DEPARTMENT OF COMMERCE

CIRCULAR

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 31

COPPER WIRE TABLES

[3d Edition]
Issued October 1, 1914

DEPARTMENT OF COMMERCE
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28. The Determination of the Optical Properties of Materials.
29. Announcement of a Change in the Value of the International Volt.
30. Lime: Its Properties and Uses.
31. Copper Wire Tables.
32. Standard Regulations for Manufactured Gas and Gas Service (2 ed.).
33. United States Government Specifications for Portland Cement.
34. The Relation of the Horsepower to the Kilowatt.
35. Melting Points of Chemical Elements.
36. The Testing and Properties of Electric Condensers.
37. Electric Wire and Cable Terminology.
38. The Physical Testing of Mechanical Rubber Goods.
39. Specifications for and Measurement of Standard Sieves.
40. Sodium Oxalate as a Standard in Volumetric Analysis.
41. Testing and Properties of Textile Materials.
42. Metallographic Testing.
43. The Metric Carat.
44. Polarimetry.
45. The Testing of Materials.
46. Testing of Barometers.
47. Units of Weight and Measure; Definitions and Tables of Equivalents.
48. Standard Methods of Gas Testing.
49. Safety Rules to be Observed in the Operation and Maintenance of Electrical Supply Utilities.

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This circular, with its tables, is of interest chiefly to electrical engineers. It was prepared at the request and with the cooperation of the Standards Committee of the American Institute of Electrical Engineers. The tables are based upon the international standard values for the resistivity, temperature coefficient, and density of copper, as defined by the International Electrotechnical Commission. The first edition was issued April 1, 1912. The second edition was issued January 1, 1914, the main difference between the editions being slight changes in the basis of computation of resistance at the higher temperatures, as explained on page 29. This edition differs from the preceding ones mainly in the addition of Appendix V.

S. W. Stratton,
Director.

Approved:
E. F. Sweet,
Assistant Secretary.

CONTENTS

PART 1. HISTORICAL AND EXPLANATORY

PART 2. TABLES

PART 3. APPENDIXES

COPPER WIRE TABLES

PART 1. HISTORICAL AND EXPLANATORY

I. INTRODUCTION

1. STANDARD VALUES FOR RESISTIVITY AND TEMPERATURE COEFFICIENT OF COPPER

Copper wire tables are based on certain standard values for the conductivity or resistivity and the temperature coefficient of resistance of copper. When accuracy is important, the electrical engineer does not consult the wire table, but makes actual measurements of the resistivity of samples of the copper used. Frequently the resulting conductivity is expressed in per cent of the standard value assumed for conductivity. Per cent conductivity is meaningless without a knowledge of the standard value assumed, unless the same standard value is in use everywhere. But the standard value was not formerly the same everywhere, as may be seen by inspection of Table I, page 35, and confusion in the expression of per cent conductivity has accordingly resulted. The temperature coefficient of resistance is usually assumed as some fixed standard value, but the standard value was not formerly the same everywhere, and results reduced from one temperature to another have accordingly been uncertain when the temperature coefficient assumed was not stated. These conditions led the Standards Committee of the American Institute of Electrical Engineers to request the Bureau of Standards to make an investigation of the subject. This was done and resulted in the establishment of standard values based on measurements of a large number of representative samples of copper—values which in certain respects are more satisfactory than any preceding standard values. The investigation is described below. This investigation finally led to the adoption of an international copper standard by the International Electrotechnical Commission.

Table I gives a number of the most important standard values that have been in use. (See p. 39 for the table and p. 27 for a short explanation of the table.) The resistivity is uniformly given in terms of the resistance in ohms of a uniform wire 1 meter long weighing a gram. This unit of mass resistivity is conveniently designated for brevity as ohms (meter, gram). The density is also given, through which the volume resistivity may be obtained, so that resistance may be calculated from dimensions. All the standard values given are for *annealed copper*. The units of resistivity are discussed in Appendix I, p. 60.

The values formerly used in England, column 1, are those defined by the Engineering Standards Committee of the (British) Institution of Electrical Engineers in a report of August, 1904, also revised and reissued in March, 1910. The value of resistivity, 0.1508 ohm (meter, gram) at 60° F, or 15.6° C, "is taken as the Engineering Standards Committee (E. S. C.) standard for annealed high conductivity commercial copper." This value was based on results obtained by Matthiessen [1] in 1862 on supposedly pure copper. It does not actually represent Matthiessen's results, however, because it was calculated by the use of a ratio of resistivity of hard-drawn to annealed copper = 1.020, which value was not given by Matthiessen. The temperature coefficient of 0.002 38 per degree F was "adopted for commercial purposes." This is equivalent to 0.004 28 per degree C at 0° C. This value was based on the measurements of Clark, Ford, and Taylor [2] in 1899 and happens also to be the same as that determined by Dewar and Fleming [3] in 1893. The density was taken to be 555 pounds per cubic foot at 60° F or 8.89 grams per cubic centimeter at 15.6° C.

The former German copper standards (column 2) were established by the Verband Deutscher Elektrotechniker.[4] Standard copper, "Normal Kupfer," was defined to be that whose conductivity amounts to 60 (conductivity is taken to be the reciprocal of the volume resistivity expressed in ohms for a meter length and square millimeter cross section at 15° C). The density to be assumed when it is not actually determined was given as 8.91. The temperature coefficient of resistance was taken to be 0.004 at 15° C. Using these values, the resistivity in ohms (meter, gram) was calculated, and given in column 2. In order to facilitate comparison of these values with the other standard values, the data were also reduced to mass resistivity using the density, 8.89, and these results are given in column 3. These German copper standards have been in use also in Austria.

The results of Matthiessen [5] have been used more than any others heretofore in the establishment of standard values for the resistivity and temperature coefficient of copper. The ambiguities in the form in which these results were originally stated have caused disagreements in the

[1] Phil. Trans., **152**, p. 1; 1862. Pogg. Ann., **115**, p. 353; 1862. Report of Brit. Ass., p. 365; 1864. Phil. Mag., **29**, p. 361; 1865.

[2] London Elec., **42**, p. 786; 1899. Elec. World and Eng., **33**, p. 516; 1899; and **35**, p. 389; 1900.

[3] Phil. Mag., **36**, p. 271; 1893.

[4] "Normalien Vorschriften und Leitsätze," p. 68; 1907. E. T. Zs., **17**, p. 402; 1896.

[5] See note 1.

standard values based on them. Matthiessen originally expressed the conductivity as a percentage of the conductivity of pure silver and later gave an interpretation of this in B. A. ohms (meter, gram) for a hard-drawn wire. Later authorities have found varying results in reducing this to international ohms for annealed copper at various temperatures. Accordingly the term "Matthiessen Standard" has not a universally fixed significance. The Matthiessen value is not in use in Germany, but it has been computed by Prof. Lindeck,[6] of the Physikalisch-Technische Reichsanstalt, for 15° C. His result is 1.687 microhm-cm at 15° C. This has been reduced to ohms (meter, gram) at various temperatures, and given in column 4, assuming the density 8.89, and assuming "Matthiessen's temperature formula," viz, that given [7] by Matthiessen and von Bose in 1862.

The temperature formula of Matthiessen has been used in the past probably more than any other. The undesirability of using it is clear, for a number of reasons. It employs two terms, the first and second powers of temperature, while all work done up to the present for moderate temperature ranges is expressed with sufficient accuracy for practical purposes by a linear formula. It is given in terms of conductivity instead of resistance. Various persons have computed the equivalent formula in terms of resistance and some have carried out their formulas [8] to the fifth power of temperature. In either form the formula is far from being a convenient one. Furthermore, the many digits of Matthiessen's coefficients are without significance, the first, 0.003 870 1, being the mean of a number of values ranging from 0.003 735 1 to 0.003 995 4, and similarly for the second.

The copper standards adopted by the American Institute of Electrical Engineers [9] in 1893 were based upon the results of Matthiessen and are given in column 5. The resistivity of annealed copper was given as 0.141 729 international ohm (meter, gram) at 0° C, and Matthiessen's temperature formula was adopted. A wire table based on these standards was published at the same time. In the calculation of the values the following constants were used: Density = 8.89, ratio of resistivity of hard-drawn to annealed copper = 1.0226, one B. A. unit = 0.9866 international ohm.

In the 1907 Standardization Rules, Matthiessen's temperature formula was dropped by the A. I. E. E. and the linear temperature coefficient of 0.0042 at 0° C was adopted (column 6). This temperature coefficient was an average value of more than 100 determinations made in the laboratories

[6] C. Hering, "Conversion Tables," p. 104 (published by John Wiley & Sons, N. Y., 1904.)

[7] Phil. Trans., **152,** p. 1; 1862. Pogg. Ann., **115,** p. 353; 1862.

[8] Kennelly and Fessenden: Physical Review, **1,** p. 260; 1893. F. B. Crocker: London Elec., **58,** p. 968; 1907. R. T. Glazebrook: London Elec., **59,** p. 65; 1907.

[9] Trans. A. I. E. E., **10,** supplement, Oct., 1893.

of the General Electric Co. Since December, 1908, the Institute has issued its old wire table with a footnote stating that the values are consequently vitiated for temperatures other than 0° C. Both the old and the new A. I. E. E. values for the resistivity at 20° C have been in use in this country, and as these differed by 0.4 per cent, the difference was commercially important.

The values given in column 7 are those which were adopted by the Bureau of Standards and the American Institute of Electrical Engineers, and used during 1911, as a result of the investigations made at the Bureau. The International Annealed Copper Standard, given in column 8, is also based substantially on the work done at the Bureau. It was formally adopted at Berlin in September, 1913, by the International Electrotechnical Commission. It is to be noted that the temperature coefficients in columns 7 and 8 apply only to copper of the standard resistivity. The temperature coefficient of copper of different resistivities is given by the simple law of proportionality, discussed below. The wire tables in this circular are based on the values in column 8.

2. THE BASIS OF THE PRESENT TABLES—THE "INTERNATIONAL ANNEALED COPPER STANDARD"

(a) OBJECT OF THE BUREAU OF STANDARDS INVESTIGATIONS

The foregoing discussion makes evident the need which existed for data to be used in establishing reliable standard values. The differences in the old standard values for resistivity and for the temperature coefficient resulted in confusion. Apart from this, the assumption of a value for the temperature coefficient was particularly objectionable. For, since there is no good à priori reason for assuming that the temperature coefficient is the same for all samples of copper, the practice in the past of using a constant temperature coefficient for samples whose resistivity was known to vary, was not justified. The main objects of the investigation at the Bureau of Standards were, then, (1) to find whether the temperature coefficient of different samples varies, and if so to find whether there is any simple relation between the resistivity and the temperature coefficient, and (2) to determine a reliable average value for the resistivity of commercial copper. The results of the investigation were presented in two papers in volume 7, No. 1, of the Bulletin of the Bureau of Standards: "The Temperature Coefficient of Resistance of Copper," and "The Electrical Conductivity of Commercial Copper" (abstracts of which were given in Proc. A. I. E. E., **29**, p. 1995 and p. 1981; Dec., 1910). The results of the investigation and of the subsequent endeavor to establish international standard values are briefly summarized here.

(b) RESISTIVITY OF ANNEALED COPPER

For annealed samples representing the copper of 14 important refiners and wire manufacturers, measured at the Bureau of Standards, the mean results were:

Resistivity in ohms (meter, gram) at 20° C = 0.152 92.

The average deviation of the results from the various sources of samples from these means was 0.26 per cent.

The results of a large collection of data were also put at the disposal of the Bureau by the American Brass Co. For samples representing more than 100 000 000 pounds of wire bar copper, the mean results were:

Resistivity, in ohms (meter, gram) at 20° C = 0.152 63.

Both of these mean values of mass resistivity differ from the formerly used standard value, 0.153 022 ohms (meter, gram), by less than 0.26 per cent, which is the above average deviation from the mean. It was therefore concluded that it would be best to continue the use of said standard value for the mass resistivity of annealed copper, in the preparation of wire tables and in the expression of percent conductivity, etc. Accordingly, the formerly used standard resistivity at 20° C, together with the temperature coefficient determined in the investigation (giving the values tabulated in column 7, p. 39), were adopted and used as standard by the Bureau and by the American Institute of Electrical Engineers for a year or more. The results of the investigation were put before the engineers of other countries, and an endeavor was made to have an international value adopted. A proposal from Germany of a value differing slightly from the former American standard value was considered a suitable basis for an international standard, and the proposed value was finally adopted by the International Electrotechnical Commission in 1913. The new value is to be known as the International Annealed Copper Standard,[10] and is equivalent to

0.15328 ohm (meter, gram) at 20° C.

This resistivity is one-sixth per cent greater than the former American standard value (column 7, p. 39), and is one-third per cent greater than 0.15278, the mean of the experimental values published by the Bureau of Standards, and just given in the preceding paragraph. The International Annealed Copper Standard can therefore be considered as fairly representa-

[10] This name is used to indicate either the international resistivity in particular, or the whole set of values including temperature coefficient and density.

tive of average commercial copper. One of the advantages of this particular value is that in terms of conductivity it is an exact round number, viz,

$$58. \frac{1}{\text{ohm}} \text{ (meter, mm}^2\text{) at } 20^\circ \text{ C.}$$

The units of mass resistivity and volume resistivity are interrelated through the density; this was taken as 8.89 grams per cm^3 at 20° C, by the International Electrotechnical Commission. The International Annealed Copper Standard, in various units of mass resistivity and volume resistivity, is:

0.15328 ohm (meter, gram) at 20° C,
875.20 ohms (mile, pound)[11] at 20° C,
0.017241 ohm (meter, mm^2) at 20° C,
1.7241 microhm-cm at 20° C,
0.67879 microhm-inch at 20° C,
10.371 ohms (mil, foot) at 20° C.

In connection with the investigation made at the Bureau, a number of the companies who furnished samples of copper made chemical analyses. As a result of analyses of about 40 samples, the following is given as a fair average of the chemical content of commercial copper:

	Per cent
Copper	99.91
Silver	.03
Oxygen	.052
Arsenic	.002
Antimony	.002
Sulphur	.002
Iron	.002
Nickel	Trace.
Lead	Trace.
Zinc	Trace.

(c) THE TEMPERATURE COEFFICIENT OF RESISTANCE OF COPPER

While a standard resistivity is properly decided arbitrarily, the value of the temperature coefficient is a matter for experiment to decide. The Bureau of Standards' investigation of the temperature coefficient showed that there are variations of the temperature coefficient with different samples, but that the relation of conductivity to temperature coefficient is substantially a simple proportionality. This relation is in corroboration of the results of Matthiessen [12] and others for differences in conductivity due to chemical differences in samples; but this investigation showed that it holds also and with greater precision for physical differences, such as those caused

[11] The term "ohms (mile, pound)" is exactly equivalent to "pounds per mile-ohm," which is sometimes used. Either term means the product of ohms per mile into pounds per mile. "Ohms (mile, pound)" is chosen here, because of its agreement in form with "ohms (meter, gram)."

[12] Matthiessen and Vogt: Phil. Trans., **154**, p. 167; 1864.

by annealing or hard-drawing. Further evidence in regard to this relation has been obtained from the Physikalisch-Technische Reichsanstalt, of Germany. The results of tests at that institution show this relation for a wide range of conductivity, and the mean values agree well with those obtained at the Bureau of Standards. Some data have also been published by Prof. Lindeck,[13] of the Reichsanstalt, tending to show that the proportional relation holds also, but only roughly, for aluminum and for iron. The results obtained at the Bureau of Standards showed that, for copper samples of conductivity above 94 per cent, the actual temperature coefficients agreed with the values calculated from the conductivities within 0.000 01, i. e., about 0.3 per cent since the coefficients are of the order of 0.003 9. Tests made in 1913 by Mr. Geo. L. Heath, chief chemist of the Calumet & Hecla Smelting Works, showed that the law of proportionality holds over a much wider range of conductivity. He found that for 19 samples of cast copper whose only impurity was arsenic (besides the usual trace of oxygen), and whose conductivity ranged from 94 to 30 per cent, the actual temperature coefficients agreed with the values calculated from the conductivities within 0.000 1. The general law, then, may be expressed in the form of the following practical rule: *The 20° C temperature coefficient of a sample of copper is given by multiplying the number expressing the percent conductivity by 0.003 93.* The practical importance of this relation is evident, for it gives the temperature coefficient of any sample when the conductivity is known. Thus, the temperature coefficient for the range of conductivity of commercial copper may be exhibited by Table II, p. 40. Also, there are sometimes cases when the temperature coefficient is more easily measured than the conductivity, and the conductivity can be computed from the measured temperature coefficient. (The value, 0.003 93, is slightly different from the value given in Vol. 7, No. 1, of the Bureau Bulletin. This difference is necessitated by the change to a new standard of resistivity.)

Cases sometimes arise in practice where a temperature coefficient of resistance must be assumed. It may be concluded from the foregoing results that the best value to assume for the temperature coefficient of good commercial *annealed* copper wire is that corresponding to 100 per cent conductivity, viz:

$$\alpha_0 = 0.004\ 27,\ \alpha_{15} = 0.004\ 01,\ \alpha_{20} = \mathbf{0.003\ 93},\ \alpha_{25} = 0.003\ 85$$

$\left(\alpha_{20} = \frac{R_t - R_{20}}{R_{20}(t-20)}, \text{etc.}\right)$. This value was adopted as standard by the International Electrotechnical Commission in 1913. It would usually apply to instruments and machines, since they are generally wound with annealed

[13] Verhand. d. Deut. Phys. Gesell., 13, p. 65; 1911.

wire. It might be expected that the winding would reduce the temperature coefficient. But experiment has shown that distortions such as those caused by winding and ordinary handling do *not* affect the temperature coefficient, although they do affect the resistance.

Similarly, when assumption is unavoidable, the temperature coefficient of good commercial *hard-drawn* copper wire may be taken as that corresponding to a conductivity of 97.3 per cent, viz:

$$\alpha_0 = 0.004\ 14,\ \alpha_{15} = 0.003\ 90,\ \alpha_{20} = 0.003\ 82,\ \alpha_{25} = 0.003\ 75.$$

The *change of resistivity per degree* may be readily calculated, as shown in Appendix II, page 65, taking account of the expansion of the metal with rise of temperature. The proportional relation between temperature coefficient and conductivity may be put in the following remarkably convenient form for reducing *resistivity* from one temperature to another: *The change of resistivity of copper per degree C is a constant, independent of the temperature of reference and of the sample of copper. This "resistivity-temperature constant" may be taken, for general purposes, as 0.00060 ohm (meter, gram), or 0.0068 microhm—cm.* More exactly (see p. 66), it is:

0.000 597 ohm (meter, gram)
or, 0.000 0681 ohm (meter, mm^2)
or, 0.006 81 microhm—cm
or, 3.41 ohms (mile, pound)
or, 0.002 68 microhm—inch
or, 0.0409 ohm (mil, foot)

(d) CALCULATION OF PERCENT CONDUCTIVITY

The percent conductivity of a sample of copper is calculated by dividing the resistivity of the International Annealed Copper Standard at 20° C by the resistivity of the sample at 20° C. Either the mass resistivity or volume resistivity may be used. (See last paragraph on p. 64.) Inasmuch as the temperature coefficient of copper varies with the conductivity, it is to be noted that a different value will be found if the resistivity at some other temperature is used. This difference is of practical moment in some cases. For example, suppose the resistivity of a sample of copper is 0.1597 at 20° C; dividing 0.15328 by this, the percent conductivity is 96.0 per cent. Now the corresponding 0° C resistivity of the sample is 0.1478; dividing 0.1413 by this, the percent conductivity is calculated to be 95.6 per cent. In order that such differences shall not arise, the 20° C value of resistivity should always be used in computing the percent conductivity of copper. When the resistivity of the sample is known at some other temperature, *t*, it is very simply reduced to 20° C by adding the quantity, (20-*t*) multiplied by the "resistivity-temperature constant," given above.

(e) DENSITY OF COPPER

When it is desired to calculate the resistance of wires from dimensions, as in the calculation of wire tables, it is necessary that a density be given, in addition to the mass resistivity. *The international standard density for copper, at 20° C, is 8.89 grams per cubic centimeter.* This is the value which has been used by the A. I. E. E. and most other authorities in the past. Recent measurements have indicated this value as a mean. (See Appendix III, p. 67.) This density, 8.89, at 20° C, corresponds to a density of 8.90 at 0° C. In English units, the density at 20° C = 0.321 17 pounds per cubic inch.

(f) RESISTIVITY OF HARD-DRAWN COPPER WIRES

It was found that in general the resistivity of hard-drawn wires varies with the size of the wire, while the resistivity of annealed wires does not. The experimental evidence obtained was limited, but it showed, as was to be expected, that the difference between the resistivity of annealed and hard-drawn wires increases as the diameter of the wire decreases. This general conclusion is, however, complicated in any particular case by the particular practice of the wire drawer in regard to the number of drawings between annealings, amount of reduction to each drawing, etc. For No. 12 A. W. G. (B. & S.), the conductivity of hard-drawn wires was found to be less than the conductivity of annealed wires by *2.7 per cent.*

(g) THE HIGHEST CONDUCTIVITY FOUND

The lowest resistivity and highest conductivity found for a *hard-drawn* wire were:

Resistivity in ohms (meter, gram) at 20° C = 0.153 86
Per cent conductivity = 99.62%

and for an *annealed* wire were:

Resistivity in ohms (meter, gram) at 20° C = 0.150 45
Per cent conductivity = 101.88%

The former was a No. 12 wire, drawn from a cathode plate without melting. The latter wire was drawn directly from a mass of native lake copper which had never been melted down.

(h) ALUMINUM

On account of the commercial importance of aluminum as a conductor some investigation was made of that metal. The Aluminum Co. of America furnished a figure representing the mean conductivity of its output of all sizes of wire for five years past. As the figure is the result of many thousands of separate determinations, it is of great value. A volume resistivity of 2.828 microhm—cm, and a density of 2.70, may be considered to be good average values for commercial hard-drawn aluminum. These values give:

Mass resistivity, in ohms (meter, gram) at 20° C	= 0.0764
Mass resistivity, in ohms (mile, pound) at 20° C	=436.
Mass percent conductivity	=200.7%
Volume resistivity, in microhm—cm at 20° C	= 2.828
Volume resistivity, in microhm—inch at 20° C	= 1.113
Volume percent conductivity	= 61.0%
Density, in grams per cubic centimeter	= 2.70
Density, in pounds per cubic inch	= 0.0975

The same company furnished the results of analyses of seven representative samples of aluminum, of which the average was:

	Per cent.
Aluminum	99.57
Silicon	.29
Iron	.14

No extensive measurements are known to have been made, giving the average temperature coefficient of resistance of commercial hard-drawn aluminum; but from the experience of the Bureau a reliable approximate value can be given, viz, 0.0039 at 20° C.

3. STATUS OF THE INTERNATIONAL ANNEALED COPPER STANDARD

Ever since the American Institute of Electrical Engineers adopted the temperature coefficient, 0.0042 at 0° C, which vitiated the old wire table, the need for a new table was felt; and a recomputation of the old one had been under consideration. The need of more modern and representative data upon which to base the table had, however, been recognized, and, as stated above, the Bureau of Standards was requested to secure such data. The work was done in the first half of 1910, and reports of the investigations were presented to the Standards Committee of the Institute. At its meeting of October 14, 1910, that committee requested the Bureau of Standards to prepare copper wire tables based on the investigations, to replace the old wire table of the Institute. As a result of this action, a complete set of tables was prepared. On October 14, 1910, also, the United States Committee of the International Electrotechnical Commission voted that steps should be taken to interest the Commission in the subject of an international standardization of copper standards, and accordingly the question of standardizing the temperature coefficient was submitted to the other national committees by the United States national committee in letters of January 26, 1911. The question of a standard conductivity was considered by the national committees of several nations in September, 1911; and the result was an agreement among the representatives of Germany, France, and the United States to recommend a value proposed by Germany, differing only slightly from the value recommended by the Bureau and adopted by the Standards Committee of the American Institute of Electrical Engineers. The values for the temperature coefficent determined at the Bureau and corroborated at the German Reichsanstalt were accepted. In order to facilitate the establishment of an international standard, and at the request of the Standards Committee of the American Institute of Electrical Engineers and the United States Committee of the International Electrotechnical Commission, the publication of the copper wire tables was withheld and they were recomputed on the new basis.

