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55

4th Edition

Copper Wire Tables

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Copper Wire Tables

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Preface

Circular 31 has been revised at the request of the Committee on Wires for Electrical Conductors of the American Society for Testing Materials. To reduce internal inconsistencies, the wire diameters have been rounded to 0.1 mil and the tables are calculated from these values for diameter. Values are listed with an accuracy corresponding to that of the wire diameters. The so-called working tables have been omitted, also the aluminum-wire tables and much of the historical introduction. However, the tables have been extended to 50 gage and to a temperature of 200° C. Otherwise, as far as possible, the original discussion has been retained.

A. V. Astin, *Director.*

1.1. Standard Values for Copper

Copper wire tables are based on certain standard values for the density, 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 samples of the copper used. Frequently the resulting conductivity is expressed in percentage of the standard value assumed for conductivity. "Percentage of 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 2, page 13, and confusion in the expression of percent conductivity accordingly resulted. The temperature coefficient of resistance is usually assumed as some fixed standard value, but this standard value likewise was not formerly the same everywhere, and results reduced from one temperature to another had accordingly been uncertain when the temperature coefficient was not stated. These conditions led the Standards Committee of the American Institute of Electrical Engineers to request the National 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 were more satisfactory than any preceding standard values. The investigation is described below. This study finally led in 1913 to the adoption of an international copper standard by the International Electrotechnical Commission.

The main objects of the investigation at the National Bureau of Standards were, (1) to determine a reliable average value for the resistivity of commercial copper, and (2) to find whether the temperature coefficients differ from sample to sample, and if so to find whether there is any simple relation between the resistivity and the temperature coefficient. 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. Am. Inst. Elec. Engrs., 29, p. 1995 and 1981; Dec. 1910). The results of the investigation and of the subsequent endeavor to establish international standard values are briefly summarized here.

a. Resistivity of Annealed Copper

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

Resistivity[2] in ohm-gram/meter^2 at 20° C =0.152 92. The average deviation from this mean of the results from the various sources of samples was 0.26 percent.

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

Resistivity, in ohm-gram/meter^2 at 20° C =0.152 63.

Both of these mean values of mass resistivity differed from the then used standard value, 0.153 022 ohm-gram/meter^2, by less than 0.26 percent, 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 previously used standard resistivity at 20° C, together with the temperature coefficient determined in the investigation (giving the values tabulated in column 7, table 2), were adopted and used as standard by the NBS 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 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 known as the International Annealed Copper Standard,[3] and is equivalent to

0.153 28 ohm-gram/meter^2 at 20° C.

This mass resistivity is one-sixth percent greater than the former American standard value (column 7, table 2), and is one-third percent greater than 0.152 78, the mean of the experimental values published by the National Bureau of Standards, and given in the preceding paragraph. The International Annealed Copper Standard can therefore be considered as fairly representative of average commercial copper. One of the advantages of this particular value is that in terms of volume conductivity it is an exact whole number, viz,

58 meter/ohm-mm^2 at 20° C.

The units of mass resistivity and volume resistivity are interrelated through the density; this was taken

[2] The expression ohm-gram/meter^2 is a shortened expression for the unit (ohm/meter) (gram/meter), the term meter^2 not denoting an area. See appendix 1.

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

as 8.89 grams/cm^3 at 20° C, by the International Electrotechnical Commission. The International Annealed Copper Standard, in various units of mass and volume resistivity, is:

0.153 28	ohm-gram/meter^2 at 20° C,
875.20	ohm-pound/mile^2 at 20° C,
0.017 241	ohm-mm^2/meter at 20° C,
1.7241	microhm-cm at 20° C,
0.678 79	microhm-inch at 20° C,
10.371	ohm-circular mil/ft at 20° C.

b. 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 National 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 [4] 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 by annealing or hard-drawing. Further evidence in regard to this relation were obtained informally from the Physikalisch-Technische Reichsanstalt, of Germany. The results of tests at that institution showed this relation for a wide range of conductivity, and the mean values agreed well with those obtained at NBS. The results obtained at NBS showed that, for copper samples of conductivity above 94 percent, the actual temperature coefficients agreed with the values calculated from the conductivities within 0.000 01, i. e., about 0.3 percent as the coefficients are of the order of 0.003 9. Tests made in 1913 by 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 important impurity was arsenic (besides the usual trace of oxygen), and whose conductivity ranged from 94 to 30 percent, 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 decimal number expressing the percent conductivity by 0.003 93.* This relation between conductivity and temperature coefficient cannot, of course, be expected to apply to all types of copper alloys. For copper wires prepared by reputable manufacturers for use as electrical conductors, it may be relied upon with a considerable certainty. The practical importance of this rule 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 is shown in table 3, p. 13. Also, there are sometimes instances 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 Bulletin of the Bureau of Standards. This difference is necessitated by the change to a new standard of resistivity.)

