THE PRINCIPLES INVOLVED IN THE SELECTION AND DEFINITION OF THE FUNDAMENTAL ELECTRICAL UNITS TO BE PROPOSED FOR INTERNATIONAL ADOPTION.*

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INTRODUCTION.

In a paper presented to the International Electrical Congress at St. Louis in 1904,[1] the writer reviewed the efforts which had previously been made to secure international uniformity of the electrical units, and pointed out their failure as shown by the discrepancies in the laws thus far enacted.

These efforts practically begin with the Siemens unit and the C. G. S. system of the British Association, of which the practical unit of resistance, intended to represent 10^9 electro-magnetic units, took a concrete form.

As pointed out in the paper referred to, the error found in the B. A. unit led to the convocation of the first International Electrical Congress in 1881, which recommended that the practical electrical units be defined in terms of the C. G. S. (electro-magnetic) units, and that the unit of resistance be represented by a column of mercury 1 sq mm in cross section, at the temperature of 0° C and of a length to be determined by an international commission on the basis of new absolute measurements.

* Paper read before the American Physical Society April 25, 1908, and before the American Electrochemical Society April 30, 1908.

[1] Transactions St. Louis Int. Elec. Cong., 1, 148; 1904. This Bulletin, 1, 39; 1904.

In accordance with the above, the International Commission, which met in Paris in 1882 and 1884, recommended the following definitions:

The legal ohm is the resistance of a column of mercury 1 square millimeter in cross section and 106 centimeters in length at the temperature of melting ice.

The ampere is equal to one-tenth of a C. G. S. unit of the electro-magnetic system.

The volt is the electromotive force which will maintain a current of 1 ampere in a conductor of which the resistance is a legal ohm.

It will thus be seen that a distinction was made between the concrete and the absolute ohm. The ampere was defined in terms of absolute units, while the unit of electro-motive force was derived from a concrete unit of resistance and an absolute unit of current.

The last formal international action was taken by the Chicago Congress of 1893, which adopted the following definitions:

"*Resolved*, That the several governments represented by the delegates of this International Congress of Electricians be, and they are hereby, recommended to formally adopt as legal units of electrical measure the following:

"As a unit of resistance, the *international ohm*, which is based upon the ohm equal to 10^9 units of resistance of the C. G. S. 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, 14.4521 grammes in mass, of a constant cross-sectional area and of the length of 106.3 centimeters.

"As a unit of current, the *international ampere*, which is one-tenth of the unit of current of the C. G. S. system of electro-magnetic units, and which is represented sufficiently well for practical use by the unvarying current which, when passed through a solution of nitrate of silver, and in accordance with the accompanying specifications, deposits silver at the rate of 0.001118 of a gramme per second.

"As a unit of electromotive force, the *international volt*, which is the electromotive force that, steadily applied to a conductor

whose resistance is 1 international ohm, will produce a current of 1 international ampere, and which is represented sufficiently well for practical use by 1000/1434 of the electromotive force between the poles or electrodes of the voltaic cell known as the Clark cell, at a temperature of 15° C, and prepared in the manner described in the accompanying specifications."

The disagreement of the laws defining the units subsequently enacted by the various countries may be traced to the following causes:

First. The three fundamental units, although connected by Ohm's law, were either directly or indirectly defined in terms of concrete standards, naturally resulting in inconsistencies in the definitions, which by new measurements of the value of the Clark cell were shown to be almost one-tenth per cent.

Second. The specifications were not sufficiently definite, thus limiting the accuracy of reproduction.

Third. The *international* units were not recognized as separate and distinct from the *absolute* units on which they were based.

As some of the laws were enacted before and some after the inconsistencies in the definitions were recognized, considerable differences resulted, a subject fully discussed in the paper above referred to. For our present purpose it need only be recalled that in some cases the same unit was defined effectively in as many as three or four different ways in the same law. Official international recognition of the discrepancies between the laws was taken by the St. Louis Congress, which adopted resolutions to the effect that the questions could best be dealt with by an international commission representing the governments concerned, that such a commission might in the first instance be appointed by those countries in which legislation on electric units had been adopted, and that provision should be made for securing the adhesion of other countries prepared to adopt the conclusions of the commission. The hope was expressed that the commission referred to might eventually become a permanent one.