In the two years from September, 1911, to September, 1913, these standard values were the subject of correspondence between the national laboratories of Germany, France, England, and the United States. They were favorably considered also by various committees of engineering societies. They were finally adopted by the International Electrotechnical Commission in plenary session at Berlin on September 5, 1913.

The commission issued a publication (I. E. C. Pub. 28, March, 1914) entitled "International Standard of Resistance for Copper," giving the values adopted and explanatory notes. This publication is reprinted as Appendix V of this Circular (p. 75).

The new values have been adopted in the 1914 Standardization Rules of the American Institute of Electrical Engineers. The British Engineering Standards Committee took up, in July, 1914, the work of revising its Report on Standard Copper Conductors, to bring it into conformity with the international standard.

The fundamental quantities in the international definitions are: the conductivity, 58; the density, 8.89; and the temperature coefficient, 0.00393. (See p. 75.) All the other numerical values follow from these three (except that the coefficient of linear expansion, 0.000017, must also be taken into account in some cases). In particular, the values given for 0° C at the end of Appendix V follow from these fundamental quantities. In order to avoid misunderstanding we give here the processes by which they are calculated. The coefficient 0.00426_5 is obtained by the simple formula

$$\alpha_0 = \frac{1}{\frac{1}{\alpha_{20}} - 20.}$$

The coefficient 0.00428_2 is obtained by adding 0.000017 to this, according to formula (32) on page 66. The value of resistivity at 0° C is given by the use of the temperature coefficient of volume resistivity as follows:

$$\rho_0 = \rho_{20}\left[1 - 20.(\alpha_{20} + 0.000017)\right] = \frac{1}{0.58}\left[1 - 20.(0.003947)\right] = 1.5880$$

This mode of calculation assumes that the *resistivity* is a strictly linear function of temperature. If, instead, the *resistance* be assumed as a strictly linear function of temperature, we must write:

$$\rho_0 = \rho_{20}\left[1 - 20.\alpha_{20}\right]\left[1 - 20.(0.000017)\right] = \frac{1}{0.58}\left[1 - 20.(0.00393)\right]\left[1 - 0.00034\right]$$
$$= 1.5881$$

The Bureau proposed the simpler calculation, leading to 1.5880, but the second calculation and 1.5881 were finally adopted because it is more convenient to think of the *resistance* as the strictly linear function.

II. WIRE GAGES

1. SHORT HISTORY OF WIRE GAGES

The sizes of wires were for many years indicated in commercial practice almost entirely by gage numbers. This practice was accompanied by considerable confusion because numerous gages were in use. Wire gages are in use now less than formerly, the specification of diameter directly being, in many cases, preferred; and, furthermore, the confusion is diminishing because practice is eliminating most of the gages and is assigning well-defined fields to the remaining ones. In an article [14] written in 1887, over 30 gages were described, 19 of which were wire gages. In addition to these there were a number of proposed gages. Among the wire gages that have survived, two are used extensively in this country, viz, the "American Wire Gage" (Brown & Sharpe) and the "Steel Wire Gage" (variously called the Washburn & Moen, Roebling, and American Steel & Wire Co.'s). Three other gages are still used to some extent, viz, the Birmingham Wire Gage (Stubs), the Old English Wire Gage (London), and the Stubs' Steel Wire Gage. There are in addition certain special gages, such as the Music Wire Gage, the drill and screw gages, and the United States Standard Sheet-Metal Gage. In England one wire gage has been made legal and is in use generally, viz, the "Standard Wire Gage." The diameters of the six general wire gages mentioned are given in mils in Table IV,

[14] S. S. Wheeler: Elec. World, **10**, 254; 1887.

page 42, and in millimeters in Table V, page 43. In Germany, France, Austria, Italy, and other continental countries practically no wire gage is used; size of wires is specified directly by the diameter in millimeters. This system is sometimes called the "millimeter wire gage." In France the sizes in use are to a considerable extent based on the old Paris gage ("jauge de Paris de 1857").

The *American Wire Gauge* was devised by J. R. Brown, one of the founders of the Brown & Sharpe Manufacturing Co., in 1857. It speedily superseded the Birmingham Wire Gage in this country, which was then in general use. It is perhaps more generally known by the name "Brown & Sharpe Gage," but this name is not the one preferred by the Brown & Sharpe Co. In their catalogues they regularly refer to the gage as the "American Standard Wire Gage." The word "Standard" is probably not a good one to retain in the name of this gage, since it is not the standard gage for *all* metals in the United States; and, further, since it is not a legalized gage, as are the (British) *Standard* Wire Gage and the United States *Standard* Sheet-Metal Gage. The abbreviation for the name of this gage has usually been written "A. W. G." The American Wire Gage is now used for more metals than any other in this country, and is practically the only gage used for copper and aluminum wire, and in general for wire used in electrical work. It is the only wire gage now in use whose successive sizes are determined by a simple mathematical law. This gage is discussed in detail below (p. 24).

The "*Steel Wire Gage*" is the same gage which has been known by the names of Washburn & Moen gage and American Steel & Wire Co.'s gage. This gage also, with a number of its sizes rounded off to thousandths of an inch, has been known as the Roebling gage. The gage was established by Ichabod Washburn about the year 1830, and was named after the Washburn & Moen Manufacturing Co. This company is no longer in existence, having been merged into the American Steel & Wire Co. The latter company continued the use of the Washburn & Moen Gage for steel wire, giving it the name "American Steel & Wire Co.'s gage." The company specifies all steel wire by this gage, and states that it is used for fully 85 per cent of the total production of steel wire. This gage was also formerly used by the John A. Roebling's Sons Co., who named it the Roebling gage, as mentioned above. However, the Roebling company, who are engaged in the production of wire for electrical purposes, now prefer to use the American Wire Gage.

It may be stated [15] that in so far as wire gages continue in use in the United States, the practice has been practically standardized to the use of *two gages,* the American Wire Gage for wire used in electrical work and for general use and the Steel Wire Gage for steel wire. This is perhaps as satisfactory a state of affairs as can be hoped for as long as wire gages continue in use, since the fields covered by the two gages are distinct and definite, and both gages are used for enormous quantities of material. Neither of these two gages (except for a small portion of the Steel Wire Gage) have the irregular gradations of sizes which make many of the gages objectionable. It is neither desirable nor probable that a single gage for wires will be prescribed by legislative enactment, as was done for sheet metal by the act of Congress approved March 3, 1893, establishing the "United States Standard Sheet-Metal Gage."

The trend of practice in the gaging of materials is increasingly toward the *direct specification of the dimensions in decimal fractions of an inch,* without use of gage numbers. This has been, for a number of years, the practice of some of the large electrical and manufacturing companies of this country. The United States Navy Department, also, in June, 1911, ordered that all diameters and thicknesses of materials be specified directly in decimal fractions of an inch, omitting all reference to gage numbers. The War Department, in December, 1911, issued a similar order, for all wires. Numerous engineering societies have gone on record as in favor of the direct use of diameters. The 1914 Standardization Rules of the American Institute of Electrical Engineers state that the sizes of solid wires shall be specified by their diameters in mils (but permit the use of the gage numbers for brevity, where careful specification is not required). The American Society for Testing Materials, in their Specifications for Copper Wire, recommend that diameters instead of gage numbers be used. This is similar to the practice on the Continent of Europe, where sizes of wire are specified directly by the diameter in millimeters. The practice of specifying the diameters themselves and omitting gage numbers has the advantages that it avoids possible confusion with other gage systems and states an actual property of the wire directly. An article presenting the disadvantages of gage numbers for wires, sheets, and tubes, and the advantages of the

[15] The information about wire gages was gathered from the writings on the subject in scientific literature and in the catalogues of manufacturers, and also from special correspondence with leading manufacturers in America and Europe, undertaken by the Bureau of Standards to find out the current practices.

The name "Steel Wire Gage" was suggested by the Bureau of Standards, in its correspondence with various companies, and it met with practically unanimous approval. It was necessary to decide upon a name for this gage, and the three names which have been used for it in the past were all open to the objection that they were the names of particular companies. These companies have accepted the new name. The abbreviation of the name of the gage should be "Stl. W. G.," to distinguish it from "S. W. G.," the abbreviation for the (British) Standard Wire Gage. When it is necessary to distinguish the name of this gage from others which may be used for steel wire, e. g., the (British) Standard Wire Gage, it may be called the United States Steel Wire Gage.

exclusive use of the "decimal system," from the viewpoint of the manufacturer, was published by G. E. Goddard in the American Machinist, March 2, 1911, page 400. He states that this practice was recommended so long ago as 1895 by a joint committee of the American Society of Mechanical Engineers and the American Railway Master Mechanics' Association. This system is recommended by the Bureau of Standards as the most satisfactory method of specifying dimensions of materials. It should always be followed in careful work and in contracts and specifications, even when the gage numbers are used for rough work. The correspondence which the Bureau of Standards has had with manufacturers of wire has shown that there is a general willingness and desire to have most or all of the gages eliminated. It therefore depends largely on the consumers of wire to simplify wire-gage practice, by ordering material according to dimension rather than gage numbers. The various national engineering societies, representing the users of wire, might succeed in educating consumers by taking up this matter actively.

When gage numbers are not used, it is necessary that a certain set of *stock sizes* be considered standard, so that the manufacturers would not be required to keep in stock an unduly large number of different sizes of wire. The large companies and societies which have adopted the direct use of diameters have recognized this, having taken as standard the American Wire Gage sizes, to the nearest mil for the larger diameters and to a tenth of a mil for the smaller. (See list of sizes, Table IV, p. 42.) These sizes were adopted, in December, 1911, by the United States War Department for all wires. It seems likely that this system of sizes, based on the American Wire Gage, will be perpetuated. This is fortunate, as the American Wire Gage has advantages over all other gages, which are described below; fortunately, also, practice is eliminating the many useless figures to which the theoretical diameters in the American Wire Gage may be carried.

The objection is often raised that the use of diameters requires the employment of a *micrometer;* and that the wire gage as an instrument, marked in gage numbers, is a very rapid means of handling wires and is indispensable for use by unskilled workmen. However, the use of the wire gage as an instrument is consistent with the practice of specifying the diameters directly, provided the wire-gage is marked in mils. Wire-gages marked both in the A. W. G. numbers and in thousandths of an inch can be obtained from the manufacturers. One thus reads off directly from the wire-gage 81 mil, 64 mil, etc., just as he would No. 12, No. 14, etc. (Of course, the diameters in millimeters could be marked on the gage for those who prefer the metric system.) It should not be forgotten, however, that a wire-gage gradually wears with use, and that for accurate work a micrometer should always be used.

Of the three wire gages which have remained in use but are now nearly obsolete, the one most frequently mentioned is the *Birmingham,* sometimes called the Stubs' Wire Gage. It is said to have been introduced early in the eighteenth century, and a table of its diameters is given in Holtzapffel's "Turning" (London, 1846). Its numbers were based upon the reductions of size made in practice by drawing wire from rolled rod. Thus, rod was called No. 0, first drawing No. 1, and so on. Its gradations of size are very irregular, as shown in Fig. 1. The V-shaped diagram is simply a picture of a wire-gage, marked with the Birmingham gage on the left and the American gage on the right. A similar diagram is given in the catalogue of the Brown & Sharpe Manufacturing Co. (1903, p. 422). The distance between the diverging lines at any point is the diameter of the wire whose gage number is given on the side. The Birmingham gage is typical of most wire gages, and the irregularity of its steps is shown in marked contrast to the regularity of the steps of the American Wire Gage. This contrast is also brought out in Fig. 2, page 22.

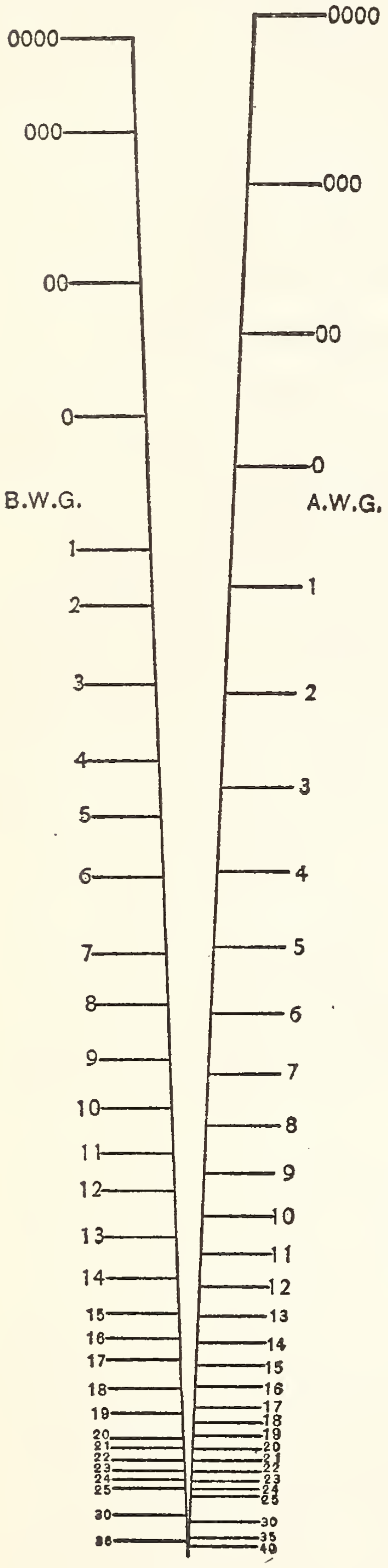

Fig. 1

Some of the later gages were based on the Birmingham. It was used extensively both in Great Britain and in the United States for many years. It has been superseded, however, and is now nearly obsolete. By the repeated copying of old specifications its use has persisted to some extent, both in England and the United States, for galvanized-iron telegraph wire. In this country such use has been limited largely to the large telegraph and telephone companies and certain departments of the Government. As stated above, the Government departments are now dropping the wire gages altogether. The telephone and telegraph companies are inclined to continue the use of the Birmingham gage, and seem to believe that the wire manufacturers prefer it. The manufacturers, however, would be glad to have wire gages eliminated, and, as stated before, it therefore depends largely on the consumers of wire to simplify wire gage practice.

The principal outstanding exception to the abandonment of the Birmingham gage heretofore has been that the Treasury Department, with certain legislative sanction, specified the Birmingham gage for use in the collection of duty on imports of wire. This gage was prescribed by the Treasury Department in 1875, after it had been ascertained that it was the standard gage "not only throughout the United States, but the world." This reason for the use of this gage does not now exist, inasmuch as the gage is now used very little in the United States, and even less in other countries. Up until 1914 the Treasury Department considered that it could not change its practice, since legislative approval had been given the Birmingham gage by the tariff acts with a provision for assessment of duty according to gage numbers, and further since a change would alter the rate of duty on certain sizes of wire. However, the 1913 Tariff Act specified the sizes of wires by the diameters in decimal parts of an inch instead of by gage numbers. This left the Treasury Department free to reject the Birmingham gage, which it did in August, 1914, adopting the American Wire Gage in its place.

The Old English or London gage, the sizes of which differ very little from those of the Birmingham gage, has had considerable use in the past for brass and copper wires, and is now used to some extent in the drawing of brass wire for weaving. It is nearly obsolete.

The Stubs' Steel Wire Gage has a somewhat limited use for tool steel wire and drill rods. This gage should not be confused with the Birmingham, which is sometimes known as Stubs' Iron Wire Gage.

The "*Standard Wire Gage*," otherwise known as the New British Standard, the English Legal Standard, or the Imperial Wire Gage, is the legal standard of Great Britain for all wires, as fixed by order in Council, August 23, 1883. It was constructed by modifying the Birmingham Wire Gage, so that the differences between successive diameters were the same for short ranges, i. e., so that a graph representing the diameters consists of a series of a few straight lines. This is shown in the graphical comparison of wire gages, Fig. 2. The curves show three typical wire gages, diameter being plotted against gage number. Attention is called to the regularity of the American Wire Gage curve, the utter irregularity of the Birmingham gage curve, and the succession of straight lines of which the Standard Wire Gage curve is composed. The lower ends of these curves are also shown, magnified 10 times.

While the Standard Wire Gage is the most used wire gage in Great Britain, we are informed by a large English electrical manufacturing company that the tendency is to adopt mils, or decimal fractions of an inch, rather than gage numbers, the same tendency as in the United States.

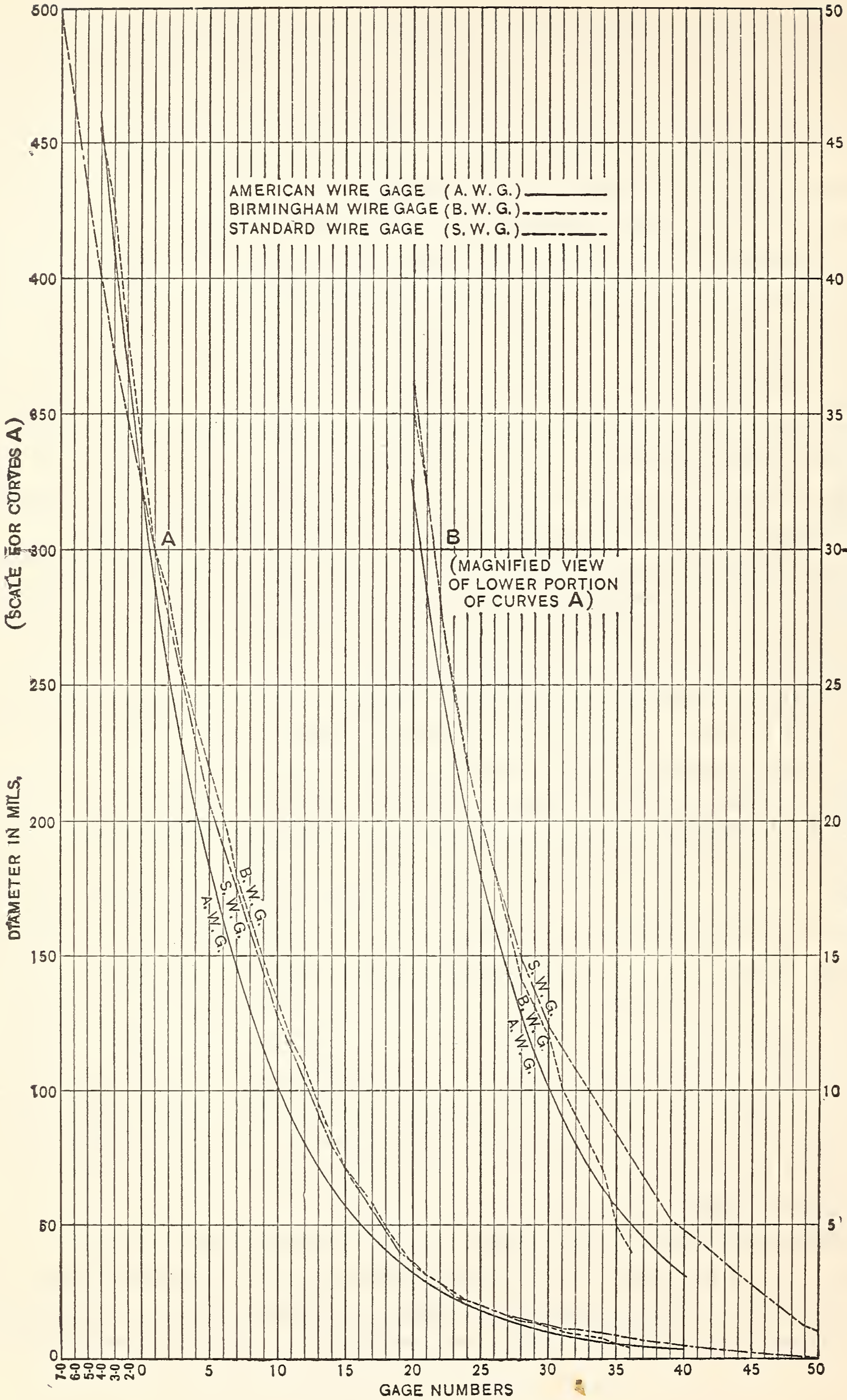

Fig. 2

To compare the curves, hold the page horizontally and glance along the curves.

There was once a movement to bring the "Standard Wire Gage" into general use in the United States. It was adopted in 1885 by the National Telephone Exchange Association, and in 1886 by the National Electric Light Association. The gage, however, never came into general use. In 1886, The Electrical World sent a letter to the principal makers and users of wire throughout the country inquiring about their practices in specifying wire and asking whether they would favor legislation enforcing the "Standard Wire Gage." The great majority of the replies showed that the "Standard Wire Gage" was not in use at all, and that the American Wire Gage was the most used, and also that there was a strong trend in favor of specifying sizes entirely by the diameter in mils.

Among the many *wire gages that have been proposed* but never came into much use may be mentioned especially Latimer Clark's Wire Gage, the Edison Standard Wire Gage, and the National Electric Light Association's Metric Wire Gage. The first of these, Clark's, was proposed in 1867, and was based on the same principle as the American Wire Gage, viz, each successive diameter obtained by multiplying the preceding by a constant. As Wheeler [16] justly remarked, its one virtue was its imitation of its prototype, the American gage. The Edison Standard Wire Gage, proposed by the Edison Electric Light Co. sometime before 1887, was based upon a different principle. The area of cross section increased proportionally with the gage numbers. No. 5 = 5000 circular mils, No. 10 = 10 000, and so on. The diameters, therefore, increased as the square root of the gage numbers. The circular mil classification is now actually used for the large sizes of copper wire and cables, but the Edison gage numbers are not used. The National Electric Light Association in 1887 dropped the (British) Standard Wire Gage, which it had adopted the year before, and adopted its Metric Wire Gage. This was nothing more than the German and French millimeter wire gage, giving numbers to the successive sizes, calling 0.1 mm diameter No. 1, 0.2 mm No. 2, and so on.

2. THE AMERICAN WIRE GAGE

(a) GENERAL USE OF THE AMERICAN WIRE GAGE

As stated above, in the United States practically the only gage now used for *copper* wire is the American Wire Gage (B. & S.). In sizes larger than No. 0000 A. W. G. copper conductors are practically always stranded. Sizes of stranded conductors are specified by the total cross section in circular mils. It is becoming more and more the practice for the large electrical

[16] See note 14, p. 16.

companies and others to omit gage numbers; and the stock sizes of copper wire used and specified by those who follow this practice are the American Wire Gage sizes, to the nearest mil for the larger diameters and to a tenth of a mil for the smaller. (See list of sizes in American Wire Gage, Table IV, p. 42.) Those who use the gage numbers do not draw or measure wires to a greater accuracy than this; and we accordingly see that a single system of sizes of copper wire is in use in this country, both by those who use gage numbers and those who do not.

(b) THE CHARACTERISTICS OF THE AMERICAN WIRE GAGE

The American Wire Gage has the property, in common with a number of other gages, that its sizes represent approximately the successive steps in the process of wire drawing. Also, like many other gages, its numbers are retrogressive, a larger number denoting a smaller wire, corresponding to the operations of drawing.

Its sizes are not so utterly arbitrary and the differences between successive diameters are more regular than those of other gages, since it is based upon a simple mathematical law. The gage is formed by the specification of two diameters and the law that a given number of intermediate diameters are formed by geometrical progression. Thus, the diameter of No. 0000 is defined as 0.4600 inch and of No. 36 as 0.0050 inch. There are 38 sizes between these two, hence the ratio of any diameter to the diameter of the next great number $= \sqrt[39]{\frac{.4600}{.0050}} = \sqrt[39]{92} = 1.122\,932\,2$. The square of this ratio $= 1.2610$. The sixth power of the ratio, i. e., the ratio of any diameter to the diameter of the sixth greater number $= 2.0050$. The fact that this ratio is so nearly 2. is the basis of numerous useful relations which are given below in "Wire table short cuts."

The law of geometrical progression on which the gage is based may be expressed in either of the three following manners: (1) the ratio of any diameter to the next smaller is a *constant number;* (2) the difference between any two successive diameters is a *constant per cent* of the smaller of the two diameters; (3) the difference between any two successive diameters is a *constant ratio* times the next smaller difference between two successive diameters.