[4] Matthiessen and Vogt, Phil. Trans. **154**, 167 (1864).

Instances 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 percent conductivity, viz:

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

$$\left[\alpha_{20}=\frac{R_t-R_{20}}{R_{20}(t-20)},\ \text{etc.}\right]$$

This value was adopted as standard by the International Electrotechnical Commission in 1913. It would usually apply to instruments and machines, since their windings generally are of annealed copper wire. It might be expected that the act of winding would reduce the temperature coefficient, but experiment has shown that distortions such as those caused by winding and ordinary handling do not appreciably affect the temperature coefficient, although they may slightly affect the resistance.

Similarly, when an assumption is unavoidable, the temperature coefficient of good commercial hard-drawn copper wire may be taken as that corresponding to a conductivity of 97.5 percent, viz:

$$\alpha_0=0.004\ 15,\ \alpha_{20}=0.003\ 83,\ \alpha_{25}=0.003\ 76,\ \text{etc.}$$

The change of resistivity per degree may be readily calculated, as shown in appendix 2, page 30, 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 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-gram/meter^2 per °C, or 0.0068 microhm-cm per °C. More exactly (see p. 30) it is, per degree C:

0.000 597 ohm-gram/meter^2
or, 3.41 ohm-pound/mile^2
or, 0.000 0681 ohm-mm^2/meter
or, 0.006 81 microhm-cm
or, 0.002 68 microhm-inch
or, 0.0409 ohm-circular mil/ft.

The International Electrotechnical Commission specified the temperature coefficient of standard copper to be 0.00393 at 20° C, for the resistance between points fixed on a wire which is allowed to expand freely. This value is based upon measurements made at the NBS by Dellinger[5] in the intervals 10° to 100° C. Over this temperature interval the temperature-resistance curve was found to be linear. In 1914 Northrup[6] published data on a sample of copper, of 99.4 percent conductivity, from 20° C to above its melting point. He found the resistance-temperature curve to be linear to about 500° C, with the resistance rising slightly faster than the first power of temperature above 500° C.

Recently W. F. Roeser of the Bureau obtained the following unpublished data for a sample of high purity copper when heated in a vacuum; where R_t and R_0 are the resistances at t° C and 0° C, respectively.

Temperature °C	R_t/R_0
−100	0. 557
0	1. 000
100	1. 431
200	1. 862
300	2. 299
400	2. 747
500	3. 210

The graph for these data is a straight line between 0° and 300° C with a slightly upward curvature above 300° C. These results, together with those cited above seem to justify the assumption that has been made in calculating these tables that the resistance-temperature curve for copper is linear up to 200° C, and probably in the interval −100 to +300° C to the accuracy to which the use of tables is justified.

c. 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. 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.

[5] J. H. Dellinger, The temperature coefficient of resistance of copper. Bul. BS, **7**, No. 1 (1910).

[6] E. F. Northrup, Resistivity of copper in the temperature range 20° C to 1450° C, J. Franklin Inst. **177**, 1 (1914).