In accordance with the provisions of the above resolution, invitations were extended to England, France, Austria, Belgium, and the United States, by Professor Warburg, president of the

Reichsanstalt, on behalf of Germany, for a conference which was held in Berlin in October, 1905. The decisions reached by the Berlin Conference[2] were as follows:

(1) That only two electrical units shall be chosen as fundamental units.

(2) The international ohm, defined by the resistance of a column of mercury, and the international ampere, defined by the deposition of silver, are to be taken as the fundamental electrical units.

(3) The international volt is the electromotive force which produces an electric current of 1 international ampere in a conductor whose resistance is 1 international ohm.

Recommendations were also made that more detailed specifications be adopted for the mercury ohm, and that the Weston cadmium cell with solid hydrated cadmium sulphate and a 12 to 13 per cent cadmium amalgam be adopted as the standard cell.

The opinions were further expressed by the conference:

"(1) That the information before it is not sufficient to enable it to propose any alteration in the formerly accepted value for the ampere.

"(2) That the information before it is not sufficient to enable it to lay down exact directions in respect to the silver voltameter and the standard cell.

"(3) That if a proposal for a change in the accepted value of the ampere is to be brought from any source before a formal conference to be held later, an agreement in writing on the point should be come to previously between the parties interested. If differences of opinion in the matter can not be removed, a new preliminary conference should be held. The same procedure should be observed in regard to the specifications for the silver voltameter and the standard cell, in the event of such specifications being submitted to a formal conference from any quarter."

The recommendations made at the conference by Professor Carhart and by the Bureau of Standards, that the volt be selected as the second fundamental unit were rejected, as were also the

[2] Verh. Int. Konf. Elektr. Masseinheiten, p. 42.

recommendations of the Bureau advocating a systematic program of absolute measurements before the next International Electrical Congress was called.

The conclusions reached by the Berlin Conference should be regarded as preliminary in view of the fact that considerable work has since been done on both the standard cell and coulometer, particularly as the conference expressed the opinion[3] that the information before it was not then sufficient to enable it to lay down exact directions with respect to the silver voltameter and the standard cell.

The questions likely to be considered by the next International Congress, for which it is proposed to issue a call in the near future, are as follows:

(1) The selection of the two units to be taken as fundamental, and in terms of which all the others will be derived.

(2) The adoption of specifications for the units selected.

(3) The adoption of numerical values in the definitions of the fundamental units.

(4) The definition of the remaining international electrical units in terms of the two taken as fundamental.

(5) The definition and naming of the international magnetic units.

(6) The discussion of international photometric standards.

Of these, the last two topics will not be discussed in this paper.

THE CHOICE OF FUNDAMENTAL UNITS.

As it is universally agreed that the ohm be taken as one of the two fundamental units, the question is reduced to the choice between the ampere and the volt, defined respectively in terms of the coulometer and standard cell, as the second unit.

In the opinion of the writer[4] it would be well, before a final decision is made, to consider fully the principles involved in the choice, which should, of course, be made on the basis of merit and without prejudice or undue deference to previous practice.

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[3] Verh. Int Konf. Elek. Masseinh., p. 50.

[4] Wolff, loc. cit., pp. 50–59.

Arranged in the order of their importance, these are:

(1) Accuracy of Reproduction from Specifications.
(2) Concreteness.
(3) Ease of Reproduction.

1. ACCURACY OF REPRODUCTION.

The factors determining the accuracy of reproduction in the case of the coulometer and the standard cell may be stated to be: (*a*) The nature of the fundamental principle underlying the definition; (*b*) the purity of the materials employed; (*c*) the number of measurements involved in the realization of the definition.