The regularity of the American Wire Gage is shown by the curve on page 22, where it is graphically compared with two other wire gages. The gage is represented by an ordinary exponential curve. The curve would be a straight line if plotted to a logarithmic scale of diameters and a uniform scale of gage numbers.

(c) WIRE TABLE SHORT CUTS

Since the American Wire Gage is formed by geometrical progression, the wire table is easily reproduced from the ratio and one of the sizes as a starting point. There happen to be a number of approximate relations which make it possible practically to reproduce the wire table by remembering a few remarkably simple formulas and data. The resistance, mass, and cross section vary with the square of the diameter, hence by the use of the square of the ratio of one diameter to the next, viz, 1.2610, it is possible to deduce the resistance, mass, or cross section of any size from the next. This number may be carried in the mind as approximately 1¼. Furthermore, since the cube of this number is so very nearly 2., it follows that every three gage numbers the resistance and mass per unit length and also the cross section are doubled or halved. The foregoing sentence is a concise expression of the chief "wire table short cut." It is extremely simple to find, say, ohms per 1000 feet mentally, starting from the values for No. 10, as in the illustrative table below (p. 27). The approximate factors for finding values for the next three sizes after any given size, are 1¼, 1.6, 2.0. Furthermore, every 10 gage numbers the resistance and mass per unit length and the cross section are approximately multiplied or divided by 10.

No. 10 copper wire has approximately a resistance of 1 ohm per 1000 feet at 20° C, a diameter of 0.1 inch, and a cross section of 10 000 circular mils. The mass may also be remembered for No. 10, viz, 31.4 pounds per 1000 feet; but it will probably be found easier to remember it for No. 5, 100 pounds per 1000 feet; or for No. 2, 200 pounds per 1000 feet.

Very simple approximate formulas may be remembered for computing data for any size of wire. Let:

n = gage number (Take No. 0 = 0, No. 00 = −1, etc.).
R = ohms per 1000 feet at 20° C.
M = pounds per 1000 feet.
$C. M.$ = cross section in circular mils.

$$R = 10^{\frac{n-10}{10}} = \frac{10^{\frac{n}{10}}}{10} \qquad (1)$$

$$M = 10^{\frac{25-n}{10}} \qquad (2)$$

$$C. M. = 10^{\frac{50-n}{10}} = \frac{10^{5}}{10^{\frac{n}{10}}} \qquad (3)$$

These formulas may be expressed also in the following form, common or Briggs' logarithms being used:

$$\log (10R) = \frac{n}{10} \tag{4}$$

$$\log M = \frac{25 - n}{10} \tag{5}$$

$$\log \frac{C.M.}{100\,000} = -\frac{n}{10} \tag{6}$$

These formulas are also sometimes given in the equivalent but less useful form:

$$R = \frac{2^{\frac{n}{3}}}{10} \tag{7}$$

$$M = \frac{10^{2.5}}{2^{\frac{n}{3}}} = \frac{320}{2^{\frac{n}{3}}} \tag{8}$$

$$C.M. = \frac{100\,000}{2^{\frac{n}{3}}} \tag{9}$$

Formulas (1) and (4), (2) and (5) give results correct within 2 per cent for all sizes up to No. 20, and the maximum error is 5 per cent for No. 40; and the errors of formulas (3) and (6) vary from 6 per cent for No. 0000 to 2 per cent for No. 20, and less than 2 per cent for No. 20 to No. 40.

The sizes of copper rods and stranded *conductors larger than No. 0000* are generally indicated by circular mils. For such cases, resistance in ohms per 1000 feet at 20° C is given approximately by combining formulas (1) and (3); $R = \frac{10\,000}{C.M.}$ or, in other terms,

$$\text{Feet per ohm} = \frac{C.M.}{10} \tag{10}$$

Similar formulas may be deduced for the ohms and mass per unit length, etc., in *metric units*. For example, we have similarly to (4), letting r = ohms per kilometer,

$$\log (10r) = \frac{N+5}{10} \tag{11}$$

The *slide rule* may be used to great advantage in connection with these approximate formulas; (4), (5), (6), and (11), in particular, are adapted to slide-rule computation. Thus, to find ohms per 1000 feet, set the gage number on the slide-rule scale usually called the logarithm scale, and the resistance is given at once by the reading on the ordinary number scale of the slide rule.

An interesting additional "wire table short cut" is the fact that between Nos. 6 and 12, inclusive, the reciprocal of the size number = the *diameter* in inches, within 3 per cent.

A convenient relation may be deduced from the approximate formula frequently used by engineers, $I = ad^{\frac{3}{2}}$, in which d is diameter of wire, a is a constant for given conditions, and I is either the *fusing current* or the current which will raise the temperature of the conductor some definite amount. For I defined either way, every 4 gage numbers I is doubled or halved.

A simple table is appended here to show the application of some of the foregoing principles. It is for resistance in ohms per 1000 feet, using No. 10 as a starting point. A similar table might be made for mass in pounds per 1000 feet, or for cross section in circular mils, or for ohms per kilometer.

Gage No.	Ohms per 1000 Feet			Gage No.	Ohms per 1000 Feet			Gage No.	Ohms per 1000 Feet			Gage No.	Ohms per 1000 Feet		
0	0.1			10	1			20	10			30	100		
1		.125		11		1.25		21		12.5		31		125	
2			.16	12			1.6	22			16	32			160
3	.2			13	2			23	20			33	200		
4		.25		14		2.5		24		25		34		250	
5			.32	15			3.2	25			32	35			320
6	.4			16	4			26	40			36	400		
7		.5		17		5		27		50		37		500	
8			.64	18			6.4	28			64	38			640
9	.8			19	8			29	80			39	800		

III. EXPLANATION OF TABLES

Table I.—This table gives a number of the more important standard values of resistivity, temperature coefficient, and density that have been in use. The particular standard temperature in each column is indicated by bold-faced type, and the values given for the various other temperatures are computed from the value at the standard temperature. In each column the temperature coefficient of that column is used in computing the resistivity at the various temperatures. In some cases, e. g., in column 1, the standard temperature is not the same for resistivity and for temperature coefficient. The temperature coefficient is in each case understood to be the "constant mass temperature coefficient of resistance," which is discussed in Appendix II, p. 65. This has not usually been specifically stated in the definition of a standard temperature coefficient. It seems fair to assume that this mode of defining the temperature coefficient is implied in the various standard values, since the temperature coefficient most frequently used in practice is that of "constant mass," i. e., the temperature coefficient as measured between potential terminals rigidly attached to the wire. The resistivity is given in each case in terms of the resistance of a uniform wire 1 meter long weighing a gram. This unit of mass resistivity is conveniently designated for brevity as ohms (meter, gram). The advantages of this unit of resistivity are set forth in Appendix I, p. 60. The values given in Table I are fully discussed above, pages 5 to 12. Column 8 gives the international standards, used as the basis of the tables of this circular.

Table II.—This table is an embodiment of the proportionality between conductivity and temperature coefficient. The temperature coefficient at 20° C, α_{20}, was computed from n, the percent conductivity expressed decimally, thus simply:

$$\alpha_{20} = n\ (0.00393).$$

(The n used here and later in the circular has no relation whatever to the n used on pp. 25 and 26.) The complete expression for calculating α_{t_1}, the temperature coefficient at any temperature, is given in the note to the table. The values given for α in the table are the "constant mass temperature coefficient of resistance," which is discussed in Appendix II, p. 65. It is to be noted that Table II gives either the conductivity when the temperature coefficient is known or the temperature coefficient when the conductivity is known. It may be again emphasized here that the proportional relation between conductivity and temperature coefficient is equivalent to the following: *The change of resistivity per degree C is a constant for copper, independent of the temperature of reference and independent of the sample of copper; this constant is*

0.000597 ohm (meter, gram),[17]
or, 0.0000681 ohm (meter, mm^2),
or, 0.00681 microhm—cm,
or, 3.41 ohms (mile, pound),
or, 0.00268 microhm—inch,
or, 0.0409 ohm (mil, foot).

The Fahrenheit equivalents of the foregoing constants or of any of the α's in Table II may be obtained by dividing by 1.8. Thus, for example, the

[17] In other words, 0.000597 ohm is the difference in resistance of two samples of the same copper, one at t° C and the other at (t+1)° C, and each weighing 1 gram, but each having the length of exactly 1 meter at the specified temperature.

20° C or 68° F temperature coefficient for copper of 100 percent conductivity is 0.00393 per degree C, or 0.00218 per degree F. Similarly, the *change of resistivity* per degree F is 0.00149 microhm—inch.

The foregoing paragraph gives two simple ways of remembering the temperature coefficient. Another method of remembering how to make temperature reductions, in extended use among engineers, is to make use of the "inferred absolute zero temperature of resistance." This is the quantity, T, given in the last column of Table II for the various conductivities. For any percent conductivity, $-T$ is the calculated temperature on the centigrade scale at which copper of that particular percent conductivity would have zero electrical resistance *provided* the temperature coefficient between 0° C and 100° C applied continuously down to the absolute zero. That is

$$T=\frac{1}{\alpha_0}$$

One advantage of these "inferred absolute zero temperatures of resistance" is their usefulness in calculating the temperature coefficient at any temperature, t_1. Thus, we have the following formulas:

$$\alpha_{t_1}=\frac{1}{T+t_1}$$

$$t-t_1=\frac{R_t-R_{t_1}}{R_{t_1}}(T+t_1)$$

The chief advantage, however, is in calculating the ratios of resistances at different temperatures, for the resistance of a copper conductor is simply proportional to its (fictitious) absolute temperature from the "inferred absolute zero." Thus, if R_t and R_{t_1} denote resistances, respectively, at any two temperatures t and t_1

$$\frac{R_t}{R_{t_1}}=\frac{T+t}{T+t_1}$$

For example, a copper wire of 100 percent conductivity, at 20° C, would have a (fictitious) absolute temperature of 254.4°, and at 50° C would have a (fictitious) absolute temperature of 284.4°. Consequently, the ratio of its resistance at 50° C to its resistance at 20° C would be $\frac{284.4}{254.4}=1.118_2$. In more convenient form for slide rule computation, this formula may be written

$$\frac{R_t}{R_{t_1}}=1+\frac{t-t_1}{T+t_1}$$

Table III.—It is a simple matter to apply the formulas for temperature reduction to resistance or resistivity measurements, but the work can sometimes be shortened by having a table of temperature corrections. In the discussion of the temperature coefficient of copper, above, it was shown that the change of resistivity per degree C is a constant for copper. Accordingly, if the *resistivity* of any sample of copper be measured at any temperature, it can be reduced to any other temperature simply by adding a constant multiplied by the temperature difference. The first and last columns of Table III give temperature of observation. The second, third, fourth, and fifth columns give the quantity to be added to an observed resistivity to reduce to 20° C.

The next three columns give factors by which to multiply observed *resistance* to reduce to resistance at 20° C. Resistance can not be reduced accurately from one temperature to another unless either the temperature coefficient of the sample or its conductivity is known. Of course, if the temperature coefficient itself is known it should be used. If the conductivity is known, the reduction can be made by the aid of these three columns of the table, which are for 96 percent, 98 percent, and 100 percent conductivity. For other conductivities, recourse may be had to interpolation or extrapolation, or to computation by the formula. The sixth column, for 96 percent conductivity, corresponds to a temperature coefficient at 20° C of 0.003 773; the seventh column, for 98 percent conductivity, to 0.003 851; and the eighth column, for 100 percent conductivity, to 0.003 930. The factors in the eighth column, for example, were computed by the expression, $\frac{1}{1+0.003\,930\,(t-20)}$, in which t is the temperature of observation.

Table IV.—This table gives the diameters in mils (thousandths of an inch) of the sizes in the six wire gages in use, as described in Section II (1), above. The diameters in the American Wire Gage are fixed by the definite law of geometrical progression, and can, of course, be calculated out to any number of figures desired. In this table they have been rounded off at the place determined by actual practice of drawers and users of wire. The diameters in the "Steel Wire Gage" were taken from a booklet called "Sizes, Weights, and Lengths of Round Wire," published in 1905 by the American Steel & Wire Co. The diameters in the Birmingham Wire Gage and the Old English gage were found by comparing a large number of wire gage tables published by various manufacturers and others. The diameters in the Stubs' Steel Wire Gage were taken from the catalogue of Brown & Sharpe Manufacturing Co. (1909, p. 521). In addition to the sizes shown, this gage has 26 larger sizes and 30 smaller sizes. The diameters in the (British) Standard Wire Gage were obtained from the Engineering Standards Committee "Report on British Standard Copper Conductors" (second issue, March, 1910).

Table V.—The same six wire gages as in Table IV are here compared by the diameters in millimeters. The diameters were found by multiplying the respective numbers in Table IV by 0.025 400 1, and rounding off, to 0.1 mm for the largest sizes and 0.001 mm for the smallest sizes.

Table VI.—Complete data on the relations of length, mass, and resistance of *annealed* copper wires of the American Wire Gage sizes are given in Tables VI and VII, pages 44 to 51. Table VI gives the data in English units, Table VII in metric units. The quantities involving resistances are given at 6 temperatures: 0° C, 25° C, 50° C, 75° C, and the two widely used standard temperatures, 15° C and 20° C. The mass per unit length and length per unit mass are given for 20° C; their variation with temperature is insignificant. The quantities in the tables were computed to five significant figures, and have been rounded off and given to four significant figures. The results are believed to be correct within 1 in the fourth significant figure. It is appreciated that four significant figures greatly exceed in precision the ordinary requirements of a wire table. This table is intended, however, chiefly as a reference table, and it is desired that working tables based upon this table should not disagree with one another. For practical working tables of annealed copper wire, Tables VIII and IX are recommended.

Data may be obtained for sizes other than those in the table either by interpolation or by independent calculation. The fundamental data, in metric units, for making the calculations are given in the explanation of Table VII. The derived data in English units, as used in the calculation of Table VI, are as follows:

Volume resistivity of annealed copper at 20° C, or 68° F, = 0.678 79 microhm-inch.

Density of copper at 20° C, or 68° F, = 0.321 17 pound per cubic inch.

The constants given above and also in the following formulas are given to a greater number of digits than is justified by their use, but it is desired to prevent small errors in the calculated values.

In the following formulas, let:

s = cross section in square inches, at 20° C.

d = density in pounds per cubic inch, at 20° C.

ρ_{20} = resistivity in microhm-inches at 20° C.

The data of Table VI may be calculated for wire of any cross section by the following formulas. (These formulas hold for any form of cross section as well as circular cross section.)

$$\text{Ohms per 1000 feet at 20° C} = \frac{1.2\,\rho_{20}}{100\,s} = \frac{0.0081455}{s}$$

$$\text{Feet per ohm at 20° C} = \frac{10^5 s}{1.2\rho_{20}} = 122770 \times s$$

$$\text{Ohms per pound at 20° C} = \frac{10^{-6}\rho_{20}}{ds^2} = \frac{2.1135}{s^2 10^6}$$

$$\text{Pounds per ohm at 20° C} = \frac{10^6 ds^2}{\rho_{20}} = 473160 \times s^2$$

$$\text{Pounds per 1000 feet at 20° C} = 12000\,ds = 3854.09 \times s$$

$$\text{Feet per pound at 20° C} = \frac{1}{12ds} = \frac{0.259465}{s}$$

Having obtained the resistances at 20° C for the various sizes of wire, the resistances at other temperatures are calculated by means of the "constant mass temperature coefficient," 0.00393, the wires being assumed to remain of constant mass and shape as the temperature changes. This corresponds to the method of measuring resistance by means of potential terminals attached permanently to a wire sample, or to the measurement of resistance of a coil of wire at various temperatures where no measurements are made either of the length or diameter. The diameters and cross sections are assumed to be exact at 20° C, and to increase or decrease with change of temperature as a copper wire would naturally do. [Thus the constant mass temperature coefficient 0.00393 is not the same as would have to be used if the diameter and length were assumed to have the stated values at all temperatures; the latter would require the "constant volume temperature coefficient" $(\alpha + \gamma) = 0.003947$ at 20° C.] The length is to be understood as 1000 feet at 20°, and to vary with the temperature. What the tables show is the resistance at various temperatures, of a wire which at 20° C is 1000 feet long and has the specified diameter, and which varies in length and diameter as well as in resistance at other temperatures. [In the first edition of this circular, the numbers given in the tables for temperatures other than 20° C were slightly different, because the diameter and length were there taken to be exact at each temperature. Thus, values at different temperatures did not hold for the same actual wire, as they do in the present tables.]

The numbers given in the several columns under the heading "Feet per ohm" are 1000 times the reciprocals of the corresponding numbers on the opposite page. That is, they give the number of feet of wire measured at 20° C, having a resistance of 1 ohm at the various temperatures.

In the table giving "Ohms per pound" the resistances in the several columns are the number of ohms resistance at the several temperatures of a pound of wire, the length and diameter of which vary with the temperature. Hence the same temperature coefficient 0.00393 is used as before.

The numbers given in the several columns under the heading "Pounds per ohm" are the reciprocals of the corresponding numbers on the opposite page.

It should be strictly borne in mind that Tables VI and VII give values for *annealed* copper whose conductivity is that of the "International Annealed Copper Standard" described above (that is, approximately, an average of the present commercial conductivity copper). If data are desired for any sample of different conductivity, and if the conductivity is known as a percentage of this standard, the data of the table involving resistance are to be corrected by the use of this percentage, thus (letting n = per cent conductivity, expressed decimally): (1) For "Ohms per 1000 feet" and "Ohms per pound" multiply the values given in Table VI by $\frac{1}{n}$. (2) For "Pounds per ohm" and "Feet per ohm" multiply the values given in Table VI by n.

An approximate average value of percent conductivity of *hard-drawn* copper may be taken to be 97.3 per cent when assumption is unavoidable. The method of finding approximate values for hard-drawn copper from the table may be stated thus: (1) For "Ohms per 1000 feet" and "Ohms per pound" increase the values given in Table VI by 2.7 per cent. (2) For "Pounds per ohm" and "Feet per ohm" decrease the values given in Table VI by 2.7 per cent. (3) "Pounds per 1000 feet" and "Feet per pound" may be considered to be given correctly by the table for either annealed or hard-drawn copper.

Table VII.—This is a complete reference table, in metric units, of the relations of length, mass, and resistance of *annealed* copper wires. It is the equivalent of Table VI, which gives the data in English units. The fundamental data from which all these tables for copper were computed are as follows:

Mass resistivity of annealed copper at 20° C $= \frac{8.89}{58} = 0.15328$ ohm (meter, gram).

Density of copper at 20° C = 8.89 grams per cubic centimeter.

Volume resistivity of annealed copper at 20° C $= \frac{100}{58} = 1.7241$ microhm-cm.

The data of Table VII may be calculated for wires of any cross section by the formulas below, using the following symbols:

s = cross section in square mm, at 20° C.
d = density in grams per cubic centimeter, at 20° C.
ρ_{20} = resistivity in microhm-cm, at 20° C.

$$\text{Ohms per kilometer at } 20° \text{ C} = \frac{10\rho_{20}}{s} = \frac{17.241}{s}$$

$$\text{Meters per ohm at } 20° \text{ C} = \frac{100\,s}{\rho_{20}} = 58.000 \times s$$

$$\text{Ohms per kilogram at } 20° \text{ C} = \frac{10\rho_{20}}{ds^2} = \frac{1.9394}{s^2}$$

$$\text{Grams per ohm at } 20° \text{ C} = \frac{100\,ds^2}{\rho_{20}} = 515.62 \times s^2$$

$$\text{Kilograms per kilometer at } 20° \text{ C} = ds = 8.89 \times s$$

$$\text{Meters per gram at } 20° \text{ C} = \frac{1}{ds} = \frac{0.112486}{s}$$

The same points regarding the computations for different temperatures, and regarding the use of the table for samples of conductivity different from the standard, which were mentioned above in the explanation of Table VI, apply to Table VII also.

Table VIII.—This "working table" for annealed copper wires is an abbreviated form of the complete Table VI. It is intended to facilitate ready reference by the practical user. In the calculation of "Ohms per 1000 feet," the diameters and the length are assumed to be exact at one temperature, as in Tables VI and VII. It makes no difference, to the order of accuracy given in this table, whether the diameters and lengths are assumed exact at 20° C or at 25° C. The values given for 65° C assume the length to be 1000 feet, and the diameters to be the stated values, at the lower temperature. However, this matter of interpretation is here unimportant, for even if the dimensions were assumed exact at the higher temperature the data would not differ by 1 in the third significant figure.

Table IX.—This "working table" in metric units is the equivalent of Table VIII, which gives the data in English units; and is an abbreviated form of the complete Table VII.

Table X.—This is a reference table, for standard annealed copper, giving "Ohms per 1000 feet" at two temperatures and "Pounds per 1000 feet," for the various sizes in the (British) Standard Wire Gage. The quantities in the table were computed to five significant figures, and have been rounded off and given to four significant figures. The results are believed to be correct within 1 in the fourth significant figure.

Table XI.—This is a reference table for standard annealed copper wire, giving "Ohms per kilometer" at 15° C and 65° C, and "Kilograms per kilometer," for selected sizes such that the diameter is in general an exact number of tenth millimeters. The sizes were selected arbitrarily, the attempt being to choose the steps from one size to another which correspond roughly to the steps in the ordinary wire gages. The data given are believed to be correct within 1 in the fourth significant figure.

Table XII.—This table gives data on bare concentric-lay cables of annealed copper. A "concentric-lay cable" is a conductor made up of a straight central wire surrounded by helical layers of bare wires, the alternate layers having a twist in opposite directions. In the first layer about the central wire, 6 wires of the same diameter are used; in the next layer, 12; then 18, 24, etc. The number of layers thus determines the number of individual wires in the cable. There are many other, more complicated forms of cables, but they are not standardized as are the concentric-lay cables. Cables of special flexibility are made up of large numbers of wires having a definite gage size, while in the case of concentric-lay cables it is the more usual practice to start with a specified total cross section for the cable and from that calculate the diameter of the wires.[18] Thus, in Tables XII and XIII, the column "Diameter of Wires" was calculated from the total cross section.

The sizes of cables are usually specified by a statement of the cross section in circular mils. (The cross section in circular mils of a single wire is the square of its diameter in mils). The sizes of stranded conductors smaller than 250 000 circular mils (i. e., No. 0000 A. W. G. or smaller) are sometimes, for brevity, stated by means of the gage number in the American Wire Gage of a solid wire having the same cross section. The sizes of conductors of special flexibility, which are made up from wires of a definite gage size, are usually specified by a statement of the number and size of the wires. The sizes of such conductors may also be stated by the approximate gage number or the approximate circular mils.

[18] The individual wire is also called a "strand." The term "strand," in general, means any wire or group of wires forming a portion of a stranded conductor or a cable. Definitions of this and other expressions in wire and cable terminology are given in this Bureau's circular No. 37.

Tables XII and XIII give the properties of the usual sizes of concentric-lay cables which are made and used in this country. The practices of manufacturers vary, but cables of this type are most commonly made up as shown under "Standard concentric stranding." For greater flexibility, concentric-lay cables are sometimes made up as shown under "Flexible concentric stranding." The first five columns of the tables apply to both kinds of stranding. The "Standard concentric stranding" here given is also given in the 1914 Standardization Rules of the American Institute of Electrical Engineers. Those rules also define "Flexible stranding," which is not to be confused with the "Flexible *concentric* stranding" in these tables. "Flexible stranding" refers to conductors of special flexibility which are made up a large number of wires having a definite gage size.

This stranding is standard both for a concentric strand which is used as one of the constituents of a rope-lay cable and also for a strand constituting the whole of a concentric-lay cable. The ranges of the sizes for the various numbers of wires are such as to give cables of a smooth gradation of flexibility.