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 percent. 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 percent. 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.

d. 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 g/cm^3. This is the value which was used by the AIEE and most other authorities even before its adoption in 1913 by the IEC. Measurements at the Bureau of Standards indicated this value as a mean. (See appendix 3, p. 31). 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 lb/in.^{3}

e. Resistivity of Hard-Drawn Copper Wire

In the early investigations, it was found that in general the resistivity of hard-drawn wire varies with the size of the wire, while the resistivity of annealed wire 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 in each drawing, etc. For No. 12 AWG, the conductivity of hard-drawn wires was found to be less than the conductivity of annealed wires by 2.7 percent. However, on the average the decrease in conductivity is somewhat less than 2.7 percent. Operators of modern copper-wire mills consider the average for all sizes of wire to be about 2.5 percent. Hence, when a conductivity must be assumed for hard-drawn copper wire, it should be taken as 97.5 percent of that of standard annealed copper.

f. Highest Conductivity Found

The lowest resistivity and highest conductivity found by Wolff and Dellinger[7] for a hard-drawn

[7] Bul. BS, **7**, 104 (1910).

wire were:

Resistivity in ohm-gram/meter^2 at 20° C	= 0.153 86
Percent conductivity	= 99.62%

and for an annealed wire were:

Resistivity in ohm-gram/meter^2 at 20° C	= 0.150 45
Percent 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.

The data given above show the highest conductivities that had been encountered at the time Circular 31 was first prepared. Since that time, however, copper wires of higher conductivity have been produced. For example, Smart, Smith, and Phillips[8] obtained wire of 99.999 percent purity for which the conductivity, when annealed at 500° C and rapidly quenched, was found to be slightly over 103 percent.

1.2. Status of International Annealed Copper Standard

When the American Institute of Electrical Engineers in 1907 adopted a temperature coefficient, 0.0042 at 0° C, which vitiated the wire table then in use, the need for a new table was felt; and a recomputation of the old one was 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 National 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 National 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, however, 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 NBS and adopted by the Standards Committee of the American Institute of Electrical Engineers. The values for the temperature coefficient determined at NBS 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 2 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 (IEC Pub. 28, March 1914) entitled "International Standard of Resistance for Copper," giving the values adopted and explanatory notes. A revised edition was published in 1925, with changes in the explanatory part only. This revised edition is reprinted as appendix 5 of this Circular (p. 34).

The fundamental quantities in the international definitions are: the conductivity, 58 meter/ohm-mm^2; the density, 8.89 grams/cm^3; and the temperature coefficient, 0.00393 per °C; all at 20° C (see p. 35). All the other numerical values follow from these three (except that the coefficient of linear expansion, 0.000017 per °C, must also be taken into account in some cases). In particular, the values given for 0° C at the end of appendix 5 follow from these fundamental quantities. In order to avoid misunderstanding, the processes by which they are calculated are here given. 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 (17) on page 30. The value of resistivity at 0° C is given by the use of the temperature coefficient of volume resistivity as follows:

$$\rho_0=\rho_{20}\left[1-20\left(\alpha_{20}+0.000017\right)\right]$$

$$=\frac{1}{0.58}\left[1-20\left(0.003947\right)\right]=1.5880.$$

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

[8] Trans. Am. Inst. Mining Met. Engrs. 143, 272, (1941)

strictly linear function of temperature, we must write:

$$\rho_0 = \rho_{20}[1-20\,\alpha_{20}]\,[1-20\,(0.000017)]$$

$$= \frac{1}{0.58}[1-20\,(0.00393)][1-0.00034] = 1.5881.$$

The NBS 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.

2. American Wire Gage

2.1. 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. In sizes larger than No. 0000 AWG copper conductors are practically always stranded. Sizes of stranded conductors are specified by the total cross section in circular mils. A mil is 0.001 inch, and the "area" in circular mils is the square of the diameter expressed in mils. It is becoming more and more the practice for the large electrical companies and others to omit gage numbers; although the stock sizes of copper wire used and specified by those who follow this practice are the American Wire Gage sizes to the nearest tenth of a mil. (See list of sizes in American Wire Gage, table 1, p. 12.) Those who use the gage numbers do not customarily 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.

2.2. 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 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 larger gage number= $\sqrt[39]{\frac{0.4600}{0.0050}} = \sqrt[39]{92} = 1.122\,932\,2$. 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 gage number=2.0050. The fact that this ratio is so nearly 2 is the basis of numerous useful relations which are given in "Wire table shortcuts."

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 percent 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.

