DEPARTMENT OF COMMERCE AND LABOR

CIRCULAR

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 21

PRECISION MEASUREMENTS OF RESISTANCE AND ELECTROMOTIVE FORCE

[1st Edition]
Issued March 1, 1910

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CONTENTS

1. INTRODUCTION

This circular relates to those tests made by the Bureau involving only the precise measurement of resistance and electromotive force. It supersedes the corresponding section of Circular No. 6 (second edition, issued February 20, 1906). The regulations and fees herein given will be put into effect March 1, 1910. Regulations regarding other electrical tests are given in other numbers of the Bureau Circular, for which see page 27.

Since the organization of the Bureau of Standards there have been submitted for test resistance standards and resistance apparatus typifying the standard design and methods of construction adopted by the leading American and European manufacturers. The Bureau is equipped with such standard apparatus and also with special apparatus designed for work of the highest precision, further typifying the best methods of construction. The experience gained in its use and in the testing work has indicated the desirability of adopting specifications for all apparatus submitted for certification. In many cases a precision even greater than warranted by the best construction and far greater than that required in the work for which the apparatus was to be employed has been requested. These questions will be more fully discussed below. The experience thus gained has led to a classification of tests with respect to accuracy, based on the construction of the apparatus as well as on the work in which it is to be employed, and standard tests have been provided for most classes of apparatus. In many cases two grades have been deemed adequate, one for the highest commercial accuracy and the other for all scientific work except special research in which the accuracy of the remaining data entering into the result justifies a still higher accuracy.

In such cases the Bureau will be glad to cooperate with investigators, not only in providing for tests of the highest precision, but also, on request, in furnishing any information at its disposal in reference to methods of measurement and the design and construction of special apparatus. The Bureau has extended a similar offer to manufacturers of electrical apparatus, with whom the most cordial relations have already been established.

2. THE INTERNATIONAL ELECTRICAL UNITS

The rapid development of the electrical industries, and the many improvements in the construction of electrical standards, electrical measuring apparatus, and methods of measurement, have together imposed increasing demands for accuracy in the units in terms of which electrical quantities are expressed.

The efforts which had been made in this direction previous to 1900 were fully set forth in a paper presented to the St. Louis International Electrical Congress in 1904.[1] This congress, recognizing the discrepancies in the laws of the countries represented, recommended that all matters relating to units of measurement be referred to an international commission which might, in the first instance, be appointed by those countries in which legislation had already been enacted, and the hope was further expressed that the commission might become a permanent one.

In accordance with the provision of the above resolution, an international conference was held in Berlin in 1905, at which England, France, Austria, Belgium, and the United States were represented. Certain recommendations were adopted, which it was agreed to propose for adoption to a congress in which all the leading countries were represented.

On behalf of England a call was therefore issued for an International Conference on Electrical Units and Standards, which met in London in October, 1908, and by which the following resolutions were adopted.

I. The conference agrees that as heretofore the magnitude of the fundamental electric units shall be determined on the electro-magnetic system of measurement with reference to the *centimeter* as the unit of length, the *gram* 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 centimeter and second; (2) the *ampere*, the unit of electric current which has the value of one-tenth (0.1) in terms of the centimeter, gram, and second; (3) the *volt*, the unit of electromotive force which has the value 100 000 000 in terms of the centimeter, the gram, and the second; (4) the *watt*, the unit of power which has the value 10 000 000 in terms of the centimeter, 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 grams in mass, of a constant cross-sectional area and of a length of 106.300 centimeters.

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.

[1] The So-called International Electrical Units, Reprint No. 3, Bulletin of the Bureau of Standards.

VII. The *international ampere* is the unvarying electric current which, when passed through a solution of nitrate of silver in water, in accordance with the Specification II attached to these resolutions, deposits silver at the rate of 0.00111800 of a gram per second.

VIII. The *international volt* is the electrical pressure, which, when steadily applied to a conductor whose resistance is 1 international ohm, will produce a current of 1 international ampere.

IX. The *international watt* is the energy expended per second by an unvarying electric current of 1 international ampere under an electric pressure of 1 international volt.

The drafting of detailed final specifications was referred to a permanent commission and, pending its appointment, to an international scientific committee of 15, appointed by the president of the conference, Lord Rayleigh. In addition to the resolutions, the following recommendations were adopted.

In cases in which it is not desired to set up the standards provided in the resolutions the conference recommends the following as working methods for the realization 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 submultiples.

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 electrical 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 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.

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 15 to advise as to the organization of the permanent commission, to formulate a plan for and to direct such work as may be necessary in connection with the maintenance of standards, fixing of values, intercomparison of standards, and to complete the work of the conference. Vacancies on the committee to be filled by cooptation.

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.

A careful inspection of the definitions shows that two distinct systems of units are defined—the "practical units" of the absolute electro-magnetic system, and the concrete units of the international system, "representing the above, and sufficiently near to them to be adopted for the purpose of electrical measurements, and as a basis for legislation." This is necessitated by the fact that at the present time the accuracy of the absolute measurements required to realize the units of the first system is considerably exceeded by the accuracy of reproduction of concrete standards from properly drawn specifications.

The *international ohm* and *ampere* were selected as primary units, but while general agreement was easily reached in regard to specifications for the construction of mercurial resistance standards, the disagreement of results of different investigators and even of the same investigator made it impossible to adopt specifications for the silver coulometer, as the cause or causes of the discrepancies, amounting to several hundredths per cent, were not known.

The adoption of a definite value for the electrochemical equivalent, 0.00111800 gram per second per unit current, still leaves both the international ampere and the international volt uncertain to the above extent. This, together with the high accuracy attainable in the reproduction of the Weston standard cell, has stood in the way of the acceptance of the value provisionally adopted by the London conference for the electromotive force of the cell, 1.0184 volts at 20° C. This difficulty would have been obviated by the selection of the volt instead of the ampere as the second fundamental unit, which would merely have required the adoption of a particular value for the Weston cell, as was advocated by the Bureau of Standards.

Arrangements have, however, been made by the international scientific committee to investigate the questions at issue by cooperative work, to be undertaken by representatives of the Physikalisch-Technische Reichsanstalt, the National Physical Laboratory, of England, the Laboratoire Central d'Électricité, and the Bureau of Standards, during the spring of 1910, in the laboratories of the Bureau of Standards, and it is hoped that, with the preliminary work in which the institutions cooperating are now engaged, agreement can be reached as to the details of the specifications and the numerical value to be adopted for the Weston normal cell. The international scientific committee has agreed to recommend that no further legislation be enacted until the cooperative work has been completed.

3. REFERENCE STANDARDS AND WORKING STANDARDS

A. RESISTANCE

Since the organization of the Bureau all resistance measurements have been referred to a considerable number of 1 ohm and 0.1 ohm precision standards of the Reichsanstalt design, verified from time to time at that institution. Beginning July 1, 1909, these were replaced by standards embodying the same principles of construction, but sealed to eliminate the influence of atmospheric humidity, as pointed out below.

The resistance material employed for standards is manganin, a copper-manganese-nickel alloy, one of a series first developed by Dr. Edward Weston, which is distinguished for the very small change in resistance exhibited with a change in its temperature, and for its small thermoelectromotive force against copper, as well as its superior constancy.

For standards of 0.1 ohm or more, silk covered manganin wire is employed, hard soldered to copper lugs, which in turn are soldered to copper terminals. The wire is wound in a single layer on a brass tube, first covered with shellacked silk gauze. After the wire is in place, the coil is shellacked and baked for at least ten hours at a temperature of 140° C.

For standards of 0.01 ohm or less, sheet manganin, hard soldered to the terminal lugs, is employed. The resistance material is in short lengths so that no further support is required. It is covered with a varnish to protect the alloy from the action of the atmosphere.

The standards of all denominations are provided with copper terminals amalgamated at the ends, located diametrically opposite each other, extending sufficiently beyond the case and above the center of gravity so that the standards can be hung in mercury cups, through which electrical connections are made. In addition, the standards of the lower denominations are provided with potential terminals so that comparisons may be made by the various methods which eliminate the errors due to contact resistances.

The standards are designed for oil immersion, the oil serving to carry away the heat developed by the current passing through the coil, and facilitating the regulation and measurement of the temperature.

The heat developed increases the temperature of the resistance material above that of the bath in which it is immersed approximately 1° C per watt for 0.1 ohm and 1 ohm standards of the above design. In air, the increase in temperature is at least five times larger. The temperature increase for standards below 0.1 ohm is generally not over 0.25° per watt in oil, depending upon the surface area of the resistance material.