The "Outside diameter in mils" is the diameter of the circle circumscribing the cable, and is calculated very simply. Thus, for a cable of 7 wires, the "outside diameter" is 3 times the diameter of one wire; for a cable of 19 wires, it is 5 times the diameter of one wire, etc. The values given for the resistance are based on the International Annealed Copper Standard, discussed above. The density used in calculating the mass is 8.89 grams per cubic centimeter, or 0.321 17 pounds per cubic inch. The effect of the twisting of the strands on the resistance and mass per unit length is allowed for, and is discussed in the following paragraphs:

Different authors and different cable companies do not agree in their methods of calculating the resistance of cables. It is usually stated that on account of the twist the lengths of the individual wires are increased, and hence the resistance of the cable is *greater* than the resistance of an "equivalent solid rod"—i. e., a solid wire or rod of the same length and of cross section equal to the total cross section of the cable (taking the cross section of each wire perpendicular to the axis of the wire). However, there is always some contact area between the wires of a cable, which has the effect of increasing the cross section and decreasing the resistance; and some authors have gone so far as to state that the resistance of a cable is *less* than that of the equivalent solid rod. The Bureau of Standards has made inquiries to ascertain the experience of cable manufacturers and others on this point. It is practically unanimously agreed that the resistance of a cable is actually greater than the resistance of an equivalent solid rod. It is shown mathematically in Appendix IV, page 71, that the percent increase of resistance of a cable with all the wires perfectly insulated from one another over the resistance of the equivalent solid rod is exactly equal to the percent decrease of resistance of a cable in which each strand makes perfect contact with a neighboring strand at all points of its surface—that is, the resistance of the equivalent solid rod is the arithmetical mean of these two extreme cases. While neither extreme case exactly represents an actual cable, still the increase of resistance is generally agreed to be very nearly equal to that of a cable in which all the wires are perfectly insulated from one another. Apparently the wires are very little distorted from their circular shape, and hence make very little contact with each other. It is shown in Appendix IV that the percent increase in resistance, and in mass as well, is equal to the percent increase in length of the wires. (The equivalent soild rod is assumed to consist of copper of the same resistivity as that in the actual cable.) A standard value of 2 percent has been adopted for this percent increase in length, by the Standards Committee of the American Institute of Electrical Engineers, and the resistances and masses in the table are accordingly made 2 percent greater than for the equivalent solid rod. This involves an assumption of a value for the "lay," or "pitch," of the cable, but the actual resistance of a cable depends further upon the tension under which the strands are wound, the age of the cable, variations of the resistivity of the wires, variations of temperature, etc., so that it is very doubtful whether any correction need be made to the tabulated values of resistance. It may be more often required to make a correction for the mass of a cable, which can be done when the "lay" is known. The effect of "lay" and the magnitude of the correction are discussed in Appendix IV, p. 71.

Table XIII.—This table gives data in metric units on bare concentric-lay cables of annealed copper; it is the equivalent of Table XII. The first column gives the size in "circular mils," since the sizes are commercially so designated (except for the smaller sizes, for which the A. W. G. number is given). The other quantities in this table are in metric units. The explanations of the calculations of Table XII given above and in Appendix IV apply to this table also.

Table XIV.—This table gives data for average commercial hard-drawn aluminum wire at 20° C, of the American Wire Gage sizes. It is based upon the values for resistivity and density given on p. 14; in brief, volume resistivity = 2.828 microhm-cm, density = 2.70 grams per cubic centimeter.

The quantities in the table were calculated by the following formulas (s = cross section in square inches):

$$\text{Ohms per 1000 feet} = \frac{0.013361}{s}$$

$$\text{Pounds per 1000 feet} = 1170.5 \times s$$

$$\text{Pounds per ohm} = 87611. \times s^2$$

$$\text{Feet per ohm} = 74847. \times s$$

Table XV.—This table is the equivalent in metric units of Table XIV, giving data for average commercial hard-drawn aluminum wire at 20° C.

The quantities in the table were calculated by the following formulas (s = cross section in mm²):

$$\text{Ohms per kilometer} = \frac{28.28}{s}$$

$$\text{Kilograms per kilometer} = 2.70 \times s$$

$$\text{Grams per ohm} = 95.474 \times s^2$$

$$\text{Meters per ohm} = 35.361 \times s$$

PART 2. TABLES

TABLE I

Various Standard Values for Resistivity, Temperature Coefficient, and Density, of Annealed Copper

Temperature C	1 England (Eng. Stds. Com., 1904)	2 Germany, Old "Normal Kupfer," density 8.91	3 Germany, Old "Normal Kupfer," assuming density 8.89	4 Lindeck, Matthiessen value, assuming density 8.89	5 A. I. E. E. before 1907 (Matthiessen value)	6 A. I. E. E., 1907 to 1910	7 Bureau of Standards and A. I. E. E., 1911	8 International Annealed Copper Standard
RESISTIVITY IN OHMS (METER, GRAM)								
0°	$0.141\ 36_2$	$0.139\ 59_0$	$0.139\ 27_7$	$0.141\ 57_1$	$0.141\ 72_9$	$0.141\ 72_9$	$0.141\ 06_8$	$0.141\ 33_2$
15°	$.150\ 43_7$	$.148\ 50_2$	$.148\ 16_4$	$.149\ 97_4$	$.150\ 14_1$	$.150\ 65_8$	$150.\ 03_4$	$.150\ 29_0$
(15.6°)	.1508							
20°	$.153\ 46_3$	$.151\ 47_0$	.151 130	$.152\ 85_1$	$.153\ 02_2$	$.153\ 63_4$	$.153\ 02_2$	.153 28
25°	$.156\ 48_8$	$.154\ 44_0$	$.154\ 09_3$	$.155\ 76_5$	$.155\ 93_8$	$.156\ 61_0$	$.156\ 01_0$	$.156\ 26_2$
TEMPERATURE COEFFICIENT OF RESISTANCE								
0°	0.004 28	$0.004\ 25_5$	$0.004\ 25_5$	(19)	(19)	0.0042	$0.004\ 27_7$	0.00426_5
15°	$.004\ 02_2$	.004	.004			$.003\ 95_1$	$.004\ 01_9$	$.00400_9$
20°	$.003\ 94_3$	$.003\ 92_2$	$.003\ 92_2$			$.003\ 87_5$	.003 94	.003 93
25°	$.003\ 86_6$	$.003\ 84_6$	$.003\ 84_6$			$.003\ 80_1$	$.003\ 86_4$	$.00385_4$
DENSITY								
	[20] 8.89	8.91	(8.89)	(8.89)	8.89	8.89	[21] 8.89	[21] 8.89

NOTE.—An explanation of table is given on p. 27.

[19] Matthiessen's formula: $\lambda_t=\lambda_0\ (1-0.003\ 870\ 1t+0.000\ 009\ 009\ t^2)$. λ_t and λ_0=reciprocal of resistance at t° and 0° C, respectively.

[20] At 15.6° C.

[21] This is the density at 20° C. It corresponds to 8.90 at 0° C.

TABLE II

Temperature Coefficients of Copper for Different Initial Temperatures (Centigrade) and Different Conductivities

Ohms (meter, gram) at 20° C	Percent conductivity	α_0	α_{15}	α_{20}	α_{25}	α_{30}	α_{50}	T
0.161 34	95%	0.004 03	0.003 80	0.003 73	0.003 67	0.003 60	0.003 36	247.8
.159 66	96%	.004 08	.003 85	.003 77	.003 70	.003 64	.003 39	245.1
.158 02	97%	.004 13	.003 89	.003 81	.003 74	.003 67	.003 42	242.3
.157 53	97.3%	.004 14	.003 90	.003 82	.003 75	.003 68	.003 43	241.5
.156 40	98%	.004 17	.003 93	.003 85	.003 78	.003 71	.003 45	239.6
.154 82	99%	.004 22	.003 97	.003 89	.003 82	.003 74	.003 48	237.0
.153 28	100%	.004 27	.004 01	**.003 93**	.003 85	.003 78	.003 52	234.5
.151 76	101%	.004 31	.004 05	.003 97	.003 89	.003 82	.003 55	231.9

NOTE.—The fundamental relation between resistance and temperature is the following:

$$R_t = R_{t_1}(1 + \alpha_{t_1}[t - t_1]),$$

where α_{t_1} is the "temperature coefficient," and t_1 is the "initial temperature" or "temperature of reference."

The values of α in the above table exhibit the fact that the temperature coefficient of copper is proportional to the conductivity. The table was calculated by means of the following formula, which holds for any percent conductivity, n, within commercial ranges, and for centigrade temperatures. (n is considered to be expressed decimally: e. g., if percent conductivity=99 per cent, n=0.99.)

$$\alpha_{t_1} = \frac{1}{\frac{1}{n(0.00393)} + (t_1 - 20)}.$$

The quantity T in the last column of the above table presents an easy way of remembering the temperature coefficient, its usefulness being evident from the following formulas:

$$t - t_1 = \frac{R_t - R_{t_1}}{R_{t_1}}(T + t_1)$$

$$\frac{R_t}{R_{t_1}} = 1 + \frac{t - t_1}{T + t_1}$$

TABLE III

Reduction of Observations to Standard Temperature

Temperature C	Corrections to reduce Resistivity to 20° C				Factors to reduce Resistance to 20° C			Temperature C
	Ohm (meter, gram)	Microhm—cm	Ohm (mile, pound)	Microhm—inch	For 96 per-cent conductivity	For 98 per-cent conductivity	For 100 per-cent conductivity	
0	+0.011 94	+0.1361	+ 68.20	+0.053 58	1.0816	1.0834	1.0853	0
5	+ .008 96	+ .1021	+ 51.15	+ .040 18	1.0600	1.0613	1.0626	5
10	+ .005 97	+ .0681	+ 34.10	+ .026 79	1.0392	1.0401	1.0409	10
11	+ .005 37	+ .0612	+ 30.69	+ .024 11	1.0352	1.0359	1.0367	11
12	+ .004 78	+ .0544	+ 27.28	+ .021 43	1.0311	1.0318	1.0325	12
13	+ .004 18	+ .0476	+ 23.87	+ .018 75	1.0271	1.0277	1.0283	13
14	+ .003 58	+ .0408	+ 20.46	+ .016 07	1.0232	1.0237	1.0242	14
15	+ .002 99	+ .0340	+ 17.05	+ .013 40	1.0192	1.0196	1.0200	15
16	+ .002 39	+ .0272	+ 13.64	+ .010 72	1.0153	1.0156	1.0160	16
17	+ .001 79	+ .0204	+ 10.23	+ .008 04	1.0114	1.0117	1.0119	17
18	+ .001 19	+ .0136	+ 6.82	+ .005 36	1.0076	1.0078	1.0079	18
19	+ .000 60	+ .0068	+ 3.41	+ .002 68	1.0038	1.0039	1.0039	19
20	0	0	0	0	1.0000	1.0000	1.0000	20
21	− .000 60	− .0068	− 3.41	− .002 68	0.9962	0.9962	0.9961	21
22	− .001 19	− .0136	− 6.82	− .005 36	.9925	.9924	.9922	22
23	− .001 79	− .0204	− 10.23	− .008 04	.9888	.9886	.9883	23
24	− .002 39	− .0272	− 13.64	− .010 72	.9851	.9848	.9845	24
25	− .002 99	− .0340	− 17.05	− .013 40	.9815	.9811	.9807	25
26	− .003 58	− .0408	− 20.46	− .016 07	.9779	.9774	.9770	26
27	− .004 18	− .0476	− 23.87	− .018 75	.9743	.9737	.9732	27
28	− .004 78	− .0544	− 27.28	− .021 43	.9707	.9701	.9695	28
29	− .005 37	− .0612	− 30.69	− .024 11	.9672	.9665	.9658	29
30	− .005 97	− .0681	− 34.10	− .026 79	.9636	.9629	.9622	30
35	− .008 96	− .1021	− 51.15	− .040 18	.9464	.9454	.9443	35
40	− .011 94	− .1361	− 68.20	− .053 58	.9298	.9285	.9271	40
45	− .014 93	− .1701	− 85.25	− .066 98	.9138	.9122	.9105	45
50	− .017 92	− .2042	−102.30	− .080 37	.8983	.8964	.8945	50
55	− .020 90	− .2382	−119.35	− .093 76	.8833	.8812	.8791	55
60	− .023 89	− .2722	−136.40	− .107 16	.8689	.8665	.8642	60
65	− .026 87	− .3062	−153.45	− .120 56	.8549	.8523	.8497	65
70	− .029 86	− .3403	−170.50	− .133 95	.8413	.8385	.8358	70
75	− .032 85	− .3743	−187.55	− .147 34	.8281	.8252	.8223	75

ENGLISH

TABLE IV

Tabular Comparison of Wire Gages

Diameters in Mils

Gage No.	American Wire Gage (B. & S.)[22]	Steel Wire Gage[23]	Birmingham Wire Gage (Stubs')	Old English Wire Gage (London)	Stubs' Steel Wire Gage	(British) Standard Wire Gage	Gage No.
7-0		490.0				500.	7-0
6-0		461.5				464.	6-0
5-0		430.5				432.	5-0
4-0	460.	393.8	454.	454.		400.	4-0
3-0	410.	362.5	425.	425.		372.	3-0
2-0	365.	331.0	380.	380.		348.	2-0
0	325.	306.5	340.	340.		324.	0
1	289.	283.0	300.	300.	227.	300.	1
2	258.	262.5	284.	284.	219.	276.	2
3	229.	243.7	259.	259.	212.	252.	3
4	204.	225.3	238.	238.	207.	232.	4
5	182.	207.0	220.	220.	204.	212.	5
6	162.	192.0	203.	203.	201.	192.	6
7	144.	177.0	180.	180.	199.	176.	7
8	128.	162.0	165.	165.	197.	160.	8
9	114.	148.3	148.	148.	194.	144.	9
10	102.	135.0	134.	134.	191.	128.	10
11	91.	120.5	120.	120.	188.	116.	11
12	81.	105.5	109.	109.	185.	104.	12
13	72.	91.5	95.	95.	182.	92.	13
14	64.	80.0	83.	83.	180.	80.	14
15	57.	72.0	72.	72.	178.	72.	15
16	51.	62.5	65.	65.	175.	64.	16
17	45.	54.0	58.	58.	172.	56.	17
18	40.	47.5	49.	49.	168.	48.	18
19	36.	41.0	42.	40.	164.	40.	19
20	32.	34.8	35.	35.	161.	36.	20
21	28.5	31.7	32.	31.5	157.	32.	21
22	25.3	28.6	28.	29.5	155.	28.	22
23	22.6	25.8	25.	27.0	153.	24.	23
24	20.1	23.0	22.	25.0	151.	22.	24
25	17.9	20.4	20.	23.0	148.	20.	25
26	15.9	18.1	18.	20.5	146.	18.	26
27	14.2	17.3	16.	18.75	143.	16.4	27
28	12.6	16.2	14.	16.50	139.	14.8	28
29	11.3	15.0	13.	15.50	134.	13.6	29
30	10.0	14.0	12.	13.75	127.	12.4	30
31	8.9	13.2	10.	12.25	120.	11.6	31
32	8.0	12.8	9.	11.25	115.	10.8	32
33	7.1	11.8	8.	10.25	112.	10.0	33
34	6.3	10.4	7.	9.50	110.	9.2	34
35	5.6	9.5	5.	9.00	108.	8.4	35
36	5.0	9.0	4.	7.50	106.	7.6	36
37	4.5	8.5		6.50	103.	6.8	37
38	4.0	8.0		5.75	101.	6.0	38
39	3.5	7.5		5.00	99.	5.2	39
40	3.1	7.0		4.50	97.	4.8	40
41		6.6			95.	4.4	41
42		6.2			92.	4.0	42
43		6.0			88.	3.6	43
44		5.8			85.	3.2	44
45		5.5			81.	2.8	45
46		5.2			79.	2.4	46
47		5.0			77.	2.0	47
48		4.8			75.	1.6	48
49		4.6			72.	1.2	49
50		4.4			69.	1.0	50

[22] The American Wire Gage sizes have here been rounded off to about the usual limits of commercial accuracy. They can be calculated to any desired accuracy by use of the law given on p. 24; and are given to four significant figures throughout on pp. 44, 48, etc.

[23] The Steel Wire Gage is the same gage which has been known by the various names: "Washburn and Moen," "Roebling," "American Steel and Wire Co.'s." Its abbreviation should be written "Stl. W. G.," to distinguish it from "S. W. G.," the usual abbreviation for the (British) Standard Wire Gage.

TABLE V **METRIC**

Tabular Comparison of Wire Gages

Diameters in Millimeters

Gage No.	American Wire Gage (B. & S.) [22]	Steel Wire Gage [23]	Birmingham Wire Gage (Stubs')	Old English Wire Gage (London)	Stubs' Steel Wire Gage	(British) Standard Wire Gage	Gage No.
7–0		12.4				12.7	7–0
6–0		11.7				11.3	6–0
5–0		10.9				11.0	5–0
4–0	11.7	10.0	11.5	11.5		10.2	4–0
3–0	10.4	9.2	10.8	10.8		9.4	3–0
2–0	9.3	8.4	9.7	9.7		8.8	2–0
0	8.3	7.8	8.6	8.6		8.2	0
1	7.3	7.2	7.6	7.6	5.77	7.6	1
2	6.5	6.7	7.2	7.2	5.56	7.0	2
3	5.8	6.2	6.6	6.6	5.38	6.4	3
4	5.2	5.7	6.0	6.0	5.26	5.9	4
5	4.6	5.3	5.6	5.6	5.18	5.4	5
6	4.1	4.9	5.2	5.2	5.11	4.9	6
7	3.7	4.5	4.6	4.6	5.05	4.5	7
8	3.3	4.1	4.2	4.2	5.00	4.1	8
9	2.91	3.77	3.76	3.76	4.93	3.66	9
10	2.59	3.43	3.40	3.40	4.85	3.25	10
11	2.30	3.06	3.05	3.05	4.78	2.95	11
12	2.05	2.68	2.77	2.77	4.70	2.64	12
13	1.83	2.32	2.41	2.41	4.62	2.34	13
14	1.63	2.03	2.11	2.11	4.57	2.03	14
15	1.45	1.83	1.83	1.83	4.52	1.83	15
16	1.29	1.59	1.65	1.65	4.45	1.63	16
17	1.15	1.37	1.47	1.47	4.37	1.42	17
18	1.02	1.21	1.24	1.24	4.27	1.22	18
19	0.91	1.04	1.07	1.02	4.17	1.02	19
20	.81	0.88	0.89	0.89	4.09	0.91	20
21	.72	.81	.81	.80	3.99	.81	21
22	.64	.73	.71	.75	3.94	.71	22
23	.57	.66	.64	.69	3.89	.61	23
24	.51	.58	.56	.64	3.84	.56	24
25	.45	.52	.51	.58	3.76	.51	25
26	.40	.46	.46	.52	3.71	.46	26
27	.36	.439	.41	.48	3.63	.42	27
28	.32	.411	.36	.42	3.53	.38	28
29	.29	.381	.330	.394	3.40	.345	29
30	.25	.356	.305	.349	3.23	.315	30
31	.227	.335	.254	.311	3.05	.295	31
32	.202	.325	.229	.286	2.92	.274	32
33	.180	.300	.203	.260	2.84	.254	33
34	.160	.264	.178	.241	2.79	.234	34
35	.143	.241	.127	.229	2.74	.213	35
36	.127	.229	.102	.191	2.69	.193	36
37	.113	.216		.165	2.62	.173	37
38	.101	.203		.146	2.57	.152	38
39	.090	.191		.127	2.51	.132	39
40	.080	.178		.114	2.46	.122	40
41		.168			2.41	.112	41
42		.157			2.34	.102	42
43		.152			2.24	.091	43
44		.147			2.16	.081	44
45		.140			2.06	.071	45
46		.132			2.01	.061	46
47		.127			1.96	.051	47
48		.122			1.90	.041	48
49		.117			1.83	.030	49
50		.112			1.75	.025	50

ENGLISH TABLE VI

Complete Wire Table, Standard Annealed Copper.

American Wire Gage (B. & S.). English Units

Gage No.	Diameter in Mils at 20° C	Cross-Section at 20° C		Ohms per 1000 Feet [24]					
		Circular Mils	Square Inches	0° C (=32° F)	15° C (=59° F)	20° C (=68° F)	25° C (=77° F)	50° C (=122° F)	75° C (=167° F)
0000	460.0	211 600.	0.1662	0.045 16	0.048 05	0.049 01	0.049 98	0.054 79	0.059 61
000	409.6	167 800.	.1318	.056 95	.060 59	.061 80	.063 02	.069 09	.075 16
00	364.8	133 100.	.1045	.071 81	.076 40	.077 93	.079 47	.087 12	.094 78
0	324.9	105 500.	.082 89	.09055	.09634	.09827	.1002	.1099	.1195
1	289.3	83 690.	.065 73	.1142	.1215	.1239	.1264	.1385	.1507
2	257.6	66 370.	.052 13	.1440	.1532	.1563	.1593	.1747	.1900
3	229.4	52 640.	.041 34	.1816	.1932	.1970	.2009	.2203	.2396
4	204.3	41 740.	.032 78	.2289	.2436	.2485	.2533	.2778	.3022
5	181.9	33 100.	.026 00	.2887	.3072	.3133	.3195	.3502	.3810
6	162.0	26 250.	.020 62	.3640	.3873	.3951	.4028	.4416	.4805
7	144.3	20 820.	.016 35	.4590	.4884	.4982	.5080	.5569	.6059
8	128.5	16 510.	.012 97	.5788	.6158	.6282	.6405	.7023	.7640
9	114.4	13 090.	.010 28	.7299	.7766	.7921	.8077	.8855	.9633
10	101.9	10 380.	.008 155	.9203	.9792	.9989	1.018	1.117	1.215
11	90.74	8234.	.006 467	1.161	1.235	1.260	1.284	1.408	1.532
12	80.81	6530.	.005 129	1.463	1.557	1.588	1.619	1.775	1.931
13	71.96	5178.	.004 067	1.845	1.963	2.003	2.042	2.239	2.436
14	64.08	4107.	.003 225	2.327	2.476	2.525	2.575	2.823	3.071
15	57.07	3257.	.002 558	2.934	3.122	3.184	3.247	3.560	3.873
16	50.82	2583.	.002 028	3.700	3.937	4.016	4.094	4.489	4.884
17	45.26	2048.	.001 609	4.666	4.964	5.064	5.163	5.660	6.158
18	40.30	1624.	.001 276	5.883	6.260	6.385	6.510	7.138	7.765
19	35.89	1288.	.001 012	7.418	7.893	8.051	8.210	9.001	9.792
20	31.96	1022.	.000 802 3	9.355	9.953	10.15	10.35	11.35	12.35
21	28.46	810.1	.000 636 3	11.80	12.55	12.80	13.05	14.31	15.57
22	25.35	642.4	.000 504 6	14.87	15.83	16.14	16.46	18.05	19.63
23	22.57	509.5	.000 400 2	18.76	19.96	20.36	20.76	22.76	24.76
24	20.10	404.0	.000 317 3	23.65	25.16	25.67	26.17	28.70	31.22
25	17.90	320.4	.000 251 7	29.82	31.73	32.37	33.00	36.18	39.36
26	15.94	254.1	.000 199 6	37.61	40.01	40.81	41.62	45.63	49.64
27	14.20	201.5	.000 158 3	47.42	50.45	51.47	52.48	57.53	62.59
28	12.64	159.8	.000 125 5	59.80	63.62	64.90	66.17	72.55	78.93
29	11.26	126.7	.000 099 53	75.40	80.23	81.83	83.44	91.48	99.52
30	10.03	100.5	.000 078 94	95.08	101.2	103.2	105.2	115.4	125.5
31	8.928	79.70	.000 062 60	119.9	127.6	130.1	132.7	145.5	158.2
32	7.950	63.21	.000 049 64	151.2	160.9	164.1	167.3	183.4	199.5
33	7.080	50.13	.000 039 37	190.6	202.8	206.9	211.0	231.3	251.6
34	6.305	39.75	.000 031 22	240.4	255.8	260.9	266.0	291.7	317.3
35	5.615	31.52	.000 024 76	303.1	322.5	329.0	335.5	367.8	400.1
36	5.000	25.00	.000 019 64	382.2	406.7	414.8	423.0	463.7	504.5
37	4.453	19.83	.000 015 57	482.0	512.8	523.1	533.4	584.8	636.2
38	3.965	15.72	.000 012 35	607.8	646.7	659.6	672.6	737.4	802.2
39	3.531	12.47	.000 009 793	766.4	815.4	831.8	848.1	929.8	1012.
40	3.145	9.888	.000 007 766	966.5	1028.	1049.	1069.	1173.	1276.