2.3. Wire Table Shortcuts

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 shortcut." It is extremely simple to find mentally, say, ohms per 1,000 feet, starting from the values for No. 10, as in the illustrative table below (p. 7). The approximate factors for finding values for the next three sizes after any given size, are 1.25, 1.6, and 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 1,000 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 1,000 feet; but it will probably be found easier to remember it for No. 5, 100 pounds per 1,000 feet; or for No. 2, 200 pounds per 1,000 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 1,000 feet at 20° C.
M=pounds per 1,000 feet.
$C.\ M.$=cross section in circular mils,

then,

$$R=10^{\frac{n-10}{10}}=\frac{10^{\frac{n}{10}}}{10} \tag{1}$$

$$M=10^{\frac{25-n}{10}} \tag{2}$$

$$C.\,M.=10^{\frac{50-n}{10}}=\frac{10^5}{10^{\frac{n}{10}}}. \tag{3}$$

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 percent for all sizes up to No. 20, and the maximum error is 5 percent for No. 40; and the errors of formulas (3) and (6) vary from 6 percent for No. 0000 to 2 percent for No. 20, and less than 2 percent for No. 20 to No. 40.

The sizes of copper rods and stranded conductors larger than No. 0000 are generally expressed by their areas in circular mils. For such cases, resistance in ohms per 1,000 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 1,000 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 shortcut" is the fact that between Nos. 6 and 12, inclusive, the reciprocal of the size number equals the diameter in inches, within 3 percent.

Another interesting shortcut relates the weight in pounds with the gage size. The following statement is taken from the manual of technical information of a cable manufacturer: "The approximate weight in pounds per 1,000 feet (for estimating purposes) for a certain size of copper wire is equal to the diameter in mils of a wire size double the gage number of the original size. For example, No. 8 AWG doubled is No. 16 AWG, for which the diameter in mils equals 50.8. Actual weight of No. 8 AWG is 50 lbs. per 1,000 ft."

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 1,000 feet, using No. 10 as a starting point. A similar table might be made for mass in pounds per 1,000 feet, or for cross section in circular mils, or for ohms per kilometer.

ge	Ohms per 1,000 feet			Gage	Ohms per 1,000 feet		
0	0. 1			26	40		
1		0. 125		27		50	
2			0. 16	28			64
3	. 2			29	80		
4		. 25		30	100		
5			. 32	31		125	
6	. 4			32			160
7		. 5		33	200		
8			. 64	34		250	
9	. 8			35			320
10	1			36	400		
11		1. 25		37		500	
12			1. 6	38			640
13	2			39	800		
14		2. 5		40	1, 000		
15			3. 2	41		1, 250	
16	4			42			1, 600
17		5		43	2, 000		
18			6. 4	44		2, 500	
19	8			45			3, 200
20	10			46	4, 000		
21		12. 5		47		5, 000	
22			16	48			6, 400
23	20			49	8, 000		
24		25		50		10, 000	
25			32				

3. Explanation of Tables

Table 1.—The American Society for Testing Materials, through their Committee on Wire for Electrical Conductors,[9] has recently recommended that the gage diameters shall be calculated as described in section 2.2. and then rounded to the nearest one-tenth mil (1 mil=0.001 inch). These rounded numbers, shown in table 1, should then be used as the gage diameters for commercial purposes. The data given in other tables of this Circular are based on such rounded diameters.

Table 2.— 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 boldfaced 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 2, p. 30. 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 1 gram. This unit of mass resistivity is conveniently designated for brevity as ohm-gram per meter square. The values given in table 2 are fully discussed in previous editions of this Circular. Column 8 gives the international standards, used as the basis of the tables of this Circular.

Table 3.—This table is an expression 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 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 2, p. 30. It is to be noted that table 3 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

0.000 597 [10] ohm-gram/meter^2,
or, 0.000 068 1 ohm-mm^2/meter,
or, 0.006 81 microhm-cm,
or, 3.41 ohm-pound/mile^2,
or, 0.002 68 microhm-inch,
or, 0.0409 ohm-circular mil/foot.

The Fahrenheit equivalents of the foregoing constants or of any of the α's in table 3 may be obtained by dividing by 1.8. Thus, for example, the 20° C or 68° F temperature coefficient for copper of 100 percent conductivity is 0.003 93 per degree C, or 0.002 18 per degree F. Similarly, the change of resistivity per degree F is 0.001 49 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 3 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° and 100° C applied continuously down to zero resistance. 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 resistance 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

[9] This committee's specification for copper wire for electrical conductors are at the present time approved as American Standards by the American Standards Association.