(*a*) The preference heretofore generally given to the coulometer can be attributed in part to the fact that its indications are assumed to be exact, being based on Faraday's law, generally regarded as a fundamental law of nature. The more recent work[5] on the coulometer seems, however, to establish the conclusion that while Faraday's law may be rigorously exact, account must certainly be taken of the possible effect of secondary reactions accompanying the electrolysis, thus complicating the results as shown by the differences obtainable in the use of coulometers of different types. On the other hand Smith[6] obtained "identical values within one or two parts in 100,000 for the electrochemical equivalent of silver for six different types" and "no influence of pressure, temperature or current density." Dushak and Hulett[7] have, however, recently found for the porous cup type a difference of almost 0.01 per cent between the deposits formed in the presence and absence of air. The difference was further established by an analysis of the deposited silver, which on heating gave up water and gas. Dushak and Hulett state that "the idea of the included matter being other than trapped electrolyte finds support, first in the constancy of the quantity of impurity in deposits formed under the same conditions, and

[5] Richards, Collins and Heimrod, Proc. Amer. Acad., **35**, p. 123; 1900. **37**, p. 415, 1902. Zs. Phys. Chem., **32**, p. 321; 1900. **41**, p. 302; 1902.
Guthe, Phys. Rev., **19**, p. 138; 1904. This Bulletin, **1**, p. 21 and p. 349; 1904–5.
Carhart, Willard and Henderson, Trans. Amer. Electrochem. Soc., **9**, p. 375; 1906.
Van Dijk, Ann. Phys., **19**, p. 249; 1906.

[6] Phil. Trans. Roy. Soc., **207**, 581; 1908.

[7] Dushak and Hulett, Trans. Amer. Electrochem. Soc., **12**, p. 257; 1908.

second, in its apparent uniform distribution throughout the silver crystals." The writer, while disclaiming any intention of discrediting the work of any of the investigators, simply desires to call especial attention to the discrepancies in their results, which indicate that either the same procedure has not been followed by all, or that unrecognized sources of variation exist. It can not, therefore, be regarded as established that the *increase of weight* in the coulometer is in strict accordance with Faraday's law.

The principle underlying the definition of the volt is equally fundamental, though not capable of expression in as simple a form as Faraday's law, since electrode potentials are determined solely by the nature, concentration, and temperature of the materials involved. In reversible cells these are not changed by the passage of small currents in either direction.

The formula which expresses the relation and which was first deduced by Helmholtz from thermodynamical principles, may be put in the form

$$Q = Ct\left(E - T\frac{dE}{dT}\right)$$

in which Q represents the *total* energy of the reaction, including that set free or absorbed in solution, hydration, change of state, etc., E the electromotive force, T the absolute temperature and Ct the number of coulombs corresponding to the reaction. It follows, therefore, that if, for the particular reaction, there is a constant relation between the number of coulombs and the total energy per gram molecule, as well as a constant relation between the free and total energy, the electromotive force must have a definite value for given external conditions.

Since the first condition does not involve any assumptions as to the simplicity or complexity of the ions, or even as to the nature of electrolysis, and since the second must be granted as being based on the fundamental principles of thermodynamics, it will be seen that the electromotive force of a reversible voltaic combination follows a law quite as rigorous as that of Faraday. In case of the silver coulometer, secondary prdoucts, the electrolysis of which would modify the result, may be formed, but in

the case of the standard cell no secondary reactions of this kind need be considered as the electromotive force of the cell is always compensated, so that there is only a negligible amount of electrolysis produced. Reactions may, however, take place between the ingredients in the cell which give rise to secondary products affecting the electromotive force, but as both Clark and Weston cells can be constructed which will maintain their values for considerable periods, such reactions are either absent or take place very slowly, so that they need not be considered in discussing the accuracy of reproduction. The question of constancy will be taken up under the next heading.

(*b*) The question of the purity of the materials employed is most important in both cases, with the advantage resting slightly with the silver coulometer, as the number of materials is less. On the one side it is necessary to start with pure silver and silver nitrate, while on the other hand pure cadmium and cadmium sulphate (or zinc and zinc sulphate), together with mercury and mercurous sulphate, are required. It will be generally admitted that the metals, silver, cadmium, zinc, and mercury can readily be prepared in the highest state of purity, as also the silver nitrate and zinc and cadmium sulphate. The recent work on the standard cell has demonstrated that mercurous sulphate of uniform electromotive properties can also be obtained by a number of different methods, so that it might be considered that there is little choice on the basis of the number of materials entering into the coulometer and cell. The question of the purity can, however, almost be eliminated if arrangements be made by the national standardizing laboratories to furnish the necessary materials, which can be prepared in considerable quantities by the best methods, so that this would not have to be done by each investigator