[24] Resistance at the stated temperatures of a wire whose length is 1000 feet at 20° C. (See explanation on p. 32.)

TABLE VI—Continued **ENGLISH**

Complete Wire Table, Standard Annealed Copper—Continued

American Wire Gage (B. & S.). English Units—Continued

Gage No.	Diameter in Mils at 20° C	Pounds per 1000 Feet	Feet per Pound	Feet per Ohm [25]					
				0° C (=32° F)	15° C (=59° F)	20° C (=68° F)	25° C (=77° F)	50° C (=122° F)	75° C (=167° F)
0000	460.0	640.5	1.561	22 140.	20 810.	20 400.	20 010.	18 250.	16 780.
000	409.6	507.9	1.968	17 560.	16 500.	16 180.	15 870.	14 470.	13 300.
00	364.8	402.8	2.482	13 930.	13 090.	12 830.	12 580.	11 480.	10 550.
0	324.9	319.5	3.130	11 040.	10 380.	10 180.	9980.	9103.	8367.
1	289.3	253.3	3.947	8758.	8232.	8070.	7914.	7219.	6636.
2	257.6	200.9	4.977	6946.	6528.	6400.	6276.	5725.	5262.
3	229.4	159.3	6.276	5508.	5177.	5075.	4977.	4540.	4173.
4	204.3	126.4	7.914	4368.	4105.	4025.	3947.	3600.	3309.
5	181.9	100.2	9.980	3464.	3256.	3192.	3130.	2855.	2625.
6	162.0	79.46	12.58	2747.	2582.	2531.	2482.	2264.	2081.
7	144.3	63.02	15.87	2179.	2048.	2007.	1969.	1796.	1651.
8	128.5	49.98	20.01	1728.	1624.	1592.	1561.	1424.	1309.
9	114.4	39.63	25.23	1370.	1288.	1262.	1238.	1129.	1038.
10	101.9	31.43	31.82	1087.	1021.	1001.	981.8	895.6	823.2
11	90.74	24.92	40.12	861.7	809.9	794.0	778.7	710.2	652.8
12	80.81	19.77	50.59	683.3	642.2	629.6	617.5	563.2	517.7
13	71.96	15.68	63.80	541.9	509.3	499.3	489.7	446.7	410.6
14	64.08	12.43	80.44	429.8	403.9	396.0	388.3	354.2	325.6
15	57.07	9.858	101.4	340.8	320.3	314.0	308.0	280.9	258.2
16	50.82	7.818	127.9	270.3	254.0	249.0	244.2	222.8	204.8
17	45.26	6.200	161.3	214.3	201.4	197.5	193.7	176.7	162.4
18	40.30	4.917	203.4	170.0	159.8	156.6	153.6	140.1	128.8
19	35.89	3.899	256.5	134.8	126.7	124.2	121.8	111.1	102.1
20	31.96	3.092	323.4	106.9	100.5	98.50	96.60	88.11	80.99
21	28.46	2.452	407.8	84.78	79.68	78.11	76.61	69.87	64.23
22	25.35	1.945	514.2	67.23	63.19	61.95	60.75	55.41	50.94
23	22.57	1.542	648.4	53.32	50.11	49.13	48.18	43.94	40.39
24	20.10	1.223	817.7	42.28	39.74	38.96	38.21	34.85	32.03
25	17.90	0.9699	1031.	33.53	31.51	30.90	30.30	27.64	25.40
26	15.94	.7692	1300.	26.59	24.99	24.50	24.03	21.92	20.15
27	14.20	.6100	1639.	21.09	19.82	19.43	19.06	17.38	15.98
28	12.64	.4837	2067.	16.72	15.72	15.41	15.11	13.78	12.67
29	11.26	.3836	2607.	13.26	12.46	12.22	11.98	10.93	10.05
30	10.03	.3042	3287.	10.52	9.885	9.691	9.504	8.669	7.968
31	8.928	.2413	4145.	8.341	7.839	7.685	7.537	6.875	6.319
32	7.950	.1913	5227.	6.614	6.217	6.095	5.977	5.452	5.011
33	7.080	.1517	6591.	5.245	4.930	4.833	4.740	4.323	3.974
34	6.305	.1203	8310.	4.160	3.910	3.833	3.759	3.429	3.152
35	5.615	.095 42	10 480.	3.299	3.101	3.040	2.981	2.719	2.499
36	5.000	.075 68	13 210.	2.616	2.459	2.411	2.364	2.156	1.982
37	4.453	.060 01	16 660.	2.075	1.950	1.912	1.875	1.710	1.572
38	3.965	.047 59	21 010.	1.645	1.546	1.516	1.487	1.356	1.247
39	3.531	.037 74	26 500.	1.305	1.226	1.202	1.179	1.075	0.9886
40	3.145	.029 93	33 410.	1.035	0.9725	0.9534	0.9350	0.8529	.7840

Table continued on next page. Explanatory notes given at end of Table VII, p. 51.

[25] Length at 20° C of a wire whose resistance is 1 ohm at the stated temperatures.

ENGLISH TABLE VI—Continued

Complete Wire Table, Standard Annealed Copper—Continued

American Wire Gage (B. & S.). English Units—Continued

Gage No.	Diameter in Mils at 20° C	Ohms per Pound					
		0° C (=32° F)	15° C (=59° F)	20° C (=68° F)	25° C (=77° F)	50° C (=122° F)	75° C (=167° F)
0000	460.0	0.000 070 51	0.000 075 02	0.000 076 52	0.000 078 03	0.000 085 54	0.000 093 06
000	409.6	.000 1121	.000 1193	.000 1217	.000 1241	.000 1360	.000 1480
00	364.8	.000 1783	.000 1897	.000 1935	.000 1973	.000 2163	.000 2353
0	324.9	.000 2835	.000 3016	.000 3076	.000 3137	.000 3439	.000 3741
1	289.3	.000 4507	.000 4795	.000 4891	.000 4988	.000 5468	.000 5949
2	257.6	.000 7166	.000 7625	.000 7778	.000 7931	.000 8695	.000 9459
3	229.4	.001 140	.001 212	.001 237	.001 261	.001 383	.001 504
4	204.3	.001 812	.001 928	.001 966	.002 005	.002 198	.002 392
5	181.9	.002 881	.003 065	.003 127	.003 188	.003 495	.003 803
6	162.0	.004 581	.004 874	.004 972	.005 069	.005 558	.006 046
7	144.3	.007 284	.007 750	.007 905	.008 061	.008 838	.009 614
8	128.5	.011 58	.012 32	.012 57	.012 82	.014 05	.015 29
9	114.4	.018 42	.019 59	.019 99	.020 38	.022 34	.024 31
10	101.9	.029 28	.031 16	.031 78	.032 41	.035 53	.038 65
11	90.74	.046 56	.049 54	.050 53	.051 53	.056 49	.061 45
12	80.81	.074 04	.078 77	.080 35	.081 93	.089 83	.097 72
13	71.96	.1177	.1253	.1278	.1303	.1428	.1554
14	64.08	.1872	.1992	.2032	.2071	.2271	.2471
15	57.07	.2976	.3167	.3230	.3294	.3611	.3929
16	50.82	.4733	.5035	.5136	.5237	.5742	.6247
17	45.26	.7525	.8007	.8167	.8328	.9130	.9932
18	40.30	1.197	1.273	1.299	1.324	1.452	1.579
19	35.89	1.903	2.024	2.065	2.105	2.308	2.511
20	31.96	3.025	3.219	3.283	3.348	3.670	3.993
21	28.46	4.810	5.118	5.221	5.323	5.836	6.349
22	25.35	7.649	8.138	8.301	8.464	9.280	10.10
23	22.57	12.16	12.94	13.20	13.46	14.76	16.05
24	20.10	19.34	20.58	20.99	21.40	23.46	25.52
25	17.90	30.75	32.72	33.37	34.03	37.31	40.59
26	15.94	48.89	52.02	53.06	54.11	59.32	64.53
27	14.20	77.74	82.72	84.37	86.03	94.32	102.6
28	12.64	123.6	131.5	134.2	136.8	150.0	163.2
29	11.26	196.6	209.1	213.3	217.5	238.5	259.4
30	10.03	312.5	332.5	339.2	345.9	379.2	412.5
31	8.928	497.0	528.7	539.3	549.9	602.9	655.9
32	7.950	790.2	840.7	857.6	874.4	958.7	1043.
33	7.080	1256.	1337.	1364.	1390.	1524.	1658.
34	6.305	1998.	2126.	2168.	2211.	2424.	2637.
35	5.615	3177.	3380.	3448.	3515.	3854.	4193.
36	5.000	5051.	5374.	5482.	5590.	6128.	6667.
37	4.453	8032.	8545.	8717.	8888.	9744.	10 600.
38	3.965	12 770.	13 590.	13 860.	14 130.	15 490.	16 860.
39	3.531	20 310.	21 610.	22 040.	22 470.	24 640.	26 800.
40	3.145	32 290.	34 350.	35 040.	35 730.	39 170.	42 620.

TABLE VI—Continued

ENGLISH

Complete Wire Table, Standard Annealed Copper—Continued

American Wire Gage (B. & S.). English Units—Continued

Gage No.	Diameter in Mils at 20° C	Pounds per Ohm					
		0° C (=32° F)	15° C (=59° F)	20° C (=68° F)	25° C (=77° F)	50° C (=122° F)	75° C (=167° F)
0000	460.0	14 180.	13 330.	13 070.	12 820.	11 690.	10 750.
000	409.6	8920.	8383.	8219.	8060.	7352.	6758.
00	364.8	5610.	5272.	5169.	5069.	4624.	4250.
0	324.9	3528.	3316.	3251.	3188.	2908.	2673.
1	289.3	2219.	2085.	2044.	2005.	1829.	1681.
2	257.6	1395.	1311.	1286.	1261.	1150.	1057.
3	229.4	877.6	824.8	808.6	793.0	723.3	664.9
4	204.3	551.9	518.7	508.5	498.7	454.9	418.1
5	181.9	347.1	326.2	319.8	313.7	286.1	263.0
6	162.0	218.3	205.2	201.1	197.3	179.9	165.4
7	144.3	137.3	129.0	126.5	124.1	113.2	104.0
8	128.5	86.34	81.15	79.55	78.02	71.16	65.41
9	114.4	54.30	51.03	50.03	49.07	44.75	41.14
10	101.9	34.15	32.10	31.47	30.86	28.15	25.87
11	90.74	21.48	20.19	19.79	19.41	17.70	16.27
12	80.81	13.51	12.69	12.45	12.21	11.13	10.23
13	71.96	8.495	7.984	7.827	7.676	7.001	6.436
14	64.08	5.342	5.021	4.922	4.828	4.403	4.048
15	57.07	3.360	3.158	3.096	3.036	2.769	2.546
16	50.82	2.113	1.986	1.947	1.909	1.742	1.601
17	45.26	1.329	1.249	1.224	1.201	1.095	1.007
18	40.30	0.8357	0.7855	0.7700	0.7552	0.6888	0.6332
19	35.89	.5256	.4940	.4843	.4750	.4332	.3982
20	31.96	.3306	.3107	.3046	.2987	.2725	.2504
21	28.46	.2079	.1954	.1915	.1879	.1713	.1575
22	25.35	.1307	.1229	.1205	.1181	.1078	.099 05
23	22.57	.082 22	.077 28	.075 76	.074 30	.067 77	.062 30
24	20.10	.051 71	.048 60	.047 65	.046 73	.042 62	.039 18
25	17.90	.032 52	.030 57	.029 97	.029 39	.026 80	.024 64
26	15.94	.020 45	.019 22	.018 85	.018 48	.016 86	.015 50
27	14.20	.012 86	.012 09	.011 85	.011 62	.010 60	.009 746
28	12.64	.008 090	.007 603	.007 454	.007 310	.006 668	.006 129
29	11.26	.005 088	.004 782	.004 688	.004 597	.004 193	.003 855
30	10.03	.003 200	.003 007	.002 948	.002 891	.002 637	.002 424
31	8.928	.002 012	.001 891	.001 854	.001 818	.001 659	.001 525
32	7.950	.001 266	.001 189	.001 166	.001 144	.001 043	.000 9588
33	7.080	.000 7959	.000 7480	.000 7333	.000 7192	.000 6560	.000 6030
34	6.305	.000 5005	.000 4704	.000 4612	.000 4523	.000 4126	.000 3792
35	5.615	.000 3148	.000 2959	.000 2901	.000 2845	.000 2595	.000 2385
36	5.000	.000 1980	. 000 1861	.000 1824	.000 1789	.000 1632	.000 1500
37	4.453	.000 1245	.000 1170	.000 1147	.000 1125	.000 1026	.000 094 33
38	3.965	.000 078 30	.000 073 60	.000 072 15	.000 070 76	.000 064 54	.000 059 33
39	3.531	.000 049 25	.000 046 28	.000 045 38	.000 044 50	.000.040 59	.000 037 31
40	3.145	.000 030 97	.000 029 11	.000 028 54	.000 027 99	.000 025 53	.000 023 46

Explanatory notes given at end of Table VII, p. 51.

METRIC

TABLE VII

Complete Wire Table, Standard Annealed Copper

American Wire Gage (B. & S.). Metric Units

Gage No.	Diameter in mm at 20° C	Cross section in mm² at 20° C	Ohms per Kilometer [26]					
			0° C	15° C	20° C	25° C	50° C	75° C
0000	11.68	107.2	0.1482	0.1576	0.1608	0.1640	0.1798	0.1956
000	10.40	85.03	.1868	.1988	.2028	.2068	.2267	.2466
00	9.266	67.43	.2356	.2507	.2557	.2607	.2858	.3110
0	8.252	53.48	.2971	.3161	.3224	.3288	.3604	.3921
1	7.348	42.41	.3746	.3986	.4066	.4145	.4545	.4944
2	6.544	33.63	.4724	.5026	.5127	.5227	.5731	.6235
3	5.827	26.67	.5956	.6338	.6465	.6592	.7227	.7862
4	5.189	21.15	.7511	.7991	.8152	.8312	.9113	.9914
5	4.621	16.77	.9471	1.008	1.028	1.048	1.149	1.250
6	4.115	13.30	1.194	1.271	1.296	1.322	1.449	1.576
7	3.665	10.55	1.506	1.602	1.634	1.667	1.827	1.988
8	3.264	8.366	1.899	2.020	2.061	2.101	2.304	2.506
9	2.906	6.634	2.395	2.548	2.599	2.650	2.905	3.161
10	2.588	5.261	3.020	3.213	3.277	3.341	3.663	3.985
11	2.305	4.172	3.807	4.051	4.132	4.213	4.619	5.025
12	2.053	3.309	4.801	5.108	5.211	5.313	5.825	6.337
13	1.828	2.624	6.054	6.442	6.571	6.700	7.345	7.991
14	1.628	2.081	7.634	8.123	8.285	8.448	9.262	10.08
15	1.450	1.650	9.627	10.24	10.45	10.65	11.68	12.71
16	1.291	1.309	12.14	12.92	13.17	13.43	14.73	16.02
17	1.150	1.038	15.31	16.29	16.61	16.94	18.57	20.20
18	1.024	0.8231	19.30	20.54	20.95	21.36	23.42	25.48
19	0.9116	.6527	24.34	25.90	26.42	26.93	29.53	32.12
20	.8118	.5176	30.69	32.65	33.31	33.96	37.24	40.51
21	.7230	.4105	38.70	41.18	42.00	42.83	46.95	51.08
22	.6438	.3255	48.80	51.92	52.96	54.00	59.21	64.41
23	.5733	.2582	61.54	65.47	66.79	68.10	74.66	81.22
24	.5106	.2047	77.60	82.56	84.21	85.87	94.14	102.4
25	.4547	.1624	97.85	104.1	106.2	108.3	118.7	129.1
26	.4049	.1288	123.4	131.3	133.9	136.5	149.7	162.9
27	.3606	.1021	155.6	165.5	168.9	172.2	188.8	205.4
28	.3211	.080 98	196.2	208.7	212.9	217.1	238.0	258.9
29	.2859	.064 22	247.4	263.2	268.5	273.8	300.1	326.5
30	.2546	.050 93	311.9	331.9	338.6	345.2	378.5	411.7
31	.2268	.040 39	393.4	418.5	426.9	435.3	477.2	519.2
32	.2019	.032 03	496.0	527.7	538.3	548.9	601.8	654.7
33	.1798	.025 40	625.5	665.5	678.8	692.2	758.8	825.5
34	.1601	.020 14	788.7	839.2	856.0	872.8	956.9	1041.
35	.1426	.015 97	994.5	1058.	1079.	1101.	1207.	1313.
36	.1270	.012 67	1254.	1334.	1361.	1388.	1522.	1655.
37	.1131	.010 05	1581.	1683.	1716.	1750.	1919.	2087.
38	.1007	.007 967	1994.	2122.	2164.	2207.	2419.	2632.
39	.089 69	.006 318	2514.	2675.	2729.	2783.	3051.	3319.
40	.079 87	.005 010	3171.	3374.	3441.	3509.	3847.	4185.

[26] Resistance at the stated temperatures of a wire whose length is 1 kilometer at 20° C.

TABLE VII—Continued **METRIC**

Complete Wire Table, Standard Annealed Copper—Continued

American Wire Gage (B. & S.). Metric Units—Continued

Gage No.	Diameter in mm at 20° C	Kilograms per Kilometer	Meters per Gram	Meters per Ohm [27]					
				0° C	15° C	20° C	25° C	50° C	75° C
0000	11.68	953.2	0.001 049	6749.	6343.	6219.	6099.	5563.	5113.
000	10.40	755.9	.001 323	5352.	5031.	4932.	4837.	4412.	4055.
00	9.266	599.5	.001 668	4245.	3989.	3911.	3836.	3499.	3216.
0	8.252	475.4	.002 103	3366.	3164.	3102.	3042.	2774.	2550.
1	7.348	377.0	.002 652	2669.	2509.	2460.	2412.	2200.	2022.
2	6.544	299.0	.003 345	2117.	1990.	1951.	1913.	1745.	1604.
3	5.827	237.1	.004 217	1679.	1578.	1547.	1517.	1384.	1272.
4	5.189	188.0	.005 318	1331.	1251.	1227.	1203.	1097.	1009.
5	4.621	149.1	.006 706	1056.	992.3	972.9	954.1	870.2	799.9
6	4.115	118.2	.008 457	837.3	787.0	771.5	756.6	690.1	634.4
7	3.665	93.78	.010 66	664.0	624.1	611.8	600.0	547.3	503.1
8	3.264	74.37	.013 45	526.6	494.9	485.2	475.9	434.0	399.0
9	2.906	58.98	.016 96	417.6	392.5	384.8	377.4	344.2	316.4
10	2.588	46.77	.021 38	331.2	311.3	305.1	299.3	273.0	250.9
11	2.305	37.09	.026 96	262.6	246.8	242.0	237.3	216.5	199.0
12	2.053	29.42	.034 00	208.3	195.8	191.9	188.3	171.7	157.8
13	1.828	23.33	.042 87	165.2	155.2	152.2	149.3	136.1	125.1
14	1.628	18.50	.054 06	131.0	123.1	120.7	118.4	108.0	99.24
15	1.450	14.67	.068 16	103.9	97.63	95.71	93.87	85.62	78.70
16	1.291	11.63	.085 95	82.38	77.43	75.90	74.44	67.90	62.41
17	1.150	9.226	.1084	65.33	61.40	60.20	59.04	53.85	49.50
18	1.024	7.317	.1367	51.81	48.69	47.74	46.82	42.70	39.25
19	0.9116	5.803	.1723	41.09	38.62	37.86	37.13	33.86	31.13
20	.8118	4.602	.2173	32.58	30.62	30.02	29.44	26.86	24.69
21	.7230	3.649	.2740	25.84	24.29	23.81	23.35	21.30	19.58
22	.6438	2.894	.3455	20.49	19.26	18.88	18.52	16.89	15.53
23	.5733	2.295	.4357	16.25	15.27	14.97	14.68	13.39	12.31
24	.5106	1.820	.5494	12.89	12.11	11.87	11.65	10.62	9.764
25	.4547	1.443	.6928	10.22	9.606	9.417	9.235	8.424	7.743
26	.4049	1.145	.8736	8.105	7.618	7.468	7.324	6.680	6.141
27	.3606	0.9078	1.102	6.428	6.041	5.922	5.808	5.298	4.870
28	.3211	.7199	1.389	5.097	4.791	4.697	4.606	4.201	3.862
29	.2859	.5709	1.752	4.042	3.799	3.725	3.653	3.332	3.063
30	.2546	.4527	2.209	3.206	3.013	2.954	2.897	2.642	2.429
31	.2268	.3590	2.785	2.542	2.389	2.342	2.297	2.095	1.926
32	.2019	.2847	3.512	2.016	1.895	1.858	1.822	1.662	1.527
33	.1798	.2258	4.429	1.599	1.503	1.473	1.445	1.318	1.211
34	.1601	.1791	5.584	1.268	1.192	1.168	1.146	1.045	0.9606
35	.1426	.1420	7.042	1.006	0.9450	0.9265	0.9086	0.8288	.7618
36	.1270	.1126	8.879	0.7974	.7495	.7347	.7206	.6572	.6041
37	.1131	.089 31	11.20	.6324	.5943	.5827	.5714	.5212	.4791
38	.1007	.070 83	14.12	.5015	.4713	.4621	.4532	.4133	.3799
39	.089 69	.056 17	17.80	.3977	.3738	.3664	.3594	.3278	.3013
40	.079 87	.044 54	22.45	.3154	.2964	.2906	.2850	.2600	.2390

Table continued on next page. Explanatory notes given at end of table.

[27] Length at 20° C of a wire whose resistance is 1 ohm at the stated temperatures.

METRIC

TABLE VII—Continued

Complete Wire Table, Standard Annealed Copper—Continued

American Wire Gage (B. & S.). Metric units—Continued

Gage No.	Diameter in mm at 20° C	Ohms per Kilogram					
		0° C	15° C	20° C	25° C	50° C	75° C
0000	11.68	0.000 155 4	0.000 165 4	0.000 168 7	0.000 172 0	0.000 188 6	0.000 205 2
000	10.40	.000 247 2	.000 263 0	.000 268 2	.000 273 5	.000 299 9	.000 326 2
00	9.266	.000 393 0	.000 418 1	.000 426 5	.000 434 9	.000 476 8	.000 518 7
0	8.252	.000 624 9	.000 664 9	.000 678 2	.000 691 5	.000 758 2	.000 824 8
1	7.348	.000 993 6	.001 057	.001 078	.001 100	.001 206	.001 311
2	6.544	.001 580	.001 681	.001 715	.001 748	.001 917	.002 085
3	5.827	.002 512	.002 673	.002 726	.002 780	.003 048	.003 316
4	5.189	.003 995	.004 250	.004 335	.004 420	.004 846	.005 272
5	4.621	.006 352	.006 758	.006 893	.007 029	.007 706	.008 383
6	4.115	.010 10	.010 75	.010 96	.011 18	.012 25	.013 33
7	3.665	.016 06	.017 09	.017 43	.017 77	.019 48	.021 20
8	3.264	.025 53	.027 17	.027 71	.028 26	.030 98	.033 70
9	2.906	.040 60	.043 20	.044 06	.044 93	.049 26	.053 59
10	2.588	.064 56	.068 69	.070 07	.071 44	.078 33	.085 21
11	2.305	.1026	.1092	.1114	.1136	.1245	.1355
12	2.053	.1632	.1737	.1771	.1806	.1980	.2154
13	1.828	.2595	.2761	.2817	.2872	.3149	.3426
14	1.628	.4127	.4391	.4479	.4567	.5007	.5447
15	1.450	.6562	.6982	.7122	.7262	.7961	.8661
16	1.291	1.043	1.110	1.132	1.155	1.266	1.377
17	1.150	1.659	1.765	1.801	1.836	2.013	2.190
18	1.024	2.638	2.807	2.863	2.919	3.201	3.482
19	0.9116	4.194	4.463	4.552	4.642	5.089	5.536
20	.8118	6.670	7.096	7.238	7.381	8.092	8.803
21	.7230	10.60	11.28	11.51	11.74	12.87	14.00
22	.6438	16.86	17.94	18.30	18.66	20.46	22.26
23	.5733	26.81	28.53	29.10	29.67	32.53	35.39
24	.5106	42.63	45.36	46.27	47.18	51.73	56.27
25	.4547	67.79	72.13	73.57	75.02	82.25	89.48
26	.4049	107.8	114.7	117.0	119.3	130.8	142.3
27	.3606	171.4	182.4	186.0	189.7	207.9	226.2
28	.3211	272.5	290.0	295.8	301.6	330.6	359.7
29	.2859	433.3	461.1	470.3	479.5	525.7	572.0
30	.2546	689.0	733.1	747.8	762.5	836.0	909.4
31	.2268	1096.	1166.	1189.	1212.	1329.	1446.
32	.2019	1742.	1854.	1891.	1928.	2114.	2299.
33	.1798	2770.	2947.	3006.	3065.	3361.	3656.
34	.1601	4404.	4686.	4780.	4874.	5344.	5813.
35	.1426	7003.	7451.	7601.	7750.	8497.	9244.
36	.1270	11 140.	11 850.	12 090.	12 320.	13 510.	14 700.
37	.1131	17 710.	18 840.	19 220.	19 590.	21 480.	23 370.
38	.1007	28 150.	29 960.	30 560.	31 160.	34 160.	37 160.
39	.089 69	44 770.	47 630.	48 590.	49 540.	54 310.	59 090.
40	.079 87	71 180.	75 740.	77 260.	78 770.	86 360.	93 950.