[10] 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.

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 254.5°, and at 50° C would have a (fictitious) absolute temperature of 284.5°. Consequently, the ratio of its resistance at 50° C to its resistance at 20° C would be $\frac{284.5}{254.5}=1.118$. In a 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 4.—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 4 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 cannot 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 per cent conductivity, to 0.003 930 per °C. 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 in °C.

Table 5.—Complete data on the relations of length, mass and resistance of *annealed* copper wires of the American Wire Gage sizes are given in table 5. This table shows all data for 20° C only, in English units.

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 a footnote to table 5. The derived data in English units, as used in the calculation of table 5, 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 lb/in³.

The constants given above and also in the following formulas are given to a greater number of digits than is justified by their normal use, in order to avoid introducing small errors in the calculated values.

In the following formulas, let:

d=diameter of wire in mils, at 20° C, for a round wire.
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

Then for annealed copper wire of standard conductivity

Ohms per 1,000 feet at 20° C

$$=\frac{1.2\rho_{20}}{100s}=\frac{0.0081455}{s}=10371.2/d^2$$

Feet per ohm at 20° C

$$=\frac{10^5s}{1.2\rho_{20}}=122770s=0.096421d^2$$

Ohms per pound at 20° C

$$=\frac{10^{-6}\rho_{20}}{Ds^2}=\frac{2.1135}{s^2 10^6}=3426200/d^4$$

Pounds per ohm at 20° C

$$=\frac{10^6Ds^2}{\rho_{20}}=473160s^2=0.29187d^4/10^6$$

Pounds per 1,000 feet at 20° C

$$=12000\ Ds=3854.1s=0.0030270d^2$$

Feet per pound at 20° C

$$=\frac{1}{12Ds}=\frac{0.25946}{s}=330360/d^2.$$

The data for tables 5 to 9, inclusive, were calculated with these formulas using values of diameter in mils, d, taken from table 1. However, the formulas may be used for wire with any shape of cross section, if the cross section in square inches, s, is known.

After having obtained the resistance at 20° C for any size or shape of wire, the resistances at other temperatures are usually calculated by means of the "Constant mass temperature coefficient," 0.003 93, 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 0.003 93 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" $(a+\gamma)=0.003\,947$ at 20° C (see appendix 2).] The length is to be understood as known at 20° C, and to vary with the temperature.

Tables 6, 7, 8; and 9.—These tables extend the data which involve resistance in table 5 over the temperature range 0° to 200° C; the mass per unit of length and length per unit mass are not calculated at other than 20° C as their change with temperature is usually negligible. The quantities in the tables are computed from the listed diameter taken as exact, and are rounded to an appropriate number of places. All are in the English system of units.

The numbers given in the several columns of table 7 under the heading "Feet per ohm" are 1,000 times the reciprocals of the corresponding numbers in table 6. 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 table 8 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, 0.003 93, is used as before.

The numbers given in the several columns of table 9 under the heading "Pounds per ohm" are the reciprocals of the corresponding numbers in table 8.

Tables 10, 11, 12, 13, and 14.—These five tables are the exact equivalent to the preceding five except that they are expressed in metric units instead of English. The diameters and all other quantities were calculated on the basis of the American Wire Gage diameters, listed in table 1, taken as correct. The fundamental data from which all these tables for copper were computed are as follows:

Mass resistivity of annealed copper at 20° C= 8.89/58=0.153 28 ohm-g/m².

Density of copper at 20° C=8.89 g/cm³.

Volume resistivity of annealed copper at 20° C= 100/58=1.7241 microhm-cm.

The data of tables 10 through 14 may be calculated for wires of any cross section by the formulas below, using the following symbols:

d=diameter in mm, at 20° C, for a round wire.

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.

Ohms per kilometer at 20° C

$$=\frac{10\rho_{20}}{s}=\frac{17.241}{s}=21.952/d^2$$

Meters per ohm at 20° C

$$=\frac{100s}{\rho_{20}}=58.000s=45.553\,d^2$$

Ohms per kilogram at 20° C

$$=\frac{10\rho_{20}}{Ds^2}=\frac{1.9394}{s^2}=3.1441/d^4$$

Grams per ohm at 20° C

$$=\frac{100Ds^2}{\rho_{20}}=515.62s^2=318.06\,d^4$$

Kilograms per kilometer at 20° C

$$=Ds=8.89s=6.9822\,d^2$$

Meters per gram at 20° C

$$=\frac{1}{Ds}=\frac{0.112486}{s}=0.14322/d^2.$$

The same points regarding the computations for different temperatures, which were mentioned above in the explanation of tables 5 through 9 apply to tables 10 through 14 also.