(*c*) The greater number of materials required in the cell is more than offset on the other hand by the number of measurements, each subject to possible error, which must be made in the case of the coulometer to realize the ampere from its definition. The cell automatically takes a value determined by the materials employed, while the results of a coulometer measurement depend on two washings and subsequent weighings made with the greatest

quantitative care (particularly the last on account of the granular and loosely adherent character of the deposited silver), the regulation of the current during the run, as well as an accurate measurement of its duration.

The author wishes to lay particular stress on the fact that while standard cells set up by different individuals in different laboratories have been compared in order to establish the accuracy of reproduction, the corresponding step has not as yet been taken with reference to coulometer measurements, so that the results obtained by different investigators only establish relative reproducibility. The indirect comparison is now possible, owing to the progress made in the construction of standard cells and standard resistances which may be carried from place to place, and through which alone the results of coulometer measurements made in different localities can be accurately compared. Before making a final choice, the relative merits of the cell and coulometer with respect to accuracy of reproduction should, however, be definitely established by a systematic campaign of international cooperation involving the exchange of specifications and materials by the various national laboratories, each of which would undertake to make a careful series of coulometer measurements and to set up a considerable number of cells in accordance with the various specifications proposed. The value of the results obtainable can be further increased by the cooperation of the national bureaus with qualified individuals in the respective countries. All the results could subsequently be reduced to a common basis of comparison through the interchange of resistance standards and standard cells.

2. CONCRETENESS.

Another most important consideration is that the definitions of the units adopted as fundamental should both be capable of realization in the form of concrete standards. This makes possible the construction of standards which will maintain their values for considerable periods at least, and in terms of which measurements can, at all times, be made. It also makes possible the direct intercomparison of the concrete standards of the various laboratories by the exchange of standards designed for portability.

In this respect the standard cell has, perhaps, its greatest advantage over the silver coulometer, which merely gives the average value of a current which has been passed through it, and which has ceased to exist. The result of the measurement is, therefore, a silver deposit, and not a standard in terms of which other current measurements can be made, making it necessary to employ a standard resistance and a standard cell as secondary units to fix the results. Both the secondaries must be assumed to remain constant between coulometer measurements which are ordinarily made at long intervals. The more recent work has shown that both Clark and Weston cells can be set up which will maintain their values, within one part in 100,000, for considerable periods, and that when properly set up they will assume their normal values immediately. It is true, however, that some Weston cells have been under observation which have decreased in voltage with time. Hulett attributes this to an unstable equilibrium in the paste limb, but this can not be regarded as established, as the effect may possibly be due to imperfect washing of the mercurous sulphate prepared in strongly acid solutions, or to traces of impurities in the materials employed. A number of cells with abnormal values have been under observation at the Bureau for some time, and were included with others in a redetermination of the temperature coefficient, in the course of which it was found that they exhibited enormous hysteresis. As the mercurous sulphate was originally present in considerable excess, it seems that the retardation of the establishment of concentration equilibrium may be due to the formation of a difficultly soluble surface film. It is hoped that an analysis of the materials, which will shortly be undertaken, will definitely establish the cause of the abnormal behavior. Even though the Weston cell should be found to represent a system in unstable equilibrium, and should be rejected, the Clark cell, in which no abnormal behavior has thus far been observed, would still be available as the concrete standard of electro-motive force. The cracking at the amalgam limb can be overcome by suitable construction, and the objections on account of the high temperature coefficient can be practically eliminated by the employment of thermostats. With the attributes of *constancy* as well as *reproducibility* established, the standard cell would

have greater merit than the mercury ohm, since the mean value of a number of fillings is always taken in order to eliminate errors of filling, and since in the interval between mercury ohm measurements the results are usually carried by manganin copies and not by the primary standards.