TABLE VII—Continued **METRIC**

Complete Wire Table, Standard Annealed Copper—Continued

American Wire Gage (B. & S.). Metric Units—Continued

Gage No.	Diameter in mm at 20° C	Grams per Ohm					
		0° C	15° C	20° C	25° C	50° C	75° C
0000	11.68	6 433 000.	6 046 000.	5 928 000.	5 813 000.	5 302 000.	4 874 000.
000	10.40	4 046 000.	3 803 000.	3 728 000.	3 656 000.	3 335 000.	3 065 000.
00	9.266	2 544 000.	2 391 000.	2 344 000.	2 299 000.	2 097 000.	1 928 000.
0	8.252	1 600 000.	1 504 000.	1 474 000.	1 446 000.	1 319 000.	1 212 000.
1	7.348	1 006 000.	945 900.	927 300.	909 400.	829 500.	762 500.
2	6.544	632 900.	594 900.	583 200.	571 900.	521 700.	479 500.
3	5.827	398 100.	374 100.	366 800.	359 700.	328 100.	301 600.
4	5.189	250 300.	235 300.	230 700.	226 200.	206 300.	189 700.
5	4.621	157 400.	148 000.	145 100.	142 300.	129 800.	119 300.
6	4.115	99 020.	93 060.	91 230.	89 470.	81 610.	75 020.
7	3.665	62 270.	58 530.	57 380.	56 270	51 330.	47 180.
8	3.264	39 160.	36 810.	36 080.	35 390.	32 280.	29 670.
9	2.906	24 630.	23 150.	22 690.	22 260.	20 300.	18 660.
10	2.588	15 490.	14 560.	14 270.	14 000.	12 770.	11 740.
11	2.305	9742.	9156.	8976.	8803.	8030.	7381.
12	2.053	6127.	5758.	5645.	5536.	5050.	4642.
13	1.828	3853.	3621.	3550.	3482.	3176.	2919.
14	1.628	2423.	2277.	2233.	2190.	1997.	1836.
15	1.450	1524.	1432.	1404.	1377.	1256.	1155.
16	1.291	958.4	900.8	883.1	866.1	790.0	726.1
17	1.150	602.8	566.5	555.4	544.7	496.8	456.7
18	1.024	379.1	356.3	349.3	342.6	312.4	287.2
19	0 9116	238.4	224.1	219.7	215.4	196.5	180.6
20	.8118	149.9	140.9	138.2	135.5	123.6	113.6
21	.7230	94.30	88.63	86.88	85.21	77.72	71.44
22	.6438	59.30	55.74	54.64	53.59	48.88	44.93
23	.5733	37.30	35.05	34.36	33.70	30.74	28.26
24	.5106	23.46	22.05	21.61	21.20	19.33	17.77
25	.4547	14.75	13.86	13.59	13.33	12.16	11.18
26	.4049	9.277	8.719	8.548	8.383	7.647	7.029
27	.3606	5.835	5.484	5.376	5.272	4.809	4.420
28	.3211	3.669	3.449	3.381	3.316	3.024	2.780
29	.2859	2.308	2.169	2.126	2.085	1.902	1.748
30	.2546	1.451	1.364	1.337	1.311	1.196	1.100
31	.2268	0.9127	0.8579	0.8410	0.8248	0.7523	0.6915
32	.2019	.5740	.5395	.5289	.5187	.4731	.4349
33	.1798	.3610	.3393	.3326	.3262	.2976	.2735
34	.1601	.2270	.2134	.2092	.2052	.1871	.1720
35	.1426	.1428	.1342	.1316	.1290	.1177	.1082
36	.1270	.089 80	.084 40	.082 74	.081 15	.074 02	.068 04
37	.1131	.056 48	.053 08	.052 04	.051 03	.046 55	.042 79
38	.1007	.035 52	.033 38	.032 73	.032 10	.029 27	.026 91
39	.089 69	.022 34	.020 99	.020 58	.020 19	.018 41	.016 92
40	.079 87	.014 05	.013 20	.012 94	.012 69	.011 58	.010 64

NOTE 1.—The *fundamental resistivity* used in calculating the tables is the International Annealed Copper Standard, viz, 0.153 28 ohm (meter, gram) at 20° C. The *temperature coefficient* for this particular resistivity is $\alpha_{20}=0.00393$, or $\alpha_0=0.00427$. However, the temperature coefficient is proportional to the conductivity, and hence the change of *resistivity* per degree C is a constant, 0.000 597 ohm (meter, gram). The "constant mass" temperature coefficient of any sample is

$$\alpha_t=\frac{0.000\ 597+0.000\ 005}{\text{resistivity in ohms (meter, gram) at } t^\circ \text{ C}}$$

The *density* is 8.89 grams per cubic centimeter.

NOTE 2.—The values given in the tables are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent higher resistivity than annealed copper.

NOTE 3.—This table is intended as an ultimate reference table, and is computed to a greater precision than is desired in practice. The practical user of a wire table is referred to the "Working Tables," Nos. VIII and IX.

ENGLISH

TABLE VIII

Working Table, Standard Annealed Copper Wire

American Wire Gage (B. & S.). English Units

Gage No.	Diameter in Mils	Cross Section		Ohms per 1000 Feet [28]		Pounds per 1000 Feet
		Circular Mils	Square Inches	25° C (=77° F)	65° C (=149° F)	
0000	460.	212 000.	0.166	0.0500	0.0577	641.
000	410.	168 000.	.132	.0630	.0727	508.
00	365.	133 000.	.105	.0795	.0917	403.
0	325.	106 000.	.0829	.100	.116	319.
1	289.	83 700.	.0657	.126	.146	253.
2	258.	66 400.	.0521	.159	.184	201.
3	229.	52 600.	.0413	.201	.232	159.
4	204.	41 700.	.0328	.253	.292	126.
5	182.	33 100.	.0260	.319	.369	100.
6	162.	26 300.	.0206	.403	.465	79.5
7	144.	20 800.	.0164	.508	.586	63.0
8	128.	16 500.	.0130	.641	.739	50.0
9	114.	13 100.	.0103	.808	.932	39.6
10	102.	10 400.	.008 15	1.02	1.18	31.4
11	91.	8230.	.006 47	1.28	1.48	24.9
12	81.	6530.	.005 13	1.62	1.87	19.8
13	72.	5180.	.004 07	2.04	2.36	15.7
14	64.	4110.	.003 23	2.58	2.97	12.4
15	57.	3260.	.002 56	3.25	3.75	9.86
16	51.	2580.	.002 03	4.09	4.73	7.82
17	45.	2050.	.001 61	5.16	5.96	6.20
18	40.	1620.	.001 28	6.51	7.51	4.92
19	36.	1290.	.001 01	8.21	9.48	3.90
20	32.	1020.	.000 802	10.4	11.9	3.09
21	28.5	810.	.000 636	13.1	15.1	2.45
22	25.3	642.	.000 505	16.5	19.0	1.94
23	22.6	509.	.000 400	20.8	24.0	1.54
24	20.1	404.	.000 317	26.2	30.2	1.22
25	17.9	320.	.000 252	33.0	38.1	0.970
26	15.9	254.	.000 200	41.6	48.0	.769
27	14.2	202.	.000 158	52.5	60.6	.610
28	12.6	160.	.000 126	66.2	76.4	.484
29	11.3	127.	.000 099 5	83.4	96.3	.384
30	10.0	101.	.000 078 9	105.	121.	.304
31	8.9	79.7	.000 062 6	133.	153.	.241
32	8.0	63.2	.000 049 6	167.	193.	.191
33	7.1	50.1	.000 039 4	211.	243.	.152
34	6.3	39.8	.000 031 2	266.	307.	.120
35	5.6	31.5	.000 024 8	335.	387.	.0954
36	5.0	25.0	.000 019 6	423.	488.	.0757
37	4.5	19.8	.000 015 6	533.	616.	.0600
38	4.0	15.7	.000 012 3	673.	776.	.0476
39	3.5	12.5	.000 009 8	848.	979.	.0377
40	3.1	9.9	.000 007 8	1070.	1230.	.0299

NOTE 1.—The *fundamental resistivity* used in calculating the tables is the International Annealed Copper Standard viz, 0.153 28 ohm (meter, gram) at 20° C. The *temperature coefficient* for this particular resistivity is $\alpha_{20}=0.00393$, or $\alpha_0=0.004\,27$. However, the temperature coefficient is proportional to the conductivity, and hence the change of *resistivity* per degree C is a constant, 0.000 597 ohm (meter, gram). The "constant mass" temperature coefficient of any sample is

$$\alpha_t=\frac{0.000\,597+0.000\,005}{\text{resistivity in ohms (meter, gram) at } t^\circ\text{ C}}$$

The *density* is 8.89 grams per cubic centimeter.

NOTE 2.—The values given in the table are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent higher resistivity than annealed copper.

NOTE 3.—Ohms per mile, or pounds per mile, may be obtained by multiplying the respective values above by 5.28.

[28] See explanation on p. 34.

TABLE IX **METRIC**

Working Table, Standard Annealed Copper Wire

American Wire Gage (B. & S.). Metric Units

Gage No.	Diameter in mm	Cross Section in mm²	Ohms per Kilometer		Kilograms per Kilometer
			25° C	65° C	
0000	11.7	107.	0.164	0.189	953.
000	10.4	85.0	.207	.239	756.
00	9.3	67.4	.261	.301	599.
0	8.3	53.5	.329	.379	475.
1	7.3	42.4	.415	.478	377.
2	6.5	33.6	.523	.603	299.
3	5.8	26.7	.659	.761	237.
4	5.2	21.2	.831	.959	188.
5	4.6	16.8	1.05	1.21	149.
6	4.1	13.3	1.32	1.53	118.
7	3.7	10.5	1.67	1.92	93.7
8	3.3	8.37	2.10	2.43	74.4
9	2.91	6.63	2.65	3.06	58.9
10	2.59	5.26	3.34	3.86	46.8
11	2.30	4.17	4.21	4.86	37.1
12	2.05	3.31	5.31	6.13	29.4
13	1.83	2.62	6.70	7.73	23.3
14	1.63	2.08	8.45	9.75	18.5
15	1.45	1.65	10.7	12.3	14.7
16	1.29	1.31	13.4	15.5	11.6
17	1.15	1.04	16.9	19.6	9.23
18	1.02	0.823	21.4	24.7	7.32
19	0.91	.653	26.9	31.1	5.80
20	.81	.518	34.0	39.2	4.60
21	.72	.411	42.8	49.4	3.65
22	.64	.326	54.0	62.3	2.89
23	.57	.258	68.1	78.6	2.30
24	.51	.205	85.9	99.1	1.82
25	.45	.162	108.	125.	1.44
26	.40	.129	137.	158.	1.14
27	.36	.102	172.	199.	0.908
28	.32	.0810	217.	251.	.720
29	.29	.0642	274.	316.	.571
30	.25	.0509	345.	398.	.453
31	.227	.0404	435.	502.	.359
32	.202	.0320	549.	634.	.285
33	.180	.0254	692.	799.	.226
34	.160	.0201	873.	1010.	.179
35	.143	.0160	1100.	1270.	.142
36	.127	.0127	1390.	1600.	.113
37	.113	.0100	1750.	2020.	.0893
38	.101	.0080	2210.	2550.	.0708
39	.090	.0063	2780.	3210.	.0562
40	.080	.0050	3510.	4050.	.0445

NOTE 1.—The *fundamental resistivity* used in calculating the table is the International Annealed Copper Standard, viz, 0.153 28 ohm (meter, gram) at 20° C. The *temperature coefficient*, for this particular resistivity, is α_{20}= 0.003 93, or α_0= 0.004 27. However, the temperature coefficient is proportional to the conductivity, and hence the change of *resistivity* per degree C is a constant, 0.000 597 ohm (meter, gram). The "constant mass" temperature coefficient of any sample is

$$\alpha_t = \frac{0.000\ 597 + 0.000\ 005}{\text{resistivity in ohms (meter, gram) at } t^\circ \text{ C}}$$

The *density* is 8.89 grams per cubic centimeter.

NOTE 2.—The values given in the table are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent higher resistivity than annealed copper.

TABLE X

Standard Annealed Copper Wire, (British) Standard Wire Gage

Gage No.	Diameter in Mils	Cross Section		Ohms per 1000 Feet [29]		Pounds per 1000 Feet
		Circular Mils	Square Inches	15.6° C (=60° F)	65° C (=149° F)	
7-0	500.	250 000.	0.1964	0.040 77	0.048 82	756.8
6-0	464.	215 300.	.1691	.047 34	.056 69	651.7
5-0	432.	186 600.	.1466	.054 61	.065 40	564.9
4-0	400.	160 000.	.1257	.063 70	.076 28	484.3
3-0	372.	138 400.	.1087	.073 65	.088 20	418.9
2-0	348.	121 100.	.095 12	.084 16	.1008	366.6
0	324.	105 000.	.082 45	.097 09	.1163	317.8
1	300.	90 000.	.070 69	.1132	.1356	272.4
2	276.	76 180.	.059 83	.1338	.1602	230.6
3	252.	63 500.	.049 88	.1605	.1922	192.2
4	232.	53 820.	.042 27	.1894	.2268	162.9
5	212.	44 940.	.035 30	.2268	.2716	136.0
6	192.	36 860.	.028 95	.2765	.3311	111.6
7	176.	30 980.	.024 33	.3290	.3940	93.76
8	160.	25 600.	.020 11	.3981	.4768	77.49
9	144.	20 740.	.016 29	.4915	.5886	62.77
10	128.	16 380.	.012 87	.6221	.7450	49.59
11	116.	13 460.	.010 57	.7574	.9071	40.73
12	104.	10 820.	.008 495	.9423	1.128	32.74
13	92.	8464.	.006 648	1.204	1.442	25.62
14	80.	6400.	.005 027	1.592	1.907	19.37
15	72.	5184.	.004 072	1.966	2.354	15.69
16	64.	4096.	.003 217	2.488	2.980	12.40
17	56.	3136.	.002 463	3.250	3.892	9.493
18	48.	2304.	.001 810	4.424	5.297	6.974
19	40.	1600.	.001 257	6.370	7.628	4.843
20	36.	1296.	.001 018	7.864	9.418	3.923
21	32.	1024.	.000 804 2	9.953	11.92	3.098
22	28.	784.0	.000 615 8	13.00	15.57	2.373
23	24.	576.0	.000 452 4	17.69	21.19	1.744
24	22.	484.0	.000 380 1	21.06	25.22	1.465
25	20.	400.0	.000 314 2	25.48	30.51	1.211
26	18.	324.0	.000 254 5	31.46	37.67	0.9807
27	16.4	269.0	.000 211 2	37.89	45.37	.8141
28	14.8	219.0	.000 172 0	46.54	55.73	.6630
29	13.6	185.0	.000 145 3	55.09	65.97	.5599
30	12.4	153.8	.000 120 8	66.28	79.38	.4654
31	11.6	134.6	.000 105 7	75.74	90.71	.4073
32	10.8	116.6	.000 091 61	87.38	104.6	.3531
33	10.0	100.0	.000 078 54	101.9	122.1	.3027
34	9.2	84.64	.000 066 48	120.4	144.2	.2562
35	8.4	70.56	.000 055 42	144.4	173.0	.2136
36	7.6	57.76	.000 045 36	176.5	211.3	.1748
37	6.8	46.24	.000 036 32	220.4	264.0	.1400
38	6.0	36.00	.000 028 27	283.1	339.0	.1090
39	5.2	27.04	.000 021 24	376.9	451.4	.081 85
40	4.8	23.04	.000 018 10	442.4	529.7	.069 74
41	4.4	19.36	.000 015 21	526.4	630.4	.058 60
42	4.0	16.00	.000 012 57	637.0	762.8	.048 43
43	3.6	12.96	.000 010 18	786.4	941.8	.039 23
44	3.2	10.24	.000 008 042	995.3	1192.	.031 00
45	2.8	7.840	.000 006 158	1300.	1557.	.023 73
46	2.4	5.760	.000 004 524	1769.	2119.	.017 44
47	2.0	4.000	.000 003 142	2548.	3051.	.012 11
48	1.6	2.560	.000 002 011	3981.	4768.	.007 749
49	1.2	1.440	.000 001 131	7078.	8476.	.004 359
50	1.0	1.000	.000 000 785 4	10 190.	12 210.	.003 027

NOTE 1.—The *fundamental resistivity* used in calculating the table is the International Annealed Copper Standard, viz, 0.153 28 ohm (meter, gram) at 20° C. The *temperature coefficient* for this particular resistivity, is α_{20}= 0.003 93, or α_0= 0.00 4 27. However, the temperature coefficient is proportional to the conductivity, and hence the change of *resistivity* per degree C is a constant, 0.000 597 ohm (meter, gram). The "constant mass" temperature coefficient of any sample is

$$\alpha_t = \frac{0.000\ 597 + 0.000\ 005}{\text{resistivity in ohms (meter, gram) at } t° \text{ C}}$$

The *density* is 8.89 grams per cubic centimeter.

NOTE 2.—The values given in the table are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent higher resistivity than annealed copper.

NOTE 3.—Ohms per mile, or pounds per mile, may be obtained by multiplying the respective values above by 5.28.

[29] Resistance at the stated temperature of a wire whose length is 1000 feet at the lower temperature.

TABLE XI

Standard Annealed Copper Wire, "Millimeter" Wire Gage

Diameter in mm	Cross Section in mm²	Ohms per Kilometer [30]		Kilograms per Kilometer
		20° C	65° C	
10.0	78.54	0.2195	0.2583	698.2
9.0	63.62	.2710	.3189	565.6
8.0	50.27	.3430	.4037	446.9
7.0	38.48	.4480	.5272	342.1
6.0	28.27	.6098	.7176	251.4
5.0	19.64	.8781	1.033	174.6
4.5	15.90	1.084	1.276	141.4
4.0	12.57	1.372	1.615	111.7
3.5	9.621	1.792	2.109	85.53
3.0	7.069	2.439	2.871	62.84
2.5	4.909	3.512	4.134	43.64
2.0	3.142	5:488	6.459	27.93
1.8	2.545	6.775	7.974	22.62
1.6	2.011	8.575	10.09	17.87
1.4	1.539	11.20	13.18	13.69
1.2	1.131	15.24	17.94	10.05
1.0	0.7854	21.95	25.83	6.982
0.90	.6362	27.10	31.89	5.656
.80	.5027	34.30	40.37	4.469
.70	.3848	44.80	52.72	3.421
.60	.2827	60.98	71.76	2.514
.50	.1964	87.81	103.3	1.746
.45	.1590	108.4	127.6	1.414
.40	.1257	137.2	161.5	1.117
.35	0.096 21	179.2	210.9	0.8553
.30	.070 69	243.9	287.1	.6284
.25	.049 09	351.2	413.4	.4364
.20	.031 42	548.8	645.9	.2793
.15	.017 67	975.7	1148.	.1571
.10	.007 854	2195.	2583.	.069 82
.05	.001 964	8781.	10 330.	.017 46

NOTE 1.—The *fundamental resistivity* used in calculating the table is the International Annealed Copper Standard, viz, 0.153 28 ohm (meter, gram) at 20° C. The *temperature coefficient* for this particular resistivity is $\alpha_{20}=0.003\,93$, or $\alpha_0=0.004\,27$. However, the temperature coefficient is proportional to the conductivity, and hence the change of *resistivity* per degree C is a constant, 0.000 597 ohm (meter, gram). The "constant mass" temperature coefficient of any sample is

$$\alpha_t = \frac{0.000\,597 + 0.000\,005}{\text{resistivity in ohms (meter, gram) at } t^\circ \text{ C}}$$

The *density* is 8.89 grams per cubic centimeter.

NOTE 2.—The values given in the table are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent higher resistivity than annealed copper.

[30] Resistance at the stated temperature of a wire whose length is 1 kilometer at 20° C.

ENGLISH

TABLE XII

Bare Concentric-Lay Cables of Standard Annealed Copper

English Units

Size of Cable		Ohms per 1000 Feet		Pounds per 1000 Feet	Standard Concentric Stranding			Flexible Concentric Stranding		
Circular Mils	A. W. G. No.	25° C (=77° F)	65° C (=149° F)		Number of Wires	Diameter of Wires, in Mils	Outside Diameter, in Mils	Number of Wires	Diameter of Wires, in Mils	Outside Diameter, in Mils
2 000 000		0.005 39	0.006 22	6180.	127	125.5	1631.	169	108.8	1632.
1 900 000		.005 68	.006 55	5870.	127	122.3	1590.	169	106.0	1590.
1 800 000		.005 99	.006 92	5560.	127	119.1	1548.	169	103.2	1548.
1 700 000		.006 34	.007 32	5250.	127	115.7	1504	169	100.3	1504.
1 600 000		.006 74	.007 78	4940.	127	112.2	1459.	169	97.3	1460.
1 500 000		.007 19	.008 30	4630.	91	128.4	1412.	127	108.7	1413.
1 400 000		.007 70	.008 89	4320.	91	124.0	1364.	127	105.0	1365.
1 300 000		.008 30	.009 58	4010.	91	119.5	1315.	127	101.2	1315.
1 200 000		.008 99	.0104	3710.	91	114.8	1263.	127	97.2	1264.
1 100 000		.009 81	.0114	3400.	91	109.9	1209.	127	93.1	1210.
1 000 000		.0108	.0124	3090.	61	128.0	1152.	91	104.8	1153.
950 000		.0114	.0131	2930.	61	124.8	1123.	91	102.2	1124.
900 000		.0120	.0138	2780.	61	121.5	1093.	91	99.4	1094.
850 000		.0127	.0146	2620.	61	118.0	1062.	91	96.6	1063.
800 000		.0135	.0156	2470.	61	114.5	1031.	91	93.8	1031.
750 000		.0144	.0166	2320.	61	110.9	998.	91	90.8	999.
700 000		.0154	.0178	2160.	61	107.1	964.	91	87.7	965.
650 000		.0166	.0192	2010.	61	103.2	929.	91	84.5	930.
600 000		.0180	.0207	1850.	61	99.2	893.	91	81.2	893.
550 000		.0196	.0226	1700.	61	95.0	855.	91	77.7	855.
500 000		.0216	.0249	1540.	37	116.2	814.	61	90.5	815.
450 000		.0240	.0277	1390.	37	110.3	772.	61	85.9	773.
400 000		.0270	.0311	1240.	37	104.0	728.	61	81.0	729.
350 000		.0308	.0356	1080.	37	97.3	681.	61	75.7	682.
300 000		.0360	.0415	926.	37	90.0	630.	61	70.1	631.
250 000		.0431	.0498	772.	37	82.2	575.	61	64.0	576.
212 000	0000	.0509	.0587	653.	19	105.5	528.	37	75.6	533.
168 000	000	.0642	.0741	518.	19	94.0	470.	37	67.3	471.
133 000	00	.0811	.0936	411.	19	83.7	418.	37	60.0	420.
106 000	0	.102	.117	326.	19	74.5	373.	37	53.4	374.
83 700	1	.129	.149	258.	19	66.4	332.	37	47.6	333.
66 400	2	.162	.187	205.	7	97.4	292.	19	59.1	296.
52 600	3	.205	.237	163.	7	86.7	260.	19	52.6	263.
41 700	4	.259	.299	129.	7	77.2	232.	19	46.9	234.
33 100	5	.326	.376	102.	7	68.8	206.	19	41.7	209.
26 300	6	.410	.473	81.0	7	61.2	184.	19	37.2	186.
20 800	7	.519	.599	64.3	7	54.5	164.	19	33.1	166.
16 500	8	.654	.755	51.0	7	48.6	146.	19	29.5	147.