It should be strictly borne in mind that tables 5 through 14 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=percent conductivity, expressed decimally): (1) For "Ohms per 1,000 feet" and "Ohms per pound" multiply the values given in tables 5 through 9 by $1/n$. (2) For "Pounds per ohm" and "Feet per ohm" multiply the values by n, and similarly for the metric tables, 10 through 14.

An approximate average value of percent conductivity of hard-drawn copper may be taken to be 97.5 percent 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 1,000 feet" and "Ohms per pound" increase the values given in tables 5 through 9 by 2.5 percent. (2) For "Pounds per ohm" and "Feet per ohm" decrease the values by 2.5 percent. (3) "Pounds per 1,000 feet" and "Feet per pound" may be considered to be given correctly by the tables for either annealed or hard-drawn copper.

Table 15.—This is a reference table, for standard annealed copper, giving "Ohms per 1,000 feet" at two temperatures and "Pounds per 1,000 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 usually to four significant figures. The results are believed to be correct within 1 in the fourth significant figure.

Table 16.—This is a reference table for standard annealed copper wire, giving "Ohms per kilometer" at 20° 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.

Table 17.—The largest wire in the American Wire Gage has a diameter slightly less than 0.5 inch. For conductors of larger cross section, stranded conductors are used, and even for smaller conductors stranding is employed when a solid wire is not sufficiently flexible. Stranded conductors are constructed of a number of small wires in parallel, the wires being twisted to form a ropelike conductor. For any given size, the flexibility depends upon the number of wires and also upon the method of twisting. It is beyond the scope of this Circular to list data for all types of stranded conductors now in use. Data are given only for the commonly used "concentric-lay" type, for two degrees of flexibility. For other types, having the same nominal cross-sectional area, the data may differ by several percent. Such organizations as the American Society for Testing Materials or the American Institute of Electrical Engineers issue specifications which list the maximum amount by which the resistance of various stranded conductors may exceed that of an equivalent solid conductor. Since such specifications undergo frequent changes to keep up with improved manufacturing procedures, the values listed in table 17 may not agree exactly with tables issued by the national organizations. Their values should be used when they differ from table 17.

Table 17 gives data on bare concentric-lay conductors of annealed copper. A "concentric-lay conductor" is one made up of a straight central wire or wires surrounded by helical layers of bare wires, the alternate layers usually having a twist in opposite directions. In the first layer about the central core, 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 conductor. Conductors of special flexibility are made up of large numbers of wires having a definite gage size, while in the case of concentric-lay stranded conductors it is the more usual practice to start with a specified total cross section for the conductor and from that calculate the diameter of the wires. Thus, in table 17 the column "Diameter of wires" was calculated from the total cross section.

The sizes of stranded conductors 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 AWG 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.

Table 17 gives the properties of two of several types of concentric-lay conductors which are made and used in this country. The practices of manufacturers vary, but stranded conductors of these types are most commonly made up as shown under "Standard concentric stranding." For greater flexibility, concentric-lay conductors are sometimes made up as shown under "Flexible concentric stranding." These two types of stranding are designated by ASTM as "Class B" and "Class C," respectively. The first five columns of the table apply to both kinds of stranding.

The "Outside diameter in mils" is the diameter of the circle circumscribing the stranded conductor, and is calculated very simply for conductors having a single straight wire for its core. Thus, for a conductor of 7 wires, the "outside diameter" is 3 times the diameter of 1 wire; for a conductor of 19 wires, it is 5 times the diameter of 1 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 g/cm^3, or 0.321 17 lb/in.^{3} at 20° C. 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 paragraph.