3. EASE OF REPRODUCTION.

In respect to ease of reproduction the standard cell again has the advantage. In the first place the facilities required for a coulometer measurement, consisting of a precision balance, calibrated weights, platinum bowls, accurate time service, and means for accurately measuring the duration of a run, together with a supply of purified silver and silver nitrate, are to be compared with the necessary cell blanks, and a supply of specially prepared or purified cell materials. For results of the highest precision the balance must, in addition, be especially protected from temperature changes, and provision must be made for controlling the humidity in the balance case.

In the case of the coulometer the operations consist in washing, drying, and weighing the cathode dish before and after receiving its deposit, in maintaining the current at a constant value during the run, and in the measurement of the duration of the run, all of which operations and measurements must be performed with the highest quantitative care, while the operations involved in setting up a standard cell require only care in washing the mercurous sulphate, since relatively large variations in the composition of the amalgam only slightly affect the electromotive force.

Although the time required for setting up a few cells might be greater than that required for a corresponding number of coulometer measurements, if the time for purifying the materials were included, it must be remembered the latter could be prepared in considerable quantity and preserved under proper conditions for future use. This could also be undertaken by the national laboratories from which investigators could obtain them from time to time. The main conclusion under this head is, therefore, that while in the case of the coulometer special facilities are required and numerous *quantitative* measurements and manipulations must be made in order to make a single current measurement, the

manipulations required in setting up a standard cell are all *qualitative* and less in number, so that, without special facilities and in the hands of individuals of equal skill, a higher accuracy or reproduction should be obtained.

The question of ease of reproduction, while not of the highest importance, should nevertheless be considered from the standpoint of all who deal with electrical measurements of precision and who should not be compelled to depend any more than necessary on the national laboratory. It has, however, been held that facility of reproduction is no great advantage, since similar experimental difficulties result from the definition of the ohm in terms of the mercury column. With the ampere taken as the second fundamental unit the construction of mercury ohms and coulometer measurements would infrequently be undertaken, mainly by the national laboratories. In this case it is necessary to resort to wire copies of the mercury ohm on the one hand and standard cells on the other, each regarded as secondary.[8]

The case appears to be, however, very different, as in the definition of unit resistance in terms of the mercury column we are left without any satisfactory alternative, so that we are forced to resort to secondary standards, multiples and submultiples of which can readily be constructed and compared. On the other hand, we might select either the coulometer or the standard cell as the second fundamental unit. In the first case the result can only be fixed by the aid of some current measuring device, the best of which have a limited accuracy, or, as is usually done, by the combination of a standard resistance and a standard cell, the latter being taken as the secondary standard. In the second case the cell is taken directly as a fundamental standard. It will, therefore, be seen that the standard cell, which itself satisfies the requirements of a fundamental standard as well as the mercury ohm, should not be regarded in the same light as wire copies of the latter which can not be reproduced from specifications.

The question of choice should also be regarded from the standpoint of the national standardizing institution. As the selection of the ohm and ampere necessitates the adoption of the standard

[8] Mitth. Reichsanstalt, E. T. Z. **25**, 671; 1904.

cell as a secondary unit to fix results in the interval between coulometer measurements, the value to be taken for the cell will involve the errors introduced in the reproduction of the mercury ohm as well as those involved in the coulometer measurements, so that unless these together are less than the differences met with from time to time in setting up standard cells directly from the specifications or from materials drawn from the same source, the question would certainly arise as to whether the value to be adopted for the cell should be changed to correspond with each reference to the mercury ohm and coulometer, or whether weight should be given to previous results in the face of a possibly more accurate agreement between old cells and cells freshly set up. In this connection attention should be called to the practice in Germany, where the ohm and ampere are taken as fundamental units. In 1896 and 1898 two series of coulometer measurements were made to determine the values of the Clark and Weston standard cells. The results,[9] which differed by over 0.02 per cent from the directly determined ratio, were adjusted and the values of the Clark and Weston cells thus derived have been in use ever since in Germany. In effect the standard cell has been employed as a fundamental standard, since, by ignoring the definition of the ampere, the result obtained is equivalent to legalizng the values found for the standard cells.