NOTE 1.—The fundamental resistivity used in calculating the table is the International Annealed Copper Standard, viz, 0.15328 ohm (meter, gram) at 20° C (increased by 2 per cent as explained in Note 2 and on p. 37). The temperature coefficient is given in Table II. The density is 8.89 grams per cubic centimeter.

NOTE 2.—This table is in accord with standards adopted by the Standards Committee of the American Institute of Electrical Engineers, both in respect to the "Number of wires" and in respect to the correction for increase of resistance and mass due to the twist of the wires. The values given for "Ohms per 1000 feet" and "Pounds per 1000 feet" are 2 per cent greater than for a solid rod of cross section equal to the total cross section of the wires of the cable. This increment of 2 per cent means that the values are correct for cables having a lay of 1 in 15.7. For any other lay, equal to 1 in n, resistance or mass may be calculated by increasing the above tabulated values by

$$\left(\frac{493.}{n^2}-2.\right)\%.$$

TABLE XIII **METRIC**

Bare Concentric-Lay Cables of Standard Annealed Copper

Metric Units

Size of Cable, "Circular Mils" (or Gage No.)	Total Cross Section in mm²	Ohms per Kilometer		Kilograms per Kilometer	Standard Concentric Stranding			Flexible Concentric Stranding		
		25° C	65° C		Number of Wires	Diameter of Wires, in mm	Outside Diameter, in mm	Number of Wires	Diameter of Wires, in mm	Outside Diameter, in mm
2 000 000	1013.	0.0177	0.0204	9190.	127	3.19	41.4	169	2.76	41.4
1 900 000	963.	.0186	.0215	8730.	127	3.11	40.4	169	2.69	40.4
1 800 000	912.	.0197	.0227	8270.	127	3.02	39.3	169	2.62	39.3
1 700 000	861.	.0208	.0240	7810.	127	2.94	38.2	169	2.55	38.2
1 600 000	811.	.0221	.0255	7350.	127	2.85	37.1	169	2.47	37.1
1 500 000	760.	.0236	.0272	6890.	91	3.26	35.9	127	2.76	35.9
1 400 000	709.	.0253	.0292	6430.	91	3.15	34.7	127	2.67	34.7
1 300 000	659.	.0272	.0314	5970.	91	3.04	33.4	127	2.57	33.4
1 200 000	608.	.0295	.0340	5510.	91	2.92	32.1	127	2.47	32.1
1 100 000	557.	.0322	.0371	5050.	91	2.79	30.7	127	2.36	30.7
1 000 000	507.	.0354	.0408	4590.	61	3.25	29.3	91	2.66	29.3
950 000	481.	.0373	.0430	4370.	61	3.17	28.5	91	2,60	28.5
900 000	456.	.0393	.0454	4140.	61	3.09	27.8	91	2.53	27.8
850 000	431.	.0416	.0481	3910.	61	3.00	27.0	91	2.45	27.0
800 000	405.	.0442	.0511	3680.	61	2.91	26.2	91	2.38	26.2
750 000	380.	.0472	.0545	3450.	61	2.82	25.3	91	2.31	25.4
700 000	355.	.0506	.0583	3220.	61	2.72	24.5	91	2.23	24.5
650 000	329.	.0544	.0628	2990.	61	2.62	23.6	91	2.15	23.6
600 000	304.	.0590	.0681	2760.	61	2.52	22.7	91	2.06	22.7
550 000	279.	.0643	.0743	2530.	61	2.41	21.7	91	1.97	21.7
500 000	253.	.0708	.0817	2300.	37	2.95	20.7	61	2.30	20.7
450 000	228.	.0786	.0908	2070.	37	2.80	19.6	61	2.18	19.6
400 000	203.	.0885	.102	1840.	37	2.64	18.5	61	2.06	18.5
350 000	177.	.101	.117	1610.	37	2.47	17.3	61	1.92	17.3
300 000	152.	.118	.136	1380.	37	2.29	16.0	61	1.78	16.0
250 000	127.	.142	.163	1150.	37	2.09	14.6	61	1.63	14.6
A. W. G.										
0000	107.	.167	.193	972.	19	2.68	13.4	37	1.93	13.5
000	85.0	.211	.243	771.	19	2.39	11.9	37	1.71	12.0
00	67.4	.266	.307	611.	19	2.13	10.6	37	1.52	10.7
0	53.5	.334	.385	485.	19	1.89	9.46	37	1.36	9.50
1	42.4	.423	.488	385.	19	1.69	8.43	37	1.21	8.46
2	33.6	.533	.615	305.	7	2.47	7.42	19	1.50	7.51
3	26.7	.673	.777	242.	7	2.20	6.61	19	1.34	6.68
4	21.2	.849	.979	192.	7	1.96	5.88	19	1.19	5.95
5	16.8	1.07	1.23	152.	7	1.75	5.24	19	1.06	5.30
6	13.3	1.35	1.55	121.	7	1.56	4.67	19	0.944	4.72
7	10.5	1.70	1.96	95.7	7	1.39	4.16	19	.841	4.20
8	8.37	2.14	2.48	75.9	7	1.23	3.70	19	.749	3.74

NOTE 1.—The fundamental resistivity used in calculating the table is the International Annealed Copper Standard, viz, 0.15328 ohm (meter, gram) at 20° C (increased by 2 per cent as explained in Note 2 and on p. 37). The temperature coefficient is given in Table II. The density is 8.89 grams per cubic centimeter.

NOTE 2.—This table is in accord with standards adopted by the Standards Committee of the American Institute of Electrical Engineers, both in respect to the "Number of wires" and in respect to the correction for increase of resistance and mass due to the twist of the wires. The values given for "Ohms per kilometer" and "Kilograms per kilometer" are 2 per cent greater than for a solid rod of cross section equal to the total cross section of the wires of the cable. This increment of 2 per cent means that the values are correct for cables having a lay of 1 in 15.7. For any other lay, equal to 1 in n, resistance or mass may be calculated by increasing the above tabulated values by

$$\left(\frac{493.}{n^2}-2.\right)\%.$$

ENGLISH

TABLE XIV

Hard-Drawn Aluminum Wire at 20° C (or, 68° F)

English Units

American Wire Gage (B. & S.)

Gage No.	Diameter in Mils	Cross Section		Ohms per 1000 Feet	Pounds per 1000 Feet	Pounds per Ohm	Feet per Ohm
		Circular Mils	Square Inches				
0000	460.	212 000.	0.166	0.0804	195.	2420.	12 400.
000	410.	168 000.	.132	.101	154.	1520.	9860.
00	365.	133 000.	.105	.128	122.	957.	7820.
0	325.	106 000.	.0829	.161	97.0	602.	6200.
1	289.	83 700.	.0657	.203	76.9	379.	4920.
2	258.	66 400.	.0521	.256	61.0	238.	3900.
3	229.	52 600.	.0413	.323	48.4	150.	3090.
4	204.	41 700.	.0328	.408	38.4	94.2	2450.
5	182.	33 100.	.0260	.514	30.4	59.2	1950.
6	162.	26 300.	.0206	.648	24.1	37.2	1540.
7	144.	20 800.	.0164	.817	19.1	23.4	1220.
8	128.	16 500.	.0130	1.03	15.2	14.7	970.
9	114.	13 100.	.0103	1.30	12.0	9.26	770.
10	102.	10 400.	.008 15	1.64	9.55	5.83	610.
11	91.	8230.	.006 47	2.07	7.57	3.66	484.
12	81.	6530.	.005 13	2.61	6.00	2.30	384.
13	72.	5180.	.004 07	3.29	4.76	1.45	304.
14	64.	4110.	.003 23	4.14	3.78	0.911	241.
15	57.	3260.	.002 56	5.22	2.99	.573	191.
16	51.	2580.	.002 03	6.59	2.37	.360	152.
17	45.	2050.	.001 61	8.31	1.88	.227	120.
18	40.	1620.	.001 28	10.5	1.49	.143	95.5
19	36.	1290.	.001 01	13.2	1.18	.0897	75.7
20	32.	1020.	.000 802	16.7	0.939	.0564	60.0
21	28.5	810.	.000 636	21.0	.745	.0355	47.6
22	25.3	642.	.000 505	26.5	.591	.0223	37.8
23	22.6	509.	.000 400	33.4	.468	.0140	29.9
24	20.1	404.	.000 317	42.1	.371	.008 82	23.7
25	17.9	320.	.000 252	53.1	.295	.005 55	18.8
26	15.9	254.	.000 200	67.0	.234	.003 49	14.9
27	14.2	202.	.000 158	84.4	.185	.002 19	11.8
28	12.6	160.	.000 126	106.	.147	.001 38	9.39
29	11.3	127.	.000 099 5	134.	.117	.000 868	7.45
30	10.0	101.	.000 078 9	169.	.0924	.000 546	5.91
31	8.9	79.7	.000 062 6	213.	.0733	.000 343	4.68
32	8.0	63.2	.000 049 6	269.	.0581	.000 216	3.72
33	7.1	50.1	.000 039 4	339.	.0461	.000 136	2.95
34	6.3	39.8	.000 031 2	428.	.0365	.000 085 4	2.34
35	5.6	31.5	.000 024 8	540.	.0290	.000 053 7	1.85
36	5.0	25.0	.000 019 6	681.	.0230	.000 033 8	1.47
37	4.5	19.8	.000 015 6	858.	.0182	.000 021 2	1.17
38	4.0	15.7	.000 012 3	1080.	.0145	.000 013 4	0.924
39	3.5	12.5	.000 009 79	1360.	.0115	.000 008 40	.733
40	3.1	9.9	.000 007 77	1720.	.0091	.000 005 28	.581

TABLE XV

METRIC

Hard-Drawn Aluminum Wire at 20° C

Metric Units

American Wire Gage (B. & S.)

Gage No	Diameter in mm	Cross Section in mm²	Ohms per Kilometer	Kilograms per Kilometer	Grams per Ohm	Meters per Ohm
0000	11.7	107.	0.264	289.	1 100 000.	3790.
000	10.4	85.0	.333	230.	690 000.	3010.
00	9.3	67.4	.419	182.	434 000.	2380.
0	8.3	53.5	.529	144.	273 000.	1890.
1	7.3	42.4	.667	114.	172 000.	1500.
2	6.5	33.6	.841	90.8	108 000.	1190.
3	5.8	26.7	1.06	72.0	67 900.	943.
4	5.2	21.2	1.34	57.1	42 700.	748.
5	4.6	16.8	1.69	45.3	26 900	593.
6	4.1	13.3	2.13	35.9	16 900.	470.
7	3.7	10.5	2.68	28.5	10 600.	373.
8	3.3	8.37	3.38	22.6	6680.	296.
9	2.91	6.63	4.26	17.9	4200.	235.
10	2.59	5.26	5.38	14.2	2640.	186.
11	2.30	4.17	6.78	11.3	1660.	148.
12	2.05	3.31	8.55	8.93	1050.	117.
13	1.83	2.62	10.8	7.08	657.	92.8
14	1.63	2.08	13.6	5.62	413.	73.6
15	1.45	1.65	17.1	4.46	260.	58.4
16	1.29	1.31	21.6	3.53	164.	46.3
17	1.15	1.04	27.3	2.80	103.	36.7
18	1.02	0.823	34.4	2.22	64.7	29.1
19	0.91	.653	43.3	1.76	40.7	23.1
20	.81	.518	54.6	1.40	25.6	18.3
21	.72	.411	68.9	1.11	16.1	14.5
22	.64	.326	86.9	0.879	10.1	11.5
23	.57	.258	110.	.697	6.36	9.13
24	.51	.205	138.	.553	4.00	7.24
25	.45	.162	174.	.438	2.52	5.74
26	.40	.129	220.	.348	1.58	4.55
27	.36	.102	277.	.276	0.995	3.61
28	.32	.0810	349.	.219	.626	2.86
29	.29	.0642	440.	.173	.394	2.27
30	.25	.0509	555.	.138	.248	1.80
31	.227	.0404	700.	.109	.156	1.43
32	.202	.0320	883.	.0865	.0979	1.13
33	.180	.0254	1110.	.0686	.0616	0.899
34	.160	.0201	1400.	.0544	.0387	.712
35	.143	.0160	1770.	.0431	.0244	.565
36	.127	.0127	2230.	.0342	.0153	.448
37	.113	.0100	2820.	.0271	.009 63	.355
38	.101	.0080	3550.	.0215	.006 06	.282
39	.090	.0063	4480.	.0171	.003 81	.223
40	.080	.0050	5640.	.0135	.002 40	.177

PART 3. APPENDIXES

APPENDIX I. THE EXPRESSION OF RESISTIVITY

The names which have been in use for the various units of resistivity are frequently criticized. For example, "ohms per mil-foot" is unsatisfactory because the hyphen between mil and foot suggests a product and similarly "per" suggests a quotient. The name "ohms per meter-gram" is likewise objectionable, for interpretation by the usual conventions would lead to a false idea of the relations of resistance, mass, and length. Again, "microhms per cm cube" is open to the same misinterpretation. It is desirable to have names for these units which avoid this objection.

One way to select such names is to refer to the defining equations of the units and express the relations thereof by the usual conventions. Thus equations (1) and (2) below would give, for the units mentioned above, "ohm-circular-mils per foot," "ohm-grams per meter per meter," and "microhm-cm." These names (except the last) are certainly too cumbersome.

To overcome the difficulties it seems necessary to avoid the use of "per" and the hyphen in the names of the units of resistivity. There will be no misinterpretation possible if, e. g., the following expressions are used: "Resistance in ohms per foot of a uniform wire 1 mil in diameter," "resistance in ohms of a uniform wire 1 meter long weighing a gram," "resistance in microhms per centimeter of a bar 1 square centimeter in cross section." These names are exactly descriptive, and it is desirable to employ them whenever a careful statement of units is in order (the second one, e. g., is used on pages 5 and 28 of this circular). But when the unit is repeated, it is desirable to have a convenient abbreviated designation for it. We therefore use the following terms:

For mass resistivity:
- ohm (meter, gram).
- ohm (mile, pound).

For volume resistivity:
- ohm (mil, foot).
- ohm (meter, mm).
- ohm (meter, mm^2).
- microhm-cm.
- microhm-inch.

This set of abbreviated names is consistent in that each one states explicitly the units of the quantities employed in its definition. They are so similar to the older names that they can readily be understood by anyone familiar with the older expressions. "Resistivity" is definable quantitatively in terms of the resistance of a unit specimen, and hence a numerical value of resistivity is given by stating the number of ohms in such a unit specimen. The units employed in defining the different kinds of unit specimens are given in the parentheses in the foregoing expressions. An exception is to be noted in the case of the last two. These might be written, consistently with the others, "microhm (cm)" and "microhm (inch)"; but the expressions, "microhm-cm" and "microhm-inch," indicating a product, are dimensionally correct and are already in use; and it is therefore considered advisable to use these.

The units of conductivity may be written in abbreviated forms similar to the units of resistivity, e. g., $\frac{1}{\text{ohm}}$ (meter, mm²). This method of writing the units of resistivity and conductivity lends itself readily to the addition of other units, without risk of inconsistencies.

Not only the names of the units but the meaning and relations of the different units involved in the expression of resistivity are sometimes a source of confusion. The "mass resistivity," in terms of which the standard value for the resistivity of copper is expressed in this circular, is not familiar to some engineers and scientists. Few textbooks even mention "mass resistivity." Furthermore, some persons think that mass resistivity is necessarily less desirable than "volume resistivity," which is ordinarily defined as the resistance of a unit cube. An explanation and discussion of "mass resistivity," therefore, appears necessary. The advantages of this unit were appreciated a half century ago, for Lord Kelvin (Phil. Mag., 24, p. 156; 1862) said, "it is much to be desired that the *weight-measure*, rather than the diameter or the *volume-measure*, should be generally adopted for accurately specifying the gage of wires used as electric conductors." Furthermore, Matthiessen, in 1865, gave his results of resistivity measurements of the metals in ohms (meter, gram). The American Institute of Electrical Engineers in 1893 defined the standard resistivity, from which their Copper Wire Table was calculated, in terms of ohms (meter, gram). The British Engineering Standards Committee define the standard resistivity of copper in terms of the resistance in ohms of "a wire 1 meter long, weighing 1 gram." In all these cases "mass resistivity" is used, and we see that it is a well-established practice to express standard values of resistivity in terms of ohms (meter, gram). This unit is, moreover, established in commercial practice, at least for copper, as a number of the large electrical companies and copper-wire manufacturers in the United States, besides technical societies, express the resistivities of wires in terms of it. Those who employ English units exclusively use ohms (mile, pound), sometimes called "pounds per mile-ohm". This is exactly the equivalent of ohms (meter, gram), either unit being an expression of mass resistivity, which is defined quantitatively as the product of resistance per unit length and mass per unit length.

From the standpoint of the engineer and the user of conductors, especially line wires, the quantities directly concerned are the *ohms*, *mass*, and *length*, rather than the ohms, cross section, and length; and the former are the quantities actually *measured* in the usual commercial and engineering tests of copper. The measurement of cross section or density is comparatively rare, and should be so, since the mass can be more easily and accurately measured. Letting R = resistance, m = mass, l = length, s = cross section, d = density, δ = mass resistivity, ρ = volume resistivity, we have

$$\delta=\frac{R}{l}\cdot\frac{m}{l} \qquad (1)$$

Therefore the value directly obtained from the measured quantities is δ. To obtain ρ, we have

$$\rho=\frac{Rs}{l}=\frac{1}{d}\left(\frac{R}{l}\cdot\frac{m}{l}\right)=\frac{\delta}{d} \qquad (2)$$

A density must be used, in addition to the usually measured quantities, to give ρ. If instead of the actual density of the sample, which is usually unknown, a standard density d_0 is used, then we obtain a fictitious ρ,

$$\rho_0=\frac{\delta}{d_0} \qquad (3)$$

If a value is taken for δ as standard, then samples may be compared with the standard directly; but if some value of ρ is taken as standard, the intermediary quantity, density, must be specified. Thus, from the practical standpoint, the mass resistivity combines two variables in one, viz, the volume resistivity and the density. To the purchaser of copper for conducting purposes it is equally desirable to have either the conductance 1 per cent greater or the mass 1 per cent less, and it is evident that either variation would affect the mass resistivity equally.

Since conductors are usually sold by weight, the relative commercial value to users of conductors of the same or even of different metals is given simply by multiplying the cost per unit mass by the mass resistivity. This statement of relative commercial value neglects differences in insulation, differences of stranding of cables, economy of space, etc. The reasons why the mass resistivity is preferable to the volume resistivity may be summarized as follows:

1. The measurement of either cross section or density in many cases is difficult and inaccurate.

2. The direct measurement of cross section is practically impossible for irregular shapes of cross section.

3. Conductors are sold by weight rather than by volume, and therefore the information of value to most users is given directly by the mass resistivity.

Possibly one reason why the volume resistivity is still exclusively used by some people is the ease of defining it in terms of a unit cube. Such persons usually believe that their preference of volume resistivity over mass resistivity is due to the former's being more "scientific," whereas the real reason that they prefer it is because the mental picture of a unit cube is easy to retain. It is probable, however, that the worst thing about the unit of volume resistivity is the mental picture of a unit cube which accompanies it. From experience with students' examination papers college instructors soon learn that this conception too frequently leads to the gross error of thinking of resistance as proportional to volume. Indeed, practical men often use the expression "ohms per cubic centimeter." The "resistance of a unit cube" is not a practical case; wires are the usual articles whose resistance is desired to be known, and a form of expression of volume resistivity, which fits the case better, has been devised and is in extensive use. This form of expression is the "ohms (meter, mm)" or "ohms (mil, foot)" in which the greater dimension is the length of the wire and the smaller is the diameter. In these definitions we have the mental picture of a wire of a certain length and a certain diameter. When we speak of "ohms (meter, gram)" we similarly have the conception of a conductor of a certain length and a certain mass per unit length. There should be no greater difficulty about the second conception than about the first, especially since the mass per unit length can be actually determined with greater ease and accuracy than the mean diameter. The quantitative definitions of mass resistivity and volume resistivity can be made exactly symmetrical, thus: "Mass resistivity" = product of resistance per unit length into mass per unit length, and "volume resistivity" = product of resistance per unit length into volume per unit length.

54945°—14——5

It is to be noticed that the term "specific resistance" has not been used at all in this discussion. "Specific resistance" has been very extensively used in the past for the volume resistivity. The term was, however, not well chosen, and seems to be tending to go out of use and give way to "resistivity." "Specific resistance" is considered to be an unfortunately chosen name to express the resistance of a unit quantity because similar names, e. g., specific heat, specific gravity, specific inductive capacity, refer primarily, not to the property of a unit quantity of the substance, but to the *ratio* of the property of the particular substance to the same property of a standard substance. Another pedagogical stumbling block is found herein, for students are sometimes found defining "specific resistance" as the ratio of the resistance of some quantity of a metal to the resistance of the same quantity of copper. The term "resistivity" is a better name than "specific resistance," just as "conductivity" is a better term than "specific conductance" would be. "Specific resistance" has probably not been much used to express the resistance of a unit mass.

There is no à priori reason why "resistivity" could not refer to the unit mass, as some people profess to believe; and this term has not been limited to the idea of the unit cube or unit cross section, historically. For example, as mentioned above, in the old A. I. E. E. Copper Wire Table, the standard "resistivity" was given in terms of ohms (meter, gram). "Resistivity" is simply the property of a substance, and in forming its quantitative definition we are at liberty to choose any of the units of length, mass, and time, and the international electrical units, combined in those relations which experiment has shown to be correct. Since there are two common modes of defining resistivity, using the unit mass and the unit cube, it is desirable in any case where confusion might arise, to indicate which is meant by using the precise expressions "mass resistivity" and "volume resistivity." These expressions are used in Alexander Russell's Theory of Electric Cables and Networks," 1908. It may be worth remarking that no definition of resistivity is admissible which involves something not a property of the material itself. For example, we can not speak of a "cost resistivity" since a unit whose value depends on business conditions can not be considered a physical expression of the properties of unit quantity of a substance.

In the expression of "percent conductivity" there is a similar necessity for distinguishing between the definitions in terms of the unit mass and the unit cube. The term "percent conductivity" is extensively used in the copper industry, and on account of its convenience will probably continue in use. (See first sentence in section (*d*) on p. 12.) Of course the percent conductivity can be calculated from either the mass resistivity or the volume resistivity, and if the density of the sample is different from the standard density these two percent conductivities will not agree. Accordingly, the use of "percent conductivity" should be limited to copper; unless it is very carefully indicated whether it was calculated from the mass resistivity or the volume resistivity by the use of the terms "mass percent conductivity," or "volume percent conductivity." A striking example of the difference between the two percent conductivities in the case of a metal of different density from that of copper is furnished by aluminum. Thus, the "mass percent conductivity" of average commercial hard-drawn aluminum is about 200 per cent, while the "volume percent conductivity" is about 61 per cent. The general conclusion may be drawn from the foregoing that it is always desirable to state conductivity or resistivity directly in terms of the mass resistivity at a standard temperature rather than in terms of percent conductivity.

To sum up, this discussion has tried to make the following points clear; (1) That the older names for the units of resistivity are objectionable; (2) that from a practical standpoint the mass resistivity is preferable to the volume resistivity; (3) that the advantage of a mental picture to aid in defining volume resistivity is no less available in defining mass resistivity; (4) that "specific resistance" is an undesirable term; (5) that the term "resistivity" is susceptible of a certain breadth of definition; (6) that there are limitations to the proper use of "percent conductivity."

