed November 3, 1899, beg leave to submit the following report:

The resolution of reference to the sub-committee was as follows:

"That a sub-committee be requested to prepare for consideration by the full committee a detailed plan by which students who have taken a baccalaureate degree, or who have had an equivalent training, may have full and systematic advantage of the opportunities for advanced instruction and research which are now or may hereafter be offered by the Government; such a plan to include the coöperation with the Smithsonian Institution of the universities willing to accept a share of the responsibility incident thereto.

"It is understood that the financial administration of this plan should be such that whether or not Government aid be given, there shall be no discouragement of private gifts or bequests.

"It is understood that the scope of this plan should be indicated by the governmental collections and establishments which are now available, or as they may hereafter be increased or developed by the Government for its own purposes."

The undersigned members of the sub-committee have been in active correspondence and conference on the matters referred to them. They have made several visits to Washington, and have had the advantage of hearing the views of representative Regents of the Smithsonian Institution and those of the directors of the scientific bureaus of the Government. In particular, they have profited by consultations with representatives of the American Association of Agricultural Colleges and

*Report of the sub-committee appointed November 3, 1899, to the Committee of the National Educational Association, appointed July 7, 1898, to investigate the entire subject of the establishment of a National University.