Different authors and different cable companies do not agree in their methods of calculating the resistance of stranded conductors. It is usually stated that on account of the twist the lengths of the individual wires are increased, and hence the resistance of the conductor 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 stranded conductor (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 stranded conductor, 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 stranded conductor is less than that of the equivalent solid rod. The National Bureau of Standards has made inquiries to ascertain the experience of manufacturers and others on this point. It is practically unanimously agreed that the resistance of a concentric-lay stranded conductor is actually greater than the resistance of an equivalent solid rod. It is shown mathematically in appendix 4, page 32, that the percentage increase of resistance of such a conductor with all the wires perfectly insulated from one another over the resistance of the equivalent solid rod is exactly equal to the percentage decrease of resistance of a stranded conductor 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 conductor, still the increase of resistance is generally agreed to be very nearly equal to that of a stranded conductor 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 4 that the percentage increase in resistance, and in mass as well, is equal to the percentage increase in length of the wires. (The equivalent solid rod is assumed to consist of copper of the same resistivity as that in the actual stranded conductor.) A standard value of 2 to 5 percent has been adopted for this increase in length by the Committee on Wires for Electrical Conductors of the American Society for Testing Materials, and the resistances and masses in table 17 are accordingly made greater than for the equivalent solid rod. For sizes up to and including 2,000,000 circular mils the increase is 2 percent; over 2,000,000, to 3,000,000 the increase is 3 percent; over 3,000,000, to 4,000,000, 4 percent; over 4,000,000, to 5,000,000, 5 percent. These involve an assumption of a value for the "lay ratio" of the conductor, but the actual resistance of a stranded conductor 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 usefully valid correction can be made to improve upon the values of resistance as tabulated. It may be more often required to make a correction for the mass of a stranded conductor, which can be done when the lay ratio is known. The effect of "lay" and the magnitude of the correction are discussed in appendix 4, p. 32.

Table 18.—This table gives data in metric units on bare concentric-lay stranded conductors of annealed copper; it is the equivalent of table 17. The first column gives the size in "circular mils," since the sizes are commercially so designated (except for the smaller sizes, for which the AWG number is given). The other quantities in this table are in metric units. The explanations of the calculations of table 17 given above and in appendix 4 apply to this table also.

Table 19.—Factors are given in this table for computing numerical values of resistivity in any of the usual sets of units when its value is known in another set. Numerical values of percentage conductivity are not reduced to decimal fractions. For example, the numerical value for 98.3 percent conductivity is used as 98.3 not 0.983 in the conversions.

PART II. TABLES

TABLE 1. *The American Wire Gage*

Gage	Diameter at 20° C.	Gage	Diameter at 20° C.	Gage	Diameter at 20° C.	Gage	Diameter at 20° C.
	Mils		*Mils*		*Mils*		*Mils*
0000	460. 0	11	90. 7	25	17. 9	39	3. 5
000	409. 6	12	80. 8	26	15. 9	40	3. 1
00	364. 8	13	72. 0	27	14. 2	41	2. 8
0	324. 9	14	64. 1	28	12. 6	42	2. 5
1	289. 3	15	57. 1	29	11. 3	43	2. 2
2	257. 6	16	50. 8	30	10. 0	44	2. 0
3	229. 4	17	45. 3	31	8. 9	45	1. 8
4	204. 3	18	40. 3	32	8. 0	46	1. 6
5	181. 9	19	35. 9	33	7. 1	47	1. 4
6	162. 0	20	32. 0	34	6. 3	48	1. 2
7	144. 3	21	28. 5	35	5. 6	49	1. 1
8	128. 5	22	25. 3	36	5. 0	50	1. 0
9	114. 4	23	22. 6	37	4. 5		
10	101. 9	24	20. 1	38	4. 0		

Table 2. *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 OHM-GRAM/METER [2]				
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°)	**.150 8**							
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 PER °C				
0°	**0.004 28**	0.004 25$_5$	0.004 25$_5$	([11])	([11])	**0.004 2**	0.004 27$_7$	0.004 26$_5$
15°	.004 02$_2$	**.004**	**.004**			.003 95$_1$	.004 01$_9$	.004 00$_9$
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$_4$	.003 85$_4$
				DENSITY IN GRAMS/CM^3				
	[12] 8.89	8.91	(8.89)	(8.89)	8.89	8.89	[13] 8.89	[13] 8.89

Note.—An explanation of table is given on p. 8.

[11] Matthiessen's formula: $\lambda_t=\lambda_0