The baking referred to above leaves the standard free from alcohol and moisture. On exposure to atmosphere or oil at ordinary temperatures, the shellac used in insulating and protecting the winding absorbs moisture until an equilibrium condition is established with the moisture content of the atmosphere or oil. Any changes in the humidity of the atmosphere or oil will be followed, though slowly, by corresponding changes in moisture content of the shellac. As the humidity of the atmosphere changes with the seasons, the amount of moisture in the shellac will also vary with the seasons unless some means, such as hermetical sealing, is provided to eliminate the effect. Changes in the amount of moisture in the shellac change its volume, and changes in the volume alter the tension and dimensions of the wire and consequently the electrical resistance of the standard. The absorption of moisture by the shellac thus accounts for the seasonal changes observed and also in part for the increase in the resistance of comparatively new standards.

The 0.1 and 1 ohm standards are usually more constant than those of other denominations. Here the wire is of such a size that the expansion of the shellac can produce but a slight stretching, and the surface action is less than with standards in which wires of smaller diameter or thin sheets are employed. Standards of these denominations seldom show a change of more than 0.003 per cent per year after the first year, and the seasonal changes are small, usually not exceeding 0.002 per cent for 1 ohm standards under ordinary conditions.

Sealed standards.—The constancy of manganin resistance standards may be very materially increased by sealing them in cases containing a good grade of oil free from moisture. This matter is fully discussed in Reprints Nos. 73 and 107 from the Bulletin of the Bureau of Standards, copies of which will be sent, on request, to those interested. The sealed standards of the Bureau, which have been developed as a result of this investigation, embody the essential principles of the Reichsanstalt design, differing only in the dimensions and in the case being sealed and filled with carefully dried, high-grade petroleum. The cases are approximately 4 cm in diameter and 12 cm high, and the distance between the centers of the terminals is 7.7 cm, thus reducing the dimensions of the comparing bath. In measurements of the very highest precision, made in a regulated oil bath, the time required to reach temperature equilibrium is considerably reduced by the smaller dimensions. In most cases, no oil bath is required.

Since July 1, 1909, the reference standards of the Bureau have consisted of at least five 1-ohm coils of the sealed type. These are compared with each other and with the standards which have heretofore been employed to

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detect any relative changes. The construction of primary mercurial resistance standards is well under way, and when completed the results will be compared with those of other national laboratories. The plan of cooperation outlined at the London International Electrical Conference of 1908 will, it is hoped, soon be put into effect so that the unit of resistance of all the institutions will be made identical by giving proper weight to the results obtained by each. Until then the values adopted for the reference standards will be expressed as heretofore in terms of the primary mercurial standards of the Reichsanstalt.

Working standards.—Decimal multiples and submultiples of the international ohm are represented by at least two working standards of each denomination, referred from time to time to the reference standards. The multiples of the unit are of the sealed type, and the submultiples of the Reichsanstalt design. The latter, as also the units, are provided with potential terminals.

B. ELECTROMOTIVE FORCE

Standard cells.—The standards of electromotive force of the Bureau consist of a considerable number of Weston normal cells constructed in accordance with the preliminary specifications described in Reprint No. 67 from the Bulletin of the Bureau of Standards. These are maintained at 25° C in automatically regulated petroleum baths practically all the time, except during the summer months, when auxiliary cooling, which occasionally fails, must be employed.

The mean value taken for the reference cells is based on the value adopted at Chicago in 1893 for the Clark cell, set up in accordance with the specifications adopted shortly after the Chicago congress, namely, 1.434 volts at 15° C. Such cells are found to have a value higher by 0.0003 volt than Clark cells set up with specially prepared or treated mercurous sulphate. Assuming the temperature formula found at the Physikalisch-Technische Reichsanstalt, the value of the Clark cell set up with properly prepared mercurous sulphate on the same basis was taken by the Bureau as 1.42110 international volt at 25°.

On this basis, the mean value for the Weston normal cell has been found to be 1.01890 volt at 25°, or 1.01913 at 20°. The change in electromotive force with temperature is given by the formula

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

adopted by the London International Electrical Conference of 1908.

The above value of the Weston normal cell is identical within the limits of accuracy of reproduction with that heretofore employed by the Bureau of Standards, and will be retained until a satisfactory agreement has been reached by which strict international uniformity will be secured.

The value for the Weston normal cell used in England prior to the International Electrical Conference of 1908 was 1.0193_8 at 20° C. Since January 1, 1909, the value used in England has been 1.0184 at 20° C. The value used in Germany is 1.0186 at 20° C for the older Weston cells, or 1.0185 for those set up with mercurous sulphate prepared according to methods recently developed.

4. ACCURACY REQUIRED FOR VARIOUS CLASSES OF WORK

The increased application of electrical methods to many classes of physical measurements, and the more rigorous specifications for certain classes of commercial electrical apparatus, have created a demand for more precise electrical measurements. As the sensibility is, however, usually high, the measurements are frequently being made to a precision which is not justified by the needs of the work or by the apparatus used. It therefore seems desirable to point out some of the more obvious limitations.

The users of apparatus for the measurement of resistance and electromotive force may be grouped roughly into two classes—(1) those engaged in university work and in other research and testing laboratories, or in the manufacture of standards and measuring apparatus, and (2) those engaged in commercial work. Among the latter are the manufacturers of dynamo-electric machinery, power supply, telegraph and telephone companies, refiners of copper and aluminum, wire manufacturers, etc.

In some classes of work, particularly in connection with laboratory instruction in our technical schools and colleges, where the aim is to familiarize the student with the methods of electrical measurement and impress him with the precision attainable, *relative accuracy* is obviously the principal requirement, as, for example, in the comparison of two nearly equal resistances. This is the sole requirement when the ratio of two quantities is determined from the ratio of two resistances, as, for example, in the comparison of electromotive forces or resistances by the potentiometer. For absolute accuracy the values of the various quantities entering into the result must be known in terms of the international electrical units, except where the ratio of two quantities of the same kind is involved, as in the ratio coils of a Wheatstone bridge and in resistance thermometry. As pointed out in this circular, the fundamental international electrical units, the ohm and ampere, are not at present fixed to better than 0.002 and 0.01 per cent, respectively, while their relation to the corresponding absolute units is even more uncertain.

The accuracy of reproduction of the standard cell being approximately the same as that of the mercury ohm, the limit to the accuracy to which results can be expressed in terms of these concrete standards, assigning a particular value for the standard cell, may be taken as 0.002 per cent.

In precision work an accuracy of 0.01 per cent is to be considered fully adequate. To secure even this precision the work must be done with well designed apparatus suitable for the particular work. Corrections must be applied for change of values or indications with temperature, and in addition the apparatus must be checked from time to time with reliable reference standards. The changes between comparisons are frequently large and are very often overlooked, the agreement between repeated measurements of the same quantity being taken as a measure of the *absolute accuracy* of the result.

The Grade A tests listed below are provided for this class of work, certifications being made to a maximum accuracy of 0.005 per cent for resistance standards and 0.01 per cent for other resistance apparatus complying with the specifications given below. However, in cases where only relative values are required, these will be given to a precision not greater than 0.001 per cent, the limit being determined by the construction and design of the apparatus. It is recommended that such apparatus be designed so as to make possible a complete intercalibration without the aid of much accessory apparatus, as, for example, in some decade rheostats and potentiometers where the separate coils of each decade can be intercompared and the decades intercompared by a comparison of the ten coils of one decade with the first coil of the next higher decade. Apparatus will not be tested to a higher accuracy, except in special cases noted above, page 4.

In commercial work an accuracy greater than 0.1 per cent is seldom sought and less frequently attained on account of the unfavorable conditions under which the measurements must generally be made; for example, temperature uncertainty, fluctuation of the quantity to be measured, limitations to the accuracy of deflection instruments, etc. Apparatus employed for this class of work should, therefore, be tested to an accuracy sufficient to give the result to within 0.1 per cent under favorable conditions and when the apparatus is suitable for the purpose for which it is employed. This requirement is fully met by the Grade B tests listed below, the limit of accuracy being fixed at 0.025 per cent. Resistance apparatus adjusted to give this accuracy can be obtained from a number of makers, thus rendering unnecessary the application of corrections. Even for this class of work the purchase of high-grade apparatus is recommended, since its increased cost is more than offset by its greater reliability as well as the time saved in its use. Provision has been made by the Bureau of Standards for checking such apparatus, at a reduced fee, to determine whether the specifications have been complied with; in this case the corrections found are not given. However, in view of large changes frequently observed, particularly in coils of 1000 ohms and above, even the highest grade apparatus should be checked from time to time. In many cases other resistance apparatus is available, and in some cases the coils may be intercompared, thus checking any relative changes. In the absence of adequate checks the apparatus should be submitted periodically to some standardizing laboratory.

5. CLASSIFICATION OF TESTS

A. PRECISION RESISTANCE STANDARDS—ACCURACY, GRADE A

See Fee Schedule 71, p. 27

Standards submitted for certification as precision standards must satisfy the following requirements:

(1) Standards must be adjusted to within 0.1 per cent of the following nominal values in international ohms: 1, 2, 3, 4, 5, and their decimal multiples up to and including 100 000 ohms, together with the decimal submultiples of the unit, down to and including 0.0001 ohm.

(2) Standards must be of approved design and construction and must embody the main features of the Reichsanstalt type, already described, and generally adopted by the leading manufacturers.

(3) The resistance material must be distinguished by its constancy. Its change in resistance with temperature must not exceed 30 parts per million per degree centigrade at 25° C, and its thermoelectromotive force against copper must be small.

(4) To facilitate the measurement and control of the temperature, the standard must be so designed that it can be compared in an oil bath.

(5) In coils of 1 ohm and above, the resistance material should be in the form of wire of suitable size closely wound on a hollow supporting cylin-

der, and should cover a surface of at least 40 square centimeters area. In standards below 0.1 ohm sheet metal is usually employed. The surface must be sufficiently large, so that the heat developed by the test current does not cause a rise in temperature of the resistance material above that of the oil bath in which it is used of more than 0.25° C per watt.

(6) Standards of 0.1 ohm and below must be provided with potential terminals, so that all connecting resistances can be eliminated. This construction is also recommended for 1-ohm coils. The resistance in each potential lead should not exceed 0.001 ohm, to facilitate measurements by the Kelvin double-bridge method.

(7) If the resistance material is affected by atmospheric influences, it must be covered with a suitable protecting varnish.

(8) The standard must be provided with suitable copper terminals, projecting at least 1.5 cm beyond the edge of the case, for making electrical connections and for supporting it in mercury cups.

(9) Standards having a resistance of over 20 000 ohms must be subdivided and have not over 20 000 ohms per section.

(10) New standards must be accompanied by a statement concerning the resistance material used and the date and process of aging.

Standards submitted for certification will be compared with or referred to at least two of the working standards of the Bureau. The measurements will be made in an oil bath and by the Wheatstone bridge or by the Kelvin double-bridge method.

The values will generally be given to 0.001 per cent, but will in no case be certified to an accuracy greater than 0.005 per cent. This limit is determined by (*a*) the accuracy of reproduction of the international ohm from its definition, together with its comparison with wire copies estimated at about 0.002 per cent; (*b*) the accuracy of the evaluation of the multiples and submultiples from the unit estimated at 0.0002 per cent per step of 10; (*c*) changes in the Bureau reference standards between evaluations estimated to be not more than 0.002 per cent.

When the resistance material is manganin, the value can be expressed by the following equation:

$$R=N\{1+a+b\ (t-25)+c\ (t-25)^2\}$$

in which R denotes the resistance, t the temperature, N the nominal value of the standard, a the correction in parts of the whole at 25° C, and b and c the constants of the temperature formula.

For manganin the value of b is usually between -0.000010 and $+0.000030$, and the corresponding value for c is usually between -0.0000003 and -0.0000005. It will thus be seen that the changes in temperature which occur under working conditions in the laboratory, say 20 to 35° C, cause changes in resistance from the 25° C value of usually not over 0.02 per cent, and need be considered only when a higher accuracy is sought.

Since it often happens that measurements are desired to a higher relative accuracy, it is recommended that the temperature resistance equation of all precision standards be determined. For this purpose, measurements at three temperatures suffice. These will generally be made at 20, 25, and 30° C to a relative accuracy better than 0.0005 per cent. In this case the formula will give the temperature correction between 20° and 30° to within ±0.0005 per cent, or at any temperature to within $\pm 0.0000002\ (t-25)^2$.

In the case of standards of the higher and lower denominations, which are seldom used in measurements requiring a relative precision much better than 0.005 per cent, a determination of the mean temperature coefficient from measurements at two temperatures will suffice. When the resistance material is known to be manganin, a closer approximation may be obtained by assuming c, in the above equation, to have its mean value -0.0000004. If the measurements are made at temperatures differing by 10° C, an error of 50 per cent in the assumed value of c introduces, within these limits, a maximum error of only 0.002 per cent.

As new standards often change more rapidly during the first few months than later, it is recommended that when such standards are submitted for test they be left in the Bureau at least a month after the completion of test outlined above, and that an additional measurement then be made at 25° C.

For standards of which the resistance-temperature formula has previously been determined in any of the national laboratories, it is recommended that measurements be made at 25° C only, since experience shows that the change in resistance with a change in temperature is the same at different times within the limits of measurement. There is, therefore, no object in making additional measurements at other temperatures.

In cases where the standard is to be employed for current measurement or otherwise unduly loaded it is desirable to know the effective difference in temperature between the resistance material and the oil bath. An additional measurement with a larger test current or higher voltage is generally sufficient for determining this relation for standards of which the resistance temperature equation is known, except when strains are produced by differential thermal expansion, by which appreciable changes in the resistance may be caused.

B. PRECISION RESISTANCE STANDARDS—ACCURACY, GRADE B

See Fee Schedule 72, p. 28

Standards submitted for certification under this schedule must be of approved design, and it is recommended that they should in general satisfy the requirements laid down for precision standards as given above. Apparatus which does not quite meet the requirements for a test under Schedule 71 may be submitted for certification under this schedule.

The measurements will be made at a temperature of 25° C only, and the results certified to an accuracy not greater than 0.025 per cent. It is not necessary to make measurements at other temperatures, since the resistance should not vary by more than the limit set with ordinary temperature changes.

C. RESISTANCE STANDARDS FOR CURRENT MEASUREMENT—ACCURACY, GRADE A

See Fee Schedule 73, p. 28

Standards submitted for certification under this schedule must be of approved design and construction, and must satisfy the following requirements:

(1) They must be decimal submultiples of 1, 2, 3, 4, or 5 ohms, between 0.0001 and 1 ohm, both inclusive.

(2) They must be adjusted within 0.2 per cent of their nominal values.

(3) The resistance material must be distinguished by constancy of its

resistance, small thermoelectromotive force against copper, and small change in its resistance with a change in temperature. This change per degree centigrade must not exceed 30 parts per million at 25° C. If it is easily oxidized, it must have a covering to protect it against the action of the atmosphere or moisture dissolved in oil.

(4) Standards below 1 ohm must be provided with separate current and potential terminals. The potential connections must be so located that any changes in the current distribution in the current terminals will introduce no appreciable errors. The resistance of each potential connection should not exceed 0.001 ohm, and the current connections should have a very low resistance and sufficient contact surface to keep the local rise in temperature within reasonable limits.

(5) The standards must be provided with a suitable tank or containing case, to be filled with oil when in use.

In standards of this type, when used with the rated full-load current, the temperature of the resistance material is generally considerably above that of the oil. The difference depends upon the area exposed to the oil and the circulation of the latter.

Standards received for test under this schedule will be compared with certain reference standards of the Bureau, and the value obtained certified to an accuracy of 0.01 per cent.

It is recommended that the test consist of three measurements—(*a*) one made with the bath at room temperature and with a small test current, to obtain the resistance, (*b*) a second measurement with the bath about 10° C above room temperature, to determine the effect of temperature, and (*c*) a measurement with the rated full-load current, to determine the effect of the test current which is due to the heating of the resistance material above the temperature of the bath. The three measurements give the data from which an equation may be derived giving the resistance with the bath at different temperatures and with any test current up to full load.

When the oil tank is provided with means for regulating the temperature by water circulation, measurements may be made at any desired temperature between 15° and 35° C. Where a suitable means for cooling the oil is not provided, measurement, in general, will not be made below the room temperature.

D. RESISTANCE STANDARDS FOR CURRENT MEASUREMENT—ACCURACY, GRADE B

See Fee Schedule 74, p. 28

Standards submitted for certification under this schedule must satisfy the following requirements:

(1) They must be of approved design and construction, and in general satisfy the requirements for certification under Schedule 73, except that they need not be designed for oil immersion.

(2) The thermoelectromotive force of the resistance material against copper must not exceed 3 microvolts per degree centigrade.

(3) The standard must be so designed that with its rated full-load current the rise in temperature above that of the room does not exceed 50° C, and the change in resistance from no load to full load must not exceed 0.1 per cent.

When the standard is to be used with different loads, it is recommended that a test be made with a small current and, also, with the rated full-load current. In some cases, an additional test at half load (0.5 the rated watts, or 0.7 the rated full-load current), is desirable, since the change in resistance with the load is not strictly proportional to the load.

When the resistance material is in short lengths, considerable heat is conducted away from the standard by the connecting lugs. In such cases, it is suggested that the lugs be sent with the standard so that the test may be made more nearly under the conditions of service, which should be stated fully in the application for the test.

Standards received for test under this schedule will be compared with reference standards of the Bureau and the values found certified to an accuracy of 0.025 per cent.

The temperature of the room in which the tests are made will be given.

E. PRECISION RESISTANCE APPARATUS—ACCURACY, GRADE A

See Fee Schedule 75, p. 29

Precision resistance apparatus consists usually of a number of resistance coils mounted from a hard-rubber support and connected to metal terminal blocks by means of which, with plugs or switches, certain combinations of the coils are effected. The requirements of such apparatus are determined by the nature and range of measurements to be made, the speed of working, and precision desired. In this discussion, only apparatus capable of giving an accuracy of 0.01 per cent will be considered. The reliability depends on the material and construction of the resistance coils, the quality of the insulation, and the contact resistances introduced by the plugs or switches.

The construction of the coils should in general be similar to that described above for precision standards. Single-layer windings on metal cylinders give the most satisfactory results. Wood spools should not be used, particularly for the coils of higher resistance, as they may absorb moisture, thus producing strains in the wire.

The changes of resistance of shellacked coils, due to atmospheric humidity, may be largely eliminated by giving them a thin coat of paraffin; this practice is highly recommended. However, the coils must not be heavily embedded in paraffin or other material, which unduly retards attainment of temperature equilibrium.

Manganin has been found by experience to be the most suitable resistance material, and is now almost exclusively employed in precision apparatus.

The terminal blocks should be firmly fastened to the hard-rubber top; this is to be particularly observed when the series plug arrangement is used, so that the removal of a plug may disturb the fit of adjacent plugs as little as possible. In order to secure a permanently high insulation, a space should always be left at the base of the blocks, by undercutting them or otherwise, sufficient to permit cleaning the surface of the hard rubber; the hard rubber should also be protected from the action of direct sunlight.

Each terminal block should be provided with an auxiliary means for making direct electrical connection to it, either a screw or a tapered hole with a traveling plug. Such a connection is often found to be convenient in the calibration of the apparatus, and sometimes in its use. For similar reasons, such a connection should be provided for all the main branch points of an apparatus.

The desired combinations of the coils are usually made by plugs or switches. A few words of caution are necessary in regard to their use and care. When plugs are used a good fit between plug and hole is essential. Both the plugs and the holes should be cleaned frequently; the surfaces should be in such condition that good contact can be made without excessive pressure, which may disturb the fit of adjacent plugs. The plugs should not be inserted with a screw motion in one direction, and be withdrawn with an opposite motion, as this may wear grooves in the holes and produce high contact resistance. When a plug is removed it should always be ascertained that adjacent plugs have not been disturbed. The importance of frequent cleaning is just as great in the case of switch contacts. The magnitude and constancy of the contact resistance depend also on the design of the contact. A plug contact of the best design and construction has a resistance of about 0.00006 ohm, and is constant when clean to 0.00002 ohm. The best switch contact has a resistance of about 0.0002 ohm, and is constant to better than 0.0001 ohm. These figures are for the best conditions, being considerably better than ordinary practice. Either type of contact, when dirty or grooved, is not reliable to 0.01 ohm, and if not cleaned often enough a film of oxide forms, which makes them still worse. Switch dial apparatus is more convenient and rapid in operation than plug apparatus, and is therefore to be preferred for most purposes.

The number of contact resistances in series should be kept small. If this can not be done, the total resistance used should, if possible, be chosen large enough so that the contact resistances are negligible in comparison with it.

The coils of low value in resistance apparatus are often adjusted much closer than necessary. This is due to the practice of specifying a certain percentage accuracy of adjustment for the coils of an apparatus without recognition of the fact that the desired precision of measurement does not require the same percentage accuracy in all the coils. Now, it is evident that coils used in series with a number of plugs or switches can not be relied upon to better than 0.001 ohm. Furthermore, in the use of resistance apparatus, the quantity to be measured is generally determined by two or more factors, at least one of which is given by a resistance adjustable in equal steps, e. g., the rheostat arm of a Wheatstone bridge. For nearly all purposes, steps of 0.1 ohm have been found sufficiently small, and apparatus with coils of smaller denomination is rarely found. The magnitude of the smallest step and the total resistance with which it is in series determine the percentage accuracy of the reading. A closer determination is sometimes made by interpolation to 0.1 or, rarely, 0.01 of a step. It is therefore evident that an accuracy exceeding 0.0005 ohm in the adjustment or calibration of the coils of lower denomination is practically superfluous. For the coils above 5 ohms, the limit is fixed by the percentage accuracy of adjustment.

Apparatus submitted for certification must satisfy the following requirements:

(1) In general, the apparatus must be capable of giving an accuracy in service of 0.01 per cent.

(2) The resistances must be adjusted to 0.1 per cent of their nominal values, except in the case of coils below 1 ohm, as noted above. While this accuracy will admit to certification under this schedule, closer adjustment is highly desirable since most users prefer to dispense with corrections.

(3) The plugs or switches must be in good condition. The variation in resistance must not exceed 0.0001 ohm for each plug and 0.0002 ohm for each switch.

(4) The insulation must be good throughout, and must be in good condition.

(5) New apparatus submitted by the makers must be accompanied by a statement concerning the resistance material used, and the date and process of aging.

To obtain 0.01 per cent accuracy the apparatus must be kept in first-class condition and the resistances checked from time to time. Since appreciable changes in resistance occur during the first year or two, new apparatus should receive special attention. Some apparatus made by the best makers has been found at the Bureau to show a permanent increase of over 0.1 per cent in resistance. This effect, like that of moisture (see above), is greater in the case of the coils of higher resistance.

The request for a test should contain a statement of the purpose and conditions of use of the apparatus. The party submitting the apparatus may be required to show that a calibration to the precision of this schedule is required in the work for which the apparatus is used. The measurements will be made at room temperature. If measurements at other temperatures, or a higher accuracy than 0.01 per cent, are required, the test will be regarded as special (see p. 24).

(a) BRIDGES, RHEOSTATS, AND SIMILAR APPARATUS

For the measurement of resistances, the Wheatstone bridge and modifications are usually employed. The bridge may have continuously variable ratio arms and one or more fixed comparison resistances, or it may have fixed ratio arms and a variable rheostat as the comparison resistance. In the measurement of resistances less than 1 ohm, the Kelvin double bridge should be used;[2] the apparatus provided for this work is usually a double set of similar ratio arms, together with a low resistance standard. The rheostat arm of a Wheatstone bridge, and rheostats in general, may consist of a simple series of coils short-circuited by plugs, or of any one of several decade arrangements. If the series plug arrangement is used, the cautions mentioned above should be observed. The decade arrangements consist of groups of equal decimal steps. They are easier and quicker to manipulate and involve fewer contact resistances. They are adaptable either to plug or switch connections.

The ratio arms of a Wheatstone bridge should be reversible. The connecting resistance to the branch points of the bridge (galvanometer or battery connection points) must be low, and should not exceed 0.0002 ohm if ratio coils as small as 1 ohm be used. There should be not more than two contact resistances in a ratio arm. In bridges of older design, the ratio coils are in series, and are thus more subject to plug troubles. For facility in calibration, auxiliary potential connections should be provided to the branch points, or terminal points of ratio arms. Connecting resistances in the bridge should always be made low, and the galvanometer and battery should be introduced at such points that the connecting resistance is in series with the rheostat arm rather than the ratio arms or the resistance

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[2] For a treatment of the theory and practice of this method, see Jaeger, Lindeck, and Diesselhorst, Zeitschrift für Instrumentenkunde, **23**, pp. 33 and 65; 1903.

under measurement. In the use of a bridge, the ratio arms should be chosen which will give a large setting of the rheostat arm, in order to obtain a high percentage accuracy of reading, provided that such a choice is consistent with sensibility.

A slide wire is often used in rheostats and bridges. When the resistance of the contact is in series with the other resistances, and its constancy must be relied upon, trouble arises sooner or later; this construction is seldom to be recommended. Where the sliding contact functions otherwise, as when its resistance enters only in the battery or galvanometer circuit, very satisfactory results may be obtained. In some cases the wire and contact should be oil immersed. It should be ascertained that negligible or constant resistances are introduced at the junctions of the ends of the slide wire with the rest of the apparatus.

A regular test will include the determination of resistance of each coil and the magnitude and constancy of zero and connecting resistances (each charged for as one coil) of each arm or separate portion. If there is a slide wire, its total resistance will be determined and charged for as one coil, and it will be calibrated at 10 points, or every half turn if it is wound on a cylinder. If the plug or switch contacts are in such condition that they must be cleaned in order that the accuracy of this schedule may be attained, an extra fee will be charged, as per table of fees.

The certificate will ordinarily give the corrections in international ohms. Corrections to rheostat coils will generally be given in terms of the "substitution equivalent," or the resistance added when the coil is introduced into the circuit in the ordinary way. Thus, in the case of a series plug connection, the substitution equivalent is not the resistance of the coil, but that of the coil minus that of the plug. In cases where the number of contacts in series is not variable, as in the decade arrangements, the substitution equivalent is identical with the coil resistance. In any case, the true resistance is found by adding to the rheostat setting the zero resistance, which includes the sum of the contact resistances. The corrections for ratio coils will include the connecting resistances in series with them.

The corrections to the coils will ordinarily be certified to an accuracy of 0.01 per cent, except the resistances below 5 ohms. The latter will be certified to 0.0005 ohm only, or to a lower accuracy if the number or condition of the contacts are unfavorable. Ratio coils will be certified to 0.005 per cent, except those below 10 ohms. Where the construction admits, the accuracy of determination of the points on a slide wire will be 0.2 of its smallest division.

It should be remembered that resistances are often not constant to 0.01 per cent, so that the certificate can not guarantee that accuracy in the use of apparatus. We can do no more than certify to the accuracy of our determination at the particular time of test.

(b) POTENTIOMETERS AND VOLT BOXES

Serving the widest variety of uses, the potentiometer is a most accurate and convenient electrical measuring apparatus. It is essentially an instrument for comparing differences of potential. This is effected by balancing them against the difference of potential in a portion of the potentiometer circuit, through which a constant current is maintained. The instrument must therefore be so constructed that the potential difference between two terminals can be varied continuously, or in sufficiently small steps, without changing the total resistance in the potentiometer circuit. In the measurement of potential differences, an unknown and a standard are successively balanced; and, provided only that the current in the instrument remains the same for the two operations, the unknown potential difference is given in terms of the standard by the ratio of the potentiometer settings. It is thus apparent that the corresponding resistances need be known only relatively. The accuracy of measurement, accordingly, depends chiefly upon the relative accuracy of the potentiometer resistances, the accuracy of the cell used as standard, and the sensitiveness of the galvanometer employed to indicate a balance. These three requirements are so well met in practice that with a potentiometer whose calibration is carefully and frequently checked, an accuracy of 0.01 per cent is very easily attainable.

Besides its accuracy, the potentiometer has the advantage of convenience. The resistances are divided into groups or decades of equal steps. The potential drop in one step of a decade equals that in ten steps of the next lower decade. The successive dial readings thus give the digits of the setting. A slide wire may take the place of several of the dials. It is only necessary to adjust the current to such a value that the standard cell is balanced across a portion of the resistance indicating its electromotive force, when the readings of the instrument will give the potential differences subsequently measured, without calculation. In addition to the direct measurement of voltage, the potentiometer furnishes a means for the precise measurement of current and of resistance when used in connection with resistance standards. By using resistance standards of decimal values the advantages of direct reading are retained for current measurements, only the insertion of the decimal point having to be considered. For flexibility, accuracy, and convenience the potentiometer is thus seen to be an admirable instrument for the measurement of the three fundamental electrical quantities. By combining measurements of two of these quantities we have also a measure of power.

The numerous types differ in the method of dividing the potential drop into decimal steps. One of the simplest forms is a series of equal coils with a slide wire having decimal subdivisions and a resistance equal to one coil. A switch makes contact with the terminal of any one of the series coils, and there is also means for making contact at any point of the slide wire. Practical considerations of construction limit the values of the resistances that may be employed when the series slide wire is used to 20 to 100 ohms per volt on the normal range. The Crompton and the Leeds & Northrup Type K potentiometers are of this form.

When high resistances, of the order of 10 000 ohms per volt, are employed, various methods are employed to make the potentiometer settings. In one type there are several dials of equal coils in series, whose steps are multiples of 10. The terminals to which the unknown potential difference is applied connect to the switches of the two end dials. Changing the resistance on the intermediate dials varies the drop between these terminals, the current being maintained constant by simultaneously changing the resistance in the battery circuit a corresponding amount. This double operation is effected by the use of double dials. The Otto Wolff potentiometer is of this type. In another type the steps of the main dial are subdivided by means of a second series of coils, which can be moved so as to shunt any one, or, in some types, any group of two or more of the steps of the main dial. Examples of this type are the Siemens & Halske and the Leeds & Northrup Standard potentiometers. A recently developed type combines the potentiometer with the deflection principle. The greater part of the unknown potential difference is balanced in the ordinary manner, and the small unbalanced remainder is indicated on a deflection instrument. This method has the advantage of speed, and an accuracy of 0.02 per cent is attainable.

The types of potentiometer differ, also, in the method of balancing the standard cell. It may be introduced at the same points as the unknown potential differences, or special connections may be provided for it. The latter arrangement is the more convenient, as it is unnecessary to disturb the setting of the instrument. This is of importance, for the constancy of the current is the fundamental assumption of the potentiometer, and should be frequently checked. Usually a single pair of tap-in points for the standard cell is not sufficient. Preferably the resistance across which the cell is balanced should be variable, inasmuch as the cells used as standards do not all have the same electromotive force, and, further, because their variation with temperature may have to be considered.[3]

A few words may be said regarding the relative advantages of high and low resistance potentiometers. The chief advantage of the low resistance is in sensibility, which increases as the resistance is reduced. In the low-resistance instrument, the effect of poor insulation and possible leakage between parts is less important than in the case of high resistance. The change of the resistances with time and their variation with atmospheric humidity are also less in the case of low resistances. (See general discussion under "Resistance standards," p. 7.) The low-resistance potentiometer has, however, the disadvantage of using a larger current, which is somewhat more difficult to maintain constant. The slide wire types often have additional minor difficulties, which can, however, be overcome by proper construction.

The range of the ordinary potentiometer is 1.5 to 1.8 volts, 0.1 volt for each step of the first or main dial. The setting is usually readable directly to 0.00001 volt. For measuring very small potential differences the range of some potentiometers may be reduced. The reduction is usually to 0.1 or 0.01 of the normal range, and is accomplished by inserting series resistance or a combination of shunt and series resistance with the main circuit. The

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[3] Full descriptions of the various types may be found in the pamphlets of instrument makers. Short treatments of the subject are given in various text-books. For careful treatments of theory and types, see—

K. Feussner; Zeitschrift für Instrumentenkunde, **10**, p. 113; 1890.
O. Wolff; Zeitschrift für Instrumentenkunde, **21**, p. 227; 1901, and **23**, p. 301; 1903.
A. Raps; Elektrotechnische Zeitschrift, **15**, p. 215; 1895, and **16**, p. 507; 1895.
R. Franke; Elektrotechnische Zeitschrift, **24**, p. 978; 1903.
J. A. Harker; Philosophical Magazine, **6**, p. 41; 1903.
R. A. Lehfeldt; Philosophical Magazine, **5**, p. 668; 1903.
H. Hausrath; Annalen der Physik, **17**, p. 735; 1905, and Zeitschrift für Instrumentenkunde, **25**, p. 353; 1905.
H. Diesselhorst; Zeitschrift für Instrumentenkunde, **26**, pp. 173 and 297; 1906, and **28**, pp. 1 and 38; 1908.
W. P. White; Zeitschrift für Instrumentenkunde, **27**, p. 210; 1907, and Physical Review, **25**, p. 334; 1907.
H. B. Brooks; Bulletin of Bureau of Standards, **2**, p. 225; 1906, and **4**, p. 275; 1908.

percentage precision of reading is thereby increased inversely as the reduction factor, unless limited by galvanometer sensibility. Special potentiometers for the measurement of low potential differences are also constructed, which are designed for the prevention of errors due to thermal electromotive forces and variable contact resistances in the potentiometer circuit. Such an instrument should be of low resistance to secure the highest sensibility.

Volt boxes.—When a potentiometer is used to measure higher voltages than 1.5 volts, a "multiplier," or volt box, is ordinarily used. A volt box is a series of resistance coils to the terminals of which is connected the unknown voltage and across a known fraction of which the drop is measured. The ratio of the total resistance to this fraction is the multiplying factor of the box. The construction is generally such as to give two or more factors. In the design of volt boxes, the need of specially good insulation must be regarded; and great care is necessary in use to prevent the high voltage under measurement from leaking to the potentiometer. The terminals of the volt box must be well separated and well insulated. The resistance should be divided into a number of coils in series, both for insulation and for dissipation of heat. The lower the resistance used the greater will be the heat developed. However, a high resistance reduces the sensibility, and is moreover less constant. The use of wooden spools and the winding of more than one layer on a spool are alike prejudicial to heat dissipation and to constancy of resistance. The resistance used should be between 100 and 300 ohms per volt.

The testing of potentiometers and volt boxes involves somewhat different measurements than are required for bridges and rheostats. A regular *test of a potentiometer* will include as many of the following measurements as are required to test the instrument completely:

(*a*) Comparison of the coils of the main dial or dials to an accuracy of one-half the smallest step or division of the instrument, except that such accuracy shall be not better than 0.01 per cent of one of the steps of the first main dial. Each zero or connecting resistance in series with the coils, which must be measured, will be charged for as one coil.

(*b*) Checking of the auxiliary compensating coils to ascertain whether their compensation is within the above accuracy.

(*c*) Determination of slide wire corrections to 0.2 of a division; at 10 points of a straight wire; at 2 points per turn of a circular wire.

(*d*) Determination of corrections to standard cell dial settings to an accuracy of 0.01 per cent.

(*e*) Determination of reduction factors for low ranges to 0.01 per cent.

(*f*) Determination of the value of one main coil in terms of the international ohm to 0.01 per cent.

The corrections to the settings are expressed in fractions of a volt for the normal range. It is to be understood that when the range is changed by a given factor, the corrections, except those for the standard cell dial, are changed by the same factor. The corrections to the standard cell dial settings are given in percentage for the following reason: The electromotive force of the standard cell, and the resistance across which it is balanced, determine the current in the potentiometer. If this resistance departs from its nominal value, the current is thereby made to depart from nominal by the same percentage amount. Every setting is accordingly affected by the same percentage error, and the corresponding percentage correction must be made. The signs of all corrections are so chosen that a positive sign means that the correction is to be added to the observed setting, a negative sign that the correction is to be subtracted. The correction to the reduction factors for low range are also given in per cent. The procedure, then, in applying the correction when a measurement is made on low range, is: first, add the volt corrections to the dial readings, then apply the percentage corrections for the current and the reduction factor, and then multiply the result by the nominal reduction factor.

The request for *test of a volt box* should state the conditions of its use, particularly the usual voltage. Test will be made either at low voltage or at maximum service voltage, as desired. It is recommended that tests be made at both low and maximum service voltage.

The multiplying factors furnished by the volt box should be integral numbers, adjusted to 0.1 per cent. The regular test will be a determination, at room temperature, of the multiplying factors to 0.01 per cent (and value of the total resistance in terms of the International Ohm).

F. PRECISION RESISTANCE APPARATUS—ACCURACY, GRADE B

See Fee Schedule 76, p. 29

Apparatus submitted for certification under this schedule must be of approved design and construction, and it is recommended that in general it satisfy the requirements laid down for precision resistance apparatus as given above. Apparatus which does not quite meet the requirements for a test under Schedule 75, but which is capable of giving the accuracy of this grade, may be accepted for test under this schedule.

Measurements will be made with the apparatus at the temperature of the room, and the results certified to an accuracy of 0.025 per cent, excepting resistances below 5 ohms. The latter will be certified to 0.001 ohm only. Potentiometers will be certified to an accuracy of two steps of the lowest dial or one-half division of the slide wire, except that the accuracy shall not exceed 0.025 per cent per coil of the first main dial.

G. PRECISION RESISTANCE APPARATUS; CHECKING—ACCURACY, GRADE C

See Fee Schedule 77, p. 29

Apparatus may be submitted under this schedule to determine whether a specified accuracy of adjustment, not better than 0.025 per cent, has been obtained; or, in the case of potentiometers, two steps of the lowest dial, or one-half division of the slide wire, accuracy not to exceed 0.025 per cent per coil of the first main dial. Coils of smaller value than 5 ohms will be checked not closer than 0.001 ohm. If all the coils are within the specified limit, the fees will be those given on page 29, under the corresponding Schedule 77. If any of the coils exceed the prescribed limit of adjustment, corrections will be given, and an additional fee will be charged for each such coil, equal to twice that of Schedule 75. If more than one-tenth of the coils thus exceed the limit of adjustment, the test will be made under Schedule 76.

H. ELECTRICAL PROPERTIES OF CONDUCTORS

See Fee Schedule 78, p. 30

Metallic wires or bars may be submitted for the determination of any one or more of the following electrical properties:

(1) Resistance per unit length.
(2) Resistance per meter-gram.
(3) Resistance per centimeter cube.
(4) The thermoelectric power against copper.
(5) Temperature resistance formula (temperature coefficient).

For any of the resistance measurements, the specimen should have (*a*) a length of between 117 and 130 centimeters (46 and 51 inches); (*b*) an area of cross-section very uniform, not larger than 1 square centimeter, and preferably not smaller than 1 square millimeter; otherwise the test will be special. The specimen should be straight, and be in the condition as regards annealing, etc., in which the test is to be made. For the measurement of the thermoelectric power against copper, the specimen should preferably be in the form of a wire of 1 square millimeter or less in cross-section, and not less than 25 centimeters in length.

Samples are ordinarily returned to the sender unless the Bureau is otherwise directed. The purpose for which the test is desired should be stated in the application. If the sample is to be used as a standard in a conductivity bridge, the points at which calibration is desired should be stated.

When the test involves the measurement of the mass per unit length, the ends of the sample should be carefully squared to facilitate the accurate measurement of the total length.

On most specimens submitted for test, an accurate resistance measurement can only be made between potential connections, which are generally made by knife edges pressing lightly against the side of the specimen. The total resistance of the sample can not, therefore, be determined directly. The resistance per unit length is obtained by measuring the resistance of a known length of the sample, usually 1 meter.

The determination of the resistance per meter-gram involves measurement of the total length and mass of the sample, and the resistance of a known fraction of the total length. The calculation is based on the assumption that the remaining fraction has the same resistance per unit length as that between the potential connections.

The determination of the resistance per centimeter cube (the specific resistance or the reciprocal of the specific conductivity) involves the measurement of the mean cross-section, as well as the resistance of a known length. The mean cross-section may be obtained from micrometer measurements of the diameter at a number of points along the sample, but a better precision is generally obtained by measuring the total mass and length and the mean density. The measurement of the density is a tedious operation, and will not be undertaken in connection with regular tests under this schedule. For practical purposes it has been found that for copper an assumed density of 8.89 gives sufficiently accurate results.

In the case of copper, results can be expressed in terms of "percentage conductivity" of the Matthiessen standard, for measurements either of resistance per meter-gram or resistance per centimeter cube. The

Matthiessen standard represents the conductivity found by Matthiessen in 1862 for soft copper, which was supposed to be pure. However, improved methods of purification have resulted in the production of soft commercial copper having a percentage conductivity of over 100 per cent on this basis. The percentage conductivity of a sample on the "meter-gram basis" is the reciprocal of the ratio of its resistance at 20° C per meter-gram to a resistance of 0.15302 ohm[4] per meter-gram at 20° C. The percentage conductivity on the "centimeter cube basis" is the reciprocal of the ratio of its specific resistance at 20° C in micro-ohms per centimeter cube to a specific resistance of 1.7213 micro-ohms per centimeter cube at 20° C. The two percentage conductivities are identical if the density of the sample is 8.89.

Since the data of value to the purchaser of conductors for power transmission, telegraphy, telephony, etc., is given by the "meter-gram" rather than the "centimeter cube" resistance, it is recommended that the former be used in the specification of conductors. The relative cost to such users of conductors of the same or even of different metals is given simply by multiplying the cost per unit mass by the resistance per meter-gram. (This statement of course neglects differences in insulation, differences of stranding of wires and cables, economy of space, etc.). The actual resistance per meter-gram at 20° C is preferred to percentage conductivity, because of the possible confusion in the use of the latter, and the fact that the use of the term "percentage conductivity" should be restricted to copper. Accordingly, to specify that the resistance per meter-gram shall be not greater than 0.1530 at 20° C is equivalent to specifying that the conductivity shall be not less than 100 per cent Matthiessen standard.

When a sample is submitted for the determination of the resistance per meter-gram, the resistance per meter and the mass per meter will be measured and given in the certificate. The computed resistance per meter-gram, and in the case of copper the percentage conductivity on the meter-gram basis, will also appear on the certificate.

When a sample is submitted for the determination of the resistance per centimeter cube (or specific resistance or conductivity), the resistance per meter, mean diameter, and mass per meter will be measured and given in the certificate. The certificate will also give the specific resistance, and in the case of copper the percentage conductivity, both calculated from the measured diameter, and on the meter-gram basis, calculated from the mass per meter. (This "meter-gram" percentage conductivity is identical with the "centimeter cube" percentage conductivity obtained on the assumption of a density of 8.89.) The latter method of determining the conductivity is not recommended; the meter-gram test contains everything but the cross-section measurement, which is very unreliable for small wires.

The resistance measurements of copper and aluminum may sometimes be made at a temperature other than 20° C. In such cases the value found will be corrected to 20° C, assuming, for the present, that the change in resistance per degree centigrade is 0.387 per cent of the value at 20° C, corresponding to a temperature coefficient of 0.42 per cent at 0° C.

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[4] This value for the resistance of the Matthiessen standard was obtained by applying the temperature coefficient found by Matthiessen to his value for the resistance at 0° C. A different 20° value is used to some extent elsewhere, derived by applying a more nearly correct temperature coefficient. But since Matthiessen's measurements at 20° C were as reliable as those at 0° C, it is clear that the use of the temperature coefficient he derived gives the correct weight to all his observations.

When a determination of temperature coefficient is desired, it will ordinarily be derived from measurements made at 20° C and 30° C.

The precision certified for resistance per unit length will be not better than 0.03 per cent, for resistance per meter-gram 0.05 per cent, and for resistance per centimeter cube 0.2 per cent. The precision given for a temperature coefficient will be that attainable by measurements of the resistance to 0.02 per cent, and of the temperature to 0.05°.

The thermoelectric power against copper of alloys to be used in resistance standards will be determined by connecting each end of the specimen to a copper wire and measuring the electromotive force in the circuit when one junction is at 20° C and the other junction at 30° C. The precision given will be that attainable by the measurement of the temperature difference to 0.05°, and the electromotive force to one microvolt, provided the specimen is sufficiently uniform to permit of this precision.

I. STANDARD CELLS

See Fee Schedule 79, p. 30

The recent improvements in the construction of Clark and Weston standard cells, obtained through a careful study of the methods of preparation and purification of the materials employed, has made it possible to set up cells from different materials agreeing with each other to two or three parts in 100 000. If the specifications published in Reprint 70, Bulletin of the Bureau of Standards, be followed, an accuracy of reproduction of at least 0.01 per cent should be attained, even under unfavorable conditions. The Weston normal cell, with its very small temperature coefficient and freedom from certain other defects, is to be preferred to the Clark. To secure the best results, such cells should be hermetically sealed, or sealed in such a manner that they can be placed in an oil bath without danger of developing a leak.

For all purposes except when the highest accuracy is sought the portable Weston cell, as put on the market by the Weston Electrical Instrument Company, and differing from the above only in that the solution of cadmium sulphate is saturated at approximately 4° C, has a considerable advantage. No oil bath is needed, and the change in electromotive force with temperature over a wide range is negligible for most purposes.

In view of the more limited accuracy of reproduction of the Clark cell, set up in accordance with the older specifications, and from which the basis of reference is derived, the results can only be certified to 0.02 per cent. Although the accuracy of reproducibility of the reference cells may be placed at two parts in 100 000, cells of the same type can be compared with an accuracy of one or two parts per million.

Cells submitted for certification will be measured at least twice against secondary standards known in terms of the reference cells of the Bureau. If the cells are so constructed that they can be measured in an oil bath, they will be measured at one temperature, 25° C, and otherwise at room temperature, which changes little during twenty-four hours, with a seasonal range of 22° to 28°.

J. SPECIAL TESTS

The special requirements of scientific investigators, manufacturers of apparatus, and others for higher precision than is considered in the foregoing schedules will be met as far as the regular work of the Bureau will permit. In investigating the behavior of electrical standards, variations are noted with certainty in a shorter time when the precision of measurement is high. The Bureau will gladly cooperate with those who need the highest precision in their work, both in the design and testing of apparatus.

A few suggestions in regard to resistance apparatus of the highest precision will be given here. To attain a higher accuracy than 0.01 per cent, the variation of the resistances with temperature must be considered. For efficient temperature control oil immersion is essential, and either the variation of the resistances with temperature should be known, and the temperature determined during measurements; or the oil should always be brought to the temperature of the calibration whenever the apparatus is used. Some means for stirring the oil is also desirable. The use of oil also enables the use of higher currents in the coils, as the heat is more readily dissipated in the oil. Oil immersion also reduces thermoelectric troubles of slide wires. It is recommended that the containing case be sealed, thus protecting the resistances from the action of atmospheric moisture. Where accurate calibration of coils under 10 ohms is desired, auxiliary potential connections to the terminal blocks are indispensable. Such connections must also be provided to the branch points and terminals of ratio coils under 100 ohms. Coils are usually connected to the blocks through copper posts. Frequently each block carries only one such post, and the terminals of adjacent coils are both soldered to its end. This construction is satisfactory for coils greater than 100 ohms, but to avoid errors in calibration of the lower values a separate post should be provided for the connection of each coil to the block. If the highest precision is desired in the use of the lower resistances, switches and plugs are unsatisfactory, and recourse must be had to the use of mercury contacts. Such contacts, when kept clean, are constant to 0.000002 ohm. Caution is however required to avoid short-circuiting the coils by stray drops of mercury between the blocks. This trouble may be eliminated by raising each metal block up on an insulating block.

Tests made to a higher accuracy than 0.01 per cent; tests of bridges, etc., at other than room temperatures; and, in general, approved tests not provided for in the other schedules, will be considered special, and a special fee will be charged for them. The application for a special test should state fully the purpose for which the apparatus has been used or is to be used in the future, the need for the test, and the precision desired. The test should be arranged for by correspondence before shipment of the apparatus. The special fee charged will depend chiefly upon the time consumed and the amount of alteration required in the regular bureau testing set-ups. An estimate will be given when possible.

6. CERTIFICATES AND REPORTS

When apparatus submitted fulfills the requirements for certification, it will be tested and given a certificate of corrections. The certificate can only indicate the corrections of the apparatus at the time of the test, and does not guarantee the constancy of the values. When there are defects which exclude an apparatus from certification, a report will be rendered giving such information as we have found. In such cases, a special fee will be charged, depending upon the time consumed.

7. GENERAL INSTRUCTIONS TO APPLICANTS FOR TESTS

APPLICATION FOR TEST.—The request for test should be made in writing, addressed to "Bureau of Standards, Washington, D. C.," and should enumerate the articles submitted for test, giving the identification marks of each—for example, maker's name and number—and should state the nature of the test desired.

NATURE OF TEST.—The classification of tests in this circular should be followed, and the schedule numbers above should be used to indicate the test desired. Applicants for the Grade A tests should state the character of the work for which the apparatus is to be employed. When the desired test is not included under the regular schedules, the applicant must comply with the requirements for special tests on page 24. When apparatus is sent simply for test, without definite instructions, the Bureau will, if practicable, decide upon the nature of the test.

CONDITION OF APPARATUS.—Before submitting apparatus for test, the applicant should ascertain that it fully satisfies the requirements for the test desired. The specifications for the various kinds of apparatus are given in the separate schedules above; these are in general liberal, but represent what experience has shown to be necessary for reliability. Apparatus of radically new design, or otherwise not included in the specifications, will be considered on its merits. All apparatus must be in good working condition; the insulation must be adequate, and contacts must be clean, etc. No repairs will be made; if they are needed, they should either be made by the applicant or the apparatus should be sent to the maker before submitting for test. All possible care will be taken in handling apparatus, but the risk of injury or breakage in shipment or under test must be borne by the applicant.

IDENTIFICATION MARKS.—All packages should bear the shipper's name and address and, when convenient, a list of the contents.

Each separate piece of apparatus, resistance standard, standard cell, or sample of material should be provided with an identification mark, which in most cases may be the maker's name and number. The identification mark should be given in the application for the test.

SHIPPING DIRECTIONS.—Apparatus or test specimens should be securely packed in cases or packages which will not be broken in transportation. The shipment in both directions is at the applicant's risk. To facilitate packing and shipping, the tops of the cases should have the return or forwarding address on the under side and should be put on with screws. Transportation charges are payable by the party desiring the test and must be prepaid. Unless otherwise arranged articles will be returned or forwarded by express "collect."

RETURN OF APPARATUS.—Regular tests will be made in the order in which the applications are received, except as this practice may be varied by grouping similar tests together. It is therefore suggested that the applicant make request for a test from two weeks to a month preceding the shipment of the apparatus. This facilitates the work of the Bureau, as well as the prompt return of the apparatus.

ADDRESS.—Apparatus submitted for test, as well as all correspondence, should be addressed simply "Bureau of Standards, Washington, D. C." Apparatus delivered in person or by messenger should be accompanied by a written request for the test.

REMITTANCES.—Fees should be sent with the request for test, in accordance with the foregoing schedules, or promptly upon receipt of bill. Certificates are not given nor is apparatus returned until the fees due thereon have been received. Remittances may be made by money order or check drawn to the order of the "Bureau of Standards."

8. OTHER ELECTRICAL TESTING

In addition to the electrical testing described in this circular, the Electrical Division of the Bureau undertakes other tests, as follows:

The testing of electrical measuring instruments is described in full in Circular No. 20; the accurate determination of the constants of condensers and inductance coils will be covered by a circular soon to be issued; magnetic testing is described in Circular No. 17. These circulars will be sent to interested parties on request.

9. SCHEDULES OF FEES FOR TESTING

SCHEDULE 71

Precision Resistance Standards

Grade A.—Maximum accuracy, 0.005 per cent

Denomination	Accuracy	I		II	III	IV
		Number of temperatures	Fee	Extra fee for additional measurement	Fee for measurement at 25° C, standards previously certified	Fee for measurement at 25° C, standards not previously certified
	Per cent					
(*a*) 1 ohm	0.005	3	$4.00	$1.25	$2.00	$2.50
(*b*) 10 "	.005	3	4.00	1.25	2.00	2.50
(*c*) 100 "	.005	3	5.00	1.50	2.50	3.00
(*d*) 1000 "	.005	3	5.00	1.50	2.50	3.00
(*e*) 10000 "	.01	2	5.00	1.50	2.50	3.00
(*f*) 100000 "	.02	2	5.00	1.50	2.50	3.00
(*g*) 0.1 "	.005	3	4.00	1.25	2.00	2.50
(*h*) 0.01 "	.005	3	5.00	1.50	2.50	3.00
(*i*) 0.001 "	.01	2	5.00	1.50	2.50	3.00
(*j*) 0.0001 "	.01	2	6.00	2.00	3.00	3.50

(*k*) For standards having values 2, 3, 4, or 5 times any of the above, and between 1 and 100 000 ohms, the fees will be 30 per cent additional.

The additional fee of II is either for a measurement made a month or more after the I measurement, the standard remaining at the Bureau between the measurements, to determine the constancy of the standard over that interval; or, for an additional measurement with a current larger than the usual test current.

Under III are included standards certified at the national testing laboratories of Germany, England, or France, accompanied by certificate, as well as standards previously certified at this Bureau.

SCHEDULE 72

Precision Resistance Standards

Grade B.—Maximum accuracy, 0.025 per cent

(Fees for measurement at one temperature, 25° C.)

(*a*) 1, 10, and 0.1 ohm standards	$1.50
(*b*) 100, 1000, 10 000, 0.01, and 0.001 ohm standards	2.00
(*c*) 100 000 and 0.0001 ohm standards	2.50

(*k*) For standards having values 2, 3, 4, or 5 times any of the above, the fees will be 30 per cent additional.

SCHEDULE 73

Resistance Standards for Current Measurement

Grade A.—Accuracy, 0.01 per cent

Denomination	I Measurement at room temperature with low test current	II Extra fee for additional measurement with low test current, 10° above room temperature	III Extra fee for additional measurement with test current not exceeding—
(*a*) 1. ohm	$2.50	$2.00	3 amp., $1.00
(*b*) .1 "	2.50	2.00	15 " 1.25
(*c*) .01 "	3.00	2.00	100 " 1.50
(*d*) .001 "	3.50	2.00	500 " 1.75
(*e*) .0001 "	4.00	2.00	1000 " 2.00

(*k*) For standards having values 2, 3, 4, or 5 times any of the above, the fees will be 40 per cent additional.

"Low test current" above signifies a test current so small as to produce no appreciable heating of the standard.

SCHEDULE 74

Resistance Standards for Current Measurement

Grade B.—Accuracy, 0.025 per cent

Denomination	I Measurement at room temperature with low test current	II Extra fee for additional measurement with test current not exceeding—
(*a*) 1. ohm	$2.00	3 amp., $0.75
(*b*) .1 "	2.00	15 " 1.00
(*c*) .01 "	2.50	100 " 1.25
(*d*) .001 "	3.00	500 " 1.50
(*e*) .0001 "	3.50	1000 " 1.75

(*k*) For standards having values 2, 3, 4, or 5 times any of the above, the fees will be 40 per cent additional.

SCHEDULE 75

Precision Resistance Apparatus

Grade A.—Accuracy (in general), 0.01 per cent

(a)	**Minimum fee for each piece of apparatus**	**$3.00**
(b)	**Rheostats, bridges (excepting ratio coils), potentiometers (excepting coils for reducing range), etc., per coil**	**.25**
(c)	**Ratio coils of bridges, per coil**	**.50**
(d)	**Calibration of slide wire, per point**	**.25**
(e)	**Reduction factors for potentiometer, per factor**	**2.00**
(f)	**Cleaning contacts, per contact**	**.10**
	VOLT BOXES, FACTORS—	
(g)	**Test with low voltage, per factor**	**1.50**
	Test with service voltage (maximum 750 volts)—	
(h)	**factors 2, 3, 5, or 10, each**	**2.00**
(i)	**factors 20, 30, 50, or 100, each**	**3.00**
(j)	**factors 200, 300, 500, or 1000, each**	**4.00**

SCHEDULE 76

Precision Resistance Apparatus

Grade B.—Accuracy (in general), 0.025 per cent

(a)	**Minimum fee for each piece of apparatus**	**$2.50**
(b)	**Rheostats, bridges (excepting ratio coils), potentiometers (excepting coils for reducing range), etc., per coil**	**.20**
(c)	**Ratio coils of bridges, per coil**	**.40**
(d)	**Calibration of slide wire, per point**	**.20**
(e)	**Reduction factors for potentiometers, per factor**	**1.50**
	VOLT BOXES, FACTORS—	
(f)	**Test with low voltage, per factor**	**1.00**
	Test with service voltage—	
(g)	**factors 2, 3, 5, or 10, each**	**1.50**
(h)	**factors 20, 30, 50, or 100, each**	**2.50**
(i)	**factors 200, 300, 500, or 1,000, each**	**3.50**

SCHEDULE 77

Precision Resistance Apparatus

Grade C.—Checking to an accuracy of 0.025 per cent

(a)	**Minimum fee for each piece of apparatus**	**$2.00**
(b)	**Rheostats, bridges (excepting ratio coils), potentiometers, etc., per coil**	**.15**
(c)	**Ratio coils of bridges, per coil**	**.30**
(d)	**Calibration of slide wire, per point**	**.15**
(e)	**Reduction factors for potentiometers, per factor**	**1.00**
	VOLT BOXES, FACTORS—	
(f)	**Test with low voltage, per factor**	**1.00**
	Test with service voltage—	
(g)	**factors 2, 3, 5, or 10, each**	**1.25**
(h)	**factors 20, 30, 50, or 100, each**	**2.00**
(i)	**factors 200, 300, 500, or 1000, each**	**3.00**

NOTE.—If the accuracy of adjustment is found not to be within the limits specified throughout, an additional fee will be charged (see p. 21).

SCHEDULE 78

Electrical Properties of Conductors

(a)	Resistance per unit length	$2.00
(b)	Resistance per meter-gram	3.00
(c)	Specific resistance (and percentage conductivity)	4.00
(d)	Resistance temperature formula	5.00
(e)	When the resistance is less than .001 ohm per meter, additional fee	1.00
(f)	For the calibration of standards for conductivity bridges (the fee may depend on the time required in making the test), per point	2.00
(g)	Thermoelectromotive force against copper	2.50

SCHEDULE 79

Standard Cells

Accuracy, 0.0002 volt

(a)	Testing standard cells at one temperature, about 25° C	$2.00

S. W. Stratton,
Director.

Approved:
Charles Nagel,
Secretary.