Further light is thrown on this phase of the question by the practice at the Reichsanstalt in reference to the unit of resistance; four manganin standards have been referred, from time to time, to the mercury units of that institution,[10] but since 1898 the mean value of the four coils has been assumed constant, as the apparent changes of the mean were found to be within the limits of accuracy with which the mercury ohms could be reproduced. It is therefore confidently predicted that the standard cell, which must be depended on between coulometer measurements, will, even if the ohm and ampere are taken as fundamental units, in effect

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[9] Kahle, Zs. Instkn. **18**, p. 229 and p. 267; 1898.
Wied. Ann., **67**, p. 1; 1899.

[10] Ber. Int. Konf., 1905, p. 63.
Zs. Instkn., **26**, p. 15; 1906

replace the coulometer, unless the accuracy attainable through the ohm and ampere is found to exceed the accuracy with which the cell can be reproduced.

This is a point of considerable importance from the standpoint of the standardizing institution, on account of the fact that standard cells and not coulometers are submitted for certification, making it necessary to adopt values for the reference cells in terms of which results are expressed.

Moreover, since in actual practice, instantaneous values of currents and voltages of any magnitude are measured with the greatest ease and accuracy directly in terms of resistance standards and standard cells, the choice of the ohm and volt as fundamental units is the more logical.

SPECIFICATIONS.

In reference to the adoption of specifications for the units chosen, attention has already been called to the opinion expressed at the Charlottenburg Conference to the effect that the information before it was not regarded as sufficient to enable it to lay down exact directions with respect to either the silver voltameter or the standard cell. Considerable work has since been done along both lines, but no systematic comparison has been made of the specifications proposed by the various investigators. As the principal object of the next congress will be to redefine the international units in terms of concrete standards reproducible to the highest attainable accuracy from specifications, the latter must be drawn with the greatest care. The various specifications proposed, which differ in regard to details, should therefore be carefully subjected to comparison by numerous investigators, so that any unrecognized defects might be brought to light. It is felt that this would be one of the important objects of the international cooperation above proposed, since, by the aid of the national laboratories, all results could be reduced to the same basis of comparison, and differences which might be found and which might furnish a clue to defects in the specifications could be further investigated.

VALUES TO BE ADOPTED FOR THE UNITS.

In the first place it is necessary to recognize that the C. G. S. system, while giving us *ideally* perfect definitions of the electrical units, fails in practice owing to the necessarily limited accuracy of the absolute measurements in comparison with the precision attainable in relative measurements. The desirability of referring results to concrete standards was recognized by the British Association in the proposal of the B. A. unit of resistance, intended and for some time supposed to represent 10^9 C. G. S. electro-magnetic units. With the advances made in the construction of the mercurial resistance standard, the first Paris Congress recommended its adoption for defining the unit of resistance, notwithstanding the great improvements made up to that time in absolute measurements, the choice being made on the basis of accuracy of reproduction of the results. This was also the principle guiding the Chicago Congress in substituting for the mean cross section of the mercury column, the mass of mercury corresponding to a stated length, following the already established practice of employing the liter instead of the cubic decimeter for volumetric work. As all resistance measurements are now referred to the mercurial unit without reference to its relation to the absolute ohm, this should also be done with the second fundamental unit. In other words, the absolute and international units should be recognized as separate and distinct, so that in the definition of the latter no reference need be made to the former. The particular values adopted in the definitions of the international units should, however, be selected to secure approximate agreement with the absolute units which they will replace for all practical as well as scientific purposes. The few measurements which it is occasionally necessary to express in absolute units could be reduced to the same by applying a correction factor obtained from the results of the various absolute measurements, all in turn fixed by being expressed in terms of the reproducible concrete standards employed to define the international units.

As the values adopted by the next conference should be allowed to stand for at least twenty-five years, to limit the confusion naturally involved in any change of the basis of reference, it

seems desirable before making a decision as to the numerical values to await the results of further absolute measurements, a number of which are already under way, since with the great advances made within the last ten years in absolute measurements it might confidently be expected to keep the errors within 0.01 per cent, thus making the difference between the absolute and international units practically negligible. With this degree of approximation the numerical values employed in the definitions could be allowed to stand indefinitely until some better method of defining the units is recognized.

The writer expressed himself on this subject at the St. Louis Congress, and found opposition to the plan, particularly on the part of some of the foreign representatives, who strongly advocated adherence to the absolute units, though recognizing the necessity of concrete standards the values of which it was proposed to alter from time to time to bring them into better accord with the latest absolute measurements. The objection of confusion as to the basis of reference in the literature has already been pointed out above. In addition, unless the question were regulated by an international commission, each national laboratory would be inclined to give greater weight to its own absolute measurements, thus defeating the aim of international uniformity. The better way would be to consider the international units as fixed for a definite period, and the relation between these and the corresponding absolute units could be reported on from time to time by an international commission in the light of all the data before it.

This should dispose of the argument in favor of the coulometer, to which considerable weight seems to have been attached, that a current can be directly measured in terms of the absolute units, whereas the unit of electromotive force must be derived from the absolute measurement of resistance and current. The definition of the ampere in terms of some specific value taken as the electro-chemical equivalent of silver would, with the unit of resistance fixed, result in fixing the value of the standard cell within the limits of error involved. The numerical value for the cell would, however, be exactly the same if derived from the

same absolute current and resistance measurements on which the definitions of the international ohm and ampere are based.

It has also been claimed that the choice of the volt as a second fundamental unit would result in the ohm entering twice into the derivation of unit current. It is, however, evident that this is not the case so long as the unit of resistance, from which the value of the cell is initially determined, remains constant. This makes the question raised an academic one, since in practice all current measurements are directly referred to a standard cell and a standard resistance.

DERIVED UNITS.

It will be generally agreed that the remaining units, capacity, inductance, magnetic flux, power, energy, etc., should all be defined in terms of the definitions adopted for the fundamental units, notwithstanding that they are now defined in terms of the C. G. S. system, as a distinction can be made by designating the units thus defined as international. If the values adopted for the international units agree with the absolute units, upon which they are based, to within even one part in 2000, as will certainly be the case, no serious objections can be made, as the replacement of the absolute units will be fully justified by the greater accuracy of reproduction made possible.

SUMMARY OF CONCLUSIONS.

(1) The decisions of the Berlin Conference of 1905 should not be regarded as binding in view of the large amount of work since published on the silver coulometer and standard cell.

(2) The international electrical units to be adopted should be regarded as separate and distinct from the absolute units on which they were originally based.

(3) The choice between the ampere and the volt should be made exclusively on the basis of merit.

(4) The principles on which the decision should be made are—

(*a*) Accuracy of reproduction from specifications.

(*b*) Concreteness.

(*c*) Ease of reproduction.

(5) The accuracy of reproduction of the coulometer remains to be established, as coulometer measurements made by different

investigators establish only relative accuracy, no accurate comparisons of the results obtained by different investigators having thus far been made.

(6) If a decision must be made at the present time and on the basis of merit, the cell should be selected on account of the advantages it offers from the standpoint of concreteness and ease of reproduction, since no greater accuracy of reproduction can be claimed for the coulometer in the light of the data at hand. In addition this choice is more logical from the standpoint of the standardizing laboratory, as it leads to fundamental units corresponding to the standards submitted for certification as well as corresponding to the practice of measuring currents in terms of standards of resistance and electromotive force.

(7) In view of the preference indicated for the coulometer at the Berlin Conference, the reproducibility of the cell and coulometer should, however, first be definitely established by systematic international cooperation, which would also result in bringing to light unrecognized defects in the specifications proposed.

(8) If the ampere is defined in terms of the coulometer the value to be taken for the standard cell, which must be depended on between coulometer measurements, must be determined at each of the national standardizing institutions, the results obtained reduced to a common basis by exchange of cells and resistance standards, and a mean value taken to insure international uniformity.

Unless the accuracy of the result, involving errors in the realization of both the ohm and ampere, is greater than that attainable in the reproduction of the cell from specifications the definition of the ampere will subsequently be ignored, making the cell in effect a primary standard. The same result can be more directly obtained by selecting the volt as the second fundamental unit, since a practically equivalent value may be assigned to the cell, in which case the corresponding value for the electro-chemical equivalent of silver need not be known to the highest accuracy, as it could only be used for the purpose of loosely defining the ampere.

WASHINGTON, September 3, 1908.