APPENDIX II. CALCULATION OF THE "RESISTIVITY-TEMPERATURE CONSTANT"

The temperature coefficient of *resistance*, as measured between potential terminals rigidly attached to the wire, expresses the change of resistance for a constant mass. The change of *resistivity* per degree involves a change of dimensions as well as this change of resistance, and hence the coefficient of expansion γ of copper must be considered as well as the temperature coefficient of resistance α. The "mass resistivity" δ depends on the mass m, the resistance R, and the length l, as follows:

$$\delta = \frac{mR}{l^2}$$

$$\delta_t = \frac{mR_{20}(1+\alpha_{20}[t-20])}{l_{20}^2(1+\gamma[t-20])^2}$$

$$=\delta_{20}(1+[\alpha_{20}-2\gamma]\,[t-20]),\ \text{(since } \gamma \text{ is very small)}.$$

For 100 percent conductivity, using ohms (meter, gram)

$$\delta_t = 0.15328\ (1 + [0.003\ 930 - 0.000\ 034]\ [t - 20])$$
$$= 0.15328 + (0.15\ 328)\ (0.003\ 896)\ (t - 20)$$
$$= 0.15328 + 0.000\ 597\ (t - 20)$$

This "resistivity-temperature constant," 0.000 597, is readily seen to be independent of the temperature of reference. It also holds for copper samples of all conductivities (in the range investigated), since, if we let the subscripts X and N denote samples of unknown and of standard conductivity, respectively,

$$\frac{\alpha_X}{\alpha_N} = \frac{\delta_N}{\delta_X},\ \text{or}\ \alpha_X \delta_X = \alpha_N \delta_N = 0.000\ 597.$$

Similarly the calculation may be made for the "volume resistivity" ρ, which involves the cross-section s:

$$\rho = \frac{Rs}{l}$$

$$\rho_t = \frac{R_{20} s_{20}\ (1 + \alpha_{20}\ [t-20])\quad (1 + 2\gamma\ [t-20])}{l_{20}\ (1 + \gamma\ [t-20])}$$

$$= \rho_{20}\ (1 + [\alpha_{20} + \gamma]\ [t-20]),\ \text{(since } \gamma \text{ is very small).}$$

For 100 percent conductivity, using microhm-cms,

$$\rho_t = 1.7241\ (1 + [0.003\ 930 + 0.000\ 017]\ [t-20])$$
$$= 1.7241\ + (1.7241)\ (0.003\ 947)\ (t-20)$$
$$= 1.7241\ +\ 0.006\ 81\ (t-20)$$

This "resistivity-temperature constant," 0.006 81, similarly holds for any temperature of reference and any conductivity.

This effect of thermal expansion in the expression of the temperature coefficient is treated on pp. 93 to 96 of Bulletin of the Bureau of Standards, Vol. 7, No. 1, in the paper on "The Temperature Coefficient of Resistance of Copper." Thus, the explanation given herewith is contained in the two formulas:

$$\alpha_\delta = \alpha_R - 2\gamma \tag{35}$$
$$\alpha_\rho = \alpha_R + \gamma \tag{32}$$

The relations of these temperature coefficients to that obtained when the measurements are made between knife-edges are given in formulas (38), (39), and (40) of the same paper. Although the effect of thermal expansion is small, it was considered desirable to take account of it, since these constants will be used in reducing the results of resistivity measurements from one temperature to another, and troublesome inconsistencies would otherwise arise. It must be carefully noted that the constants here given are different from those in the paper just referred to, owing to the different value of resistivity, and consequently of temperature coefficient, taken as corresponding to 100 per cent conductivity.

Attention is called to the great convenience of the "resistivity-temperature constant" in computing the temperature *coefficient*, α_t, at any temperature t for any sample of copper whose resistivity is known at the temperature t. Thus, $\alpha_t = \frac{0.000\ 597}{\delta_t}$. The α_t thus obtained, however, is the α_δ of formula (35) above, viz, the "temperature coefficient of mass resistivity." To obtain the more frequently used "*constant mass temperature coefficient of resistance*," (that obtained by resistance measurements between potentia terminals rigidly attached to the wire), we have

$$\alpha_t = \frac{0.000\ 597 + 0.000\ 005}{\text{ohms (meter, gram) at } t^\circ \text{ C}}$$

$$\text{Also, } \alpha_t = \frac{0.006\ 81 - 0.000\ 03}{\text{microhm-cms at } t^\circ \text{ C}}$$

$$\text{Also, } \alpha_t = \frac{3.41 + 0.03}{\text{ohms (mile, pound) at } t^\circ \text{ C}}$$

$$\text{Also, } \alpha_t = \frac{0.002\ 68 - 0.000\ 01}{\text{microhm-inches at } t^\circ \text{ C}}$$

$$\text{Also, } \alpha_t = \frac{0.0409 - 0.0002}{\text{ohms (mil, foot) at } t^\circ \text{ C}}$$

These formulas furnish a very convenient connection between the "resistivity-temperature constant" and the temperature coefficient of resistance.

APPENDIX III. THE DENSITY OF COPPER

As stated above, in Appendix I, the quantities measured in the usual engineering or commercial tests of resistivity of copper are resistance, mass, and length. The constant of the material which is actually measured is therefore the mass resistivity. When it is desired to calculate the resistance of a wire from its dimensions, it is necessary to know the density in addition to the mass resistivity. The density of copper is usually considered to vary so little from sample to sample that the volume resistivity can be calculated for a sample by the use of a standard value for the density. The density is the connecting link between mass resistivity and volume resistivity, the former being proportional to the product of the latter into the density. It is the purpose of this Appendix to present some data on the density of copper used for conductors, obtained at the Bureau of Standards in connection with the investigations of the temperature coefficient and the conductivity of copper. The average value from all the data is the figure which has been most frequently used in the past as a standard value, viz, 8.89 (at 20° C). The same value was adopted by the International Electrotechnical Commission in 1913 as a standard density. The data may be conveniently divided into three parts.

First, the density has been determined on a number of the wire samples submitted to the Bureau of Standards for ordinary conductivity tests by various companies. During the three years, 1908–1910, the density of 36 such samples was determined. These samples had been submitted by seven companies, as follows: Three smelters, three electrolytic refiners, one user of copper, who bought his material from various copper companies. The number of samples and the mean density, for each of these companies, is shown in the following table:

Number of samples	Density
8	8.882
2	8.892
3	8.869
3	8.895
4	8.918
12	8.872
4	8.878
	Mean......... 8.887

All of the 36 samples were of conductivity greater than 97.5 per cent, except one of the samples in the fourth group, for which the conductivity was 94.6 per cent and the density was 8.887.

The second group of data is that obtained from the wires which were included in the investigations of the temperature coefficient and resistivity of copper. Inasmuch as the "mass resistivity" was considered the important quantity rather than the "volume resistivity," it was not necessary in the investigation to determine the density. However, measurements were made on a few samples from three of the companies whose copper was included in the investigation, and data were obtained by Mr. George

L. Heath, of the Calumet and Hecla Smelting Works, on 18 samples of copper, a number of which were included in the Bureau of Standards investigation. The results, for the four companies, are summarized in the following table:

Number of samples	Density
3	8. 880
1	8. 895
1	8. 900
18	8. 899
	Mean......... 8. 893

All of these samples were of conductivity greater than 95 per cent.

The third group of data is that obtained at the Physikalisch-Technische Reichsanstalt, of Germany, by Prof. Lindeck,[13] and given in the Appendix [31] of the paper on "The temperature coefficient of resistance of copper." These results are for copper samples submitted for test at the Reichsanstalt during the five years, 1905-1909. The mean value of the density for the 48 samples is

8.890.

Some of these samples were of low conductivity, down to one-third of the conductivity of pure copper. Taking only the 34 samples of conductivity greater than 94 per cent, the mean value of the density is

8.881.

The final average value may be computed from the three groups of data in the following way, for example:

B. S. tests	8. 887
B. S. investigation	8. 893
Reichsanstalt	8. 890
Final average	8. 890

Or, if we use the Reichsanstalt value for only the samples whose conductivity exceeded 94 per cent, we have:

B. S. tests	8. 887
B. S. investigation	8. 893
Reichsanstalt	8. 881
Final average	8. 887

[31] Bulletin of Bureau of Standards, **7**, pp. 97-101; 1910.

Or, if we consider the Calumet and Hecla measurements and the other measurements of the second group as independent means, and again use the Reichsanstalt value for only the samples whose conductivity exceeded 94 per cent, we have:

B. S. tests	8. 887
B. S. investigation	8. 892
Calumet and Hecla	8. 899
Reichsanstalt	8. 881
Final average	8. 890

For any reasonable method of calculating the final average, we find that, to three figures, the value is

8.89.

In justification of the assumption made in engineering practice that the variations of the density of particular samples of copper from the standard mean value do not exceed the limits of commercial accuracy, the data on the samples discussed in the foregoing show that the density is usually between 8.87 and 8.91, that in a few cases it varies as far as 8.85 and 8.93, and that in extreme cases it can vary to 8.83 and 8.94. We are here referring to copper of conductivity greater than 94 per cent.

The question sometimes arises whether there is any difference in the density of annealed and of hard-drawn copper. That there is no appreciable difference was shown by experiments made by Mr. Heath on the 18 wires mentioned above, which were of 80 mils and 104 mils diameter (No. 10 and No 12 A. W. G.). The mean density of 8 annealed samples was 8.899. The mean density of 10 hard-drawn samples from the same coils was 8.898. After these hard-drawn samples were annealed their mean density was 8.900. The very small differences between these three means are too small to be considered significant. The densities of all the 18 samples varied from 8.878 to 8.916.

Finally, it is desired to point out that confusion sometimes arises over the different ways of specifying density and "specific gravity." For instance, this has led to a criticism of the value, 8.89 for density, as being too low a figure. The critic, however, had in mind the "specific gravity referred to water as 20° C." Density, defined as the number of grams per cubic centimeter, is identically equal to "specific gravity referred to water at its maximum density." A "specific gravity referred to water at 20° C" of 8.91 is equal to a density, or "specific gravity referred to water at its maximum density," of 8.8946. It is apparent that the term "specific gravity" is not definite unless it be stated to what temperature of water it is referred. Since varying interpretations can not be given the term *density*, this is the preferable term. Of course, since a metal expands as its temperature rises, its density decreases. Thus, if the density of copper is 8.89 at 20° C, it is 8.90 at 0° C. Consequently, when we state either a density or a specific gravity, the temperature of the substance whose density we are giving should be specified.

To sum up this discussion, the density of copper has been found to be 8.89 at 20° C.

APPENDIX IV. CALCULATION OF THE RESISTANCE AND MASS PER UNIT LENGTH OF CABLES

In the first place, it is proposed to show that the per cent increase of resistance of a cable with all the wires perfectly insulated from one another over the resistance of the "equivalent solid rod" is exactly equal to the per cent decrease of resistance of a cable in which each wire makes perfect contact with a neighboring wire at all points of its surface. That is, if

R_s = resistance of a solid wire or rod of the same length and of cross section equal to the total cross section of the cable (taking the cross section of each wire perpendicular to the axis of the wire),

R_1 = resistance of a cable with the individual wires perfectly insulated from one another,

R_2 = resistance of a hypothetical cable with the wires distorted into such shape that they make perfect contact at all points of their surfaces (the layers all being twisted in the same direction),

$$\text{then } R_s = \frac{R_1 + R_2}{2}$$

$R_1 > R_s$, because on account of the stranding the path of the current is longer than it would be if parallel to the axis of the cable. $R_2 < R_s$, because the path of the current is in this case parallel to the axis of the cable, which path has a greater cross section than the sum of the cross sections of each wire taken perpendicular to the axis of the wire

$$\therefore R_1 > R_s > R_2$$

In showing that R_s is just halfway between R_1 and R_2, we use the symbols:

ρ = volume resistivity

l = length along axis of cable; or length of "equivalent solid rod"

s = total cross section of the wires of the cable, taken perpendicular to axis of wire; or cross section of "equivalent solid rod"

Δl = increase of length of wire due to twisting

Δs = increase of cross section perpendicular to axis of cable due to twisting

We have:

$$R_s = \frac{\rho l}{s} \tag{1}$$

$$R_1 = \frac{\rho(l + \Delta l)}{s} \tag{2}$$

$$R_2 = \frac{\rho l}{s + \Delta s} \tag{3}$$

The following diagram shows a side view of one wire of a cable. In the diagram only one dimension of the cross section, s, is shown; the dimension perpendicular to this is unchanged by the twisting, and hence s is proportional to the dimension shown.

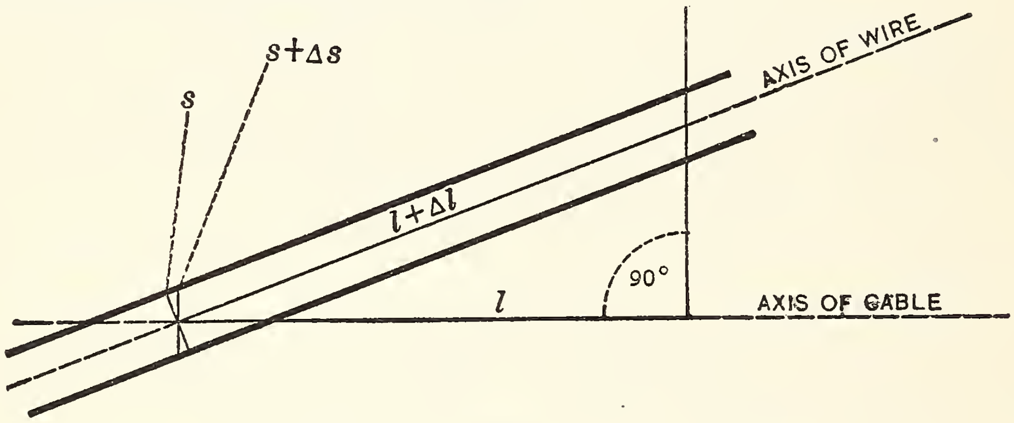

Fig. 3

By similar triangles,

$$\frac{s + \Delta s}{s} = \frac{l + \Delta l}{l}$$

$$s + \Delta s = s\left(1 + \frac{\Delta l}{l}\right) \tag{4}$$

$$\therefore R_2 = \frac{\rho l}{s\left(1 + \frac{\Delta l}{l}\right)} = \frac{\rho l}{s}\left(1 - \frac{\Delta l}{l}\right), \text{ since } \frac{\Delta l}{l} \text{ is small.} \tag{5}$$

From (2),

$$R_1 = \frac{\rho l}{s}\left(1 + \frac{\Delta l}{l}\right) \tag{6}$$

$$\therefore R_1 + R_2 = \frac{2\rho l}{s} \tag{7}$$

From (1) and (7),

$$R_s = \frac{R_1 + R_2}{2}$$

Q. E. D.

The resistance of an actual cable must be between R_1 and R_2, if the stranding operations do not change the resistivity. Although the case represented by R_2 is highly hypothetical, still the effect of contact between the wires is not zero. This is shown by the fact that the resistance of cables increases with age, which may be considered to be due to contamination of the wire surfaces. Hence the resistance of a cable is somewhat less than R_1. Manufacturers agree, however, that it is much nearer R_1 than R_s, and it is ordinarily taken as equal to R_1. By equations (1) and (6),

$$\frac{R_1 - R_s}{R_s} = \frac{\Delta l}{l}.$$

The resistance of a cable is therefore taken to be greater than R_s by a fractional amount equal to $\frac{\Delta l}{l}$. The *mass* of a cable is greater than the mass of the "equivalent solid rod" by a fractional amount exactly equal to $\frac{\Delta l}{l}$. This is readily seen, and may be considered to be due either to increase of length or to increase of cross section. There is no appreciable change of density in stranding. The increment of resistance and of mass is taken to be 2 per cent in calculating the tables of this circular. This involves the assumption of a definite value for the "lay" or pitch. The method of computing this fraction from the "lay" of the cable is given herewith. Let

d = diameter of the helical path of one wire.

L = length along axis of cable for one complete revolution of wire about axis.

$n = \frac{L}{d}$ = number of times the diameter d is contained in the length L,

"Lay" $= \frac{d}{L} = \frac{1}{n}$ = ratio of the diameter d to the length L.

The lay is usually expressed as $\frac{1}{n}$ or "1 in n"; thus we may speak of a lay of 1/20, or 1 in 20.

Consider a wire of length $(L + \Delta L)$, developed in a plane containing the axis of the cable, of length L. The developed wire and the axis make with each other the angle θ, in the figure. The third side of the triangle equals in length the circumference of the helical path of the wire.

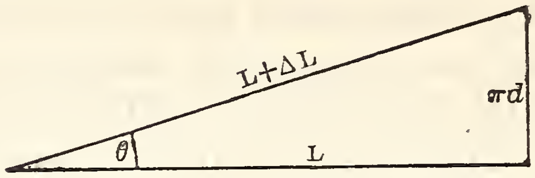

Fig. 4

$$\tan\theta = \frac{\pi d}{L} = \frac{\pi}{n}$$

$$\frac{L+\Delta L}{L} = \sec\theta = \sqrt{1+\tan^2\theta}$$

$$= \sqrt{1+\frac{\pi^2}{n^2}}$$

$$= 1 + \frac{1}{2}\left(\frac{\pi^2}{n^2}\right) - \frac{1}{8}\left(\frac{\pi^2}{n^2}\right)^2 + \cdots\cdots$$

All terms of higher order than the first are negligible for the purpose in hand; hence the correction factor to obtain resistance or mass per unit length of a cable from that of the "equivalent solid rod" is

$$\left(1+\frac{\Delta l}{l}\right) = \left(1+\frac{\Delta L}{L}\right) = 1 + \frac{1}{2}\left(\frac{\pi^2}{n^2}\right)$$

This correction factor must be computed separately for each layer of strands when the lay is different for different layers of the cable. If L is the same for each layer of the cable, the lay varies because of the change of d. It should not be forgotten that the central wire is untwisted.

The lay corresponding to a correction of 2 per cent is calculated thus:

$$1 + 2\% = 1 + \frac{1}{2}\left(\frac{9.87}{n^2}\right),$$

$$n = 15.7$$

This means that the values given in Tables XII and XIII for resistance and mass per unit length correspond to cables having a lay of 1 in 15.7. If the lay is known and is different from 1 in 15.7, resistance or mass may be calculated by multiplying the values in Tables XII and XIII by

$$1 + \left(\frac{493.}{n^2} - 2.\right)\%$$

For example, if the lay is 1 in 12, resistance or mass may be obtained by *adding* 1.4 per cent to the values in the tables. If the lay is 1 in 30, resistance or mass may be obtained by *subtracting* 1.5 per cent from the values in the tables.

APPENDIX V. PUBLICATION 28 OF INTERNATIONAL ELECTROTECHNICAL COMMISSION, "INTERNATIONAL STANDARD OF RESISTANCE FOR COPPER"

PREFACE

The electrical industry has repeatedly felt the need of a resistance standard for copper. Until quite recently there has been a lack of uniformity in the values adopted in the different countries as the standard for annealed copper, arising in the main from the varying interpretation of Matthiessen's original work for the British Association Electrical Standards Committee in 1864 on which ultimately the various values were based. Although the differences have not been very great they have been sufficiently large to prevent the various national tables for copper wires being entirely comparable.

The idea of adopting an international standard for copper was first suggested at the Chicago Congress of 1893, but the proposal unfortunately fell to the ground. During 1911, however, on the initiative of the American Institute of Electrical Engineers, the Bureau of Standards, of Washington, undertook certain experimental work, the results of which are published in the Bulletin of the Bureau for 1911, Volume 7, No. 1.[32] On the conclusion of this experimental work the international aspect of the matter was considered by the various national laboratories.

The National Committee of the United States of America also brought the subject to the notice of the I. E. C., and in May, 1912, certain definite propositions, based on the experiments carried out by the different national laboratories, were considered by a special committee of the I. E. C. then sitting in Paris. These propositions were subsequently circulated to the various national committees of the I. E. C., and at Zurich, in January, 1913, they were agreed to in principle; Dr. R. T. Glazebrook, C. B. (Director of the National Physical Laboratory of London), and Prof. Paul Janet (Director of the Laboratoire central d'Electricité of Paris) kindly undertaking to prepare the final wording of the different clauses in consultation with the Bureau of Standards, of Washington, and the Physikalisch-Technische Reichsanstalt, of Berlin.

At the plenary meeting of the I. E. C. held in Berlin in September, 1913, at which 24 nations were represented, the final recommendations, which were presented in person by Prof. Dr. E. Warburg (President of the Physikalisch-Technische Reichsanstalt of Berlin) were ratified as given in this report.

LONDON, *March, 1914.*

I. STANDARD ANNEALED COPPER

The following shall be taken as normal values for standard annealed copper:

1. At a temperature of 20° C the resistance of a wire of standard annealed copper 1 meter in length and of a uniform section of 1 square millimeter is 1/58 ohm=0.017241 . . . ohm.

2. At a temperature of 20° C the density of standard annealed copper is 8.89 grams per cubic centimeter.

3. At a temperature of 20° C the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between two potential points rigidly fixed to the wire, is 0.00393=1/254.45 . . . per degree centigrade.

4. As a consequence, it follows from (1) and (2) that at a temperature of 20° C the resistance of a wire of standard annealed copper of uniform section 1 meter in length and weighing 1 gram is (1/58)×8 8.9=0.15328 . . . ohm.

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[32] J. H. Dellinger, "Temperature coefficient of the resistance of copper;"
F. A. Wolff and J. H. Dellinger, "Electrical conductivity of commercial copper."

II. COMMERCIAL COPPER

1. The conductivity of commercial annealed copper shall be expressed as a percentage, at 20° C, of that of standard annealed copper and given to approximately 0.1 per cent.

2. The conductivity of commercial annealed copper is to be calculated on the following assumptions:

(*a*) The temperature at which measurements are to be made shall not differ from 20° C by more than ± 10° C.

(*b*) The resistance of a wire of commercial copper 1 meter in length 1 square millimeter in section increases by 0.000068 ohm per degree centigrade.

(*c*) The resistance of a wire of commercial copper 1 meter in length and 1 gram in mass increases by 0.00060 ohm per degree centigrade.

(*d*) The density of commercial annealed copper at 20° C is 8.89 grams per cubic centimeter.

This value of the density should be employed in calculations relating to the conductivity of commercial annealed copper.

From these assumptions it follows that if at a temperature of t° C, R be the resistance in ohms, of a wire "l" meters in length weighing "m" grams, the resistance of a wire of the same copper 1 meter in length and 1 square millimeter in section is:

$$Rm/(l^2 \times 8.89), \; \ldots\ldots\ldots \text{ at } t° \text{ C};$$
$$\text{and } Rm/(l^2 \times 8.89) + 0.000068\,(20-t), \; \ldots\ldots\ldots \text{ at } 20° \text{ C}.$$

The percentage of conductivity of this copper is therefore

$$100 \times \frac{1/58}{\frac{Rm}{l^2 \times 8.89} + 0.000068\,(20-t)}$$

And, similarly, the resistance of a wire of the same copper 1 meter in length weighing 1 gram is:

$$Rm/l^2, \; \ldots\ldots\ldots \text{ at } t° \text{ C};$$
$$\text{and } Rm/l^2 + 0.00060\,(20-t), \; \ldots\ldots\ldots \text{ at } 20° \text{ C}.$$

The percentage conductivity is therefore

$$100 \times \frac{0.15328}{\frac{Rm}{l^2} + 0.00060\,(20-t)}$$

Note I.—The standard values given above under (I) are the mean values resulting from a large number of tests. Amongst various specimens of copper of standard conductivity the density may differ from the standard by 0.5 per cent and the temperature coefficient of resistance may differ from the standard by 1 per cent; but within the limits indicated in (II) these differences will not affect the values of the resistance so long as the calculations are only carried to four significant figures.

Note II.—The above statements are consistent with the following physical constants of standard annealed copper:

Density at 0° C	8.90
Coefficient of linear expansion per degree centigrade	0.000017
Resistivity at 0° C, in microhm-centimeters	1.588_1
Coefficient, at 0° C, of variation of volume resistivity per degree centigrade	0.00428_2
Coefficient, at 0° C, of variation of resistance at constant mass	$0.00426_5 = 1/234.45\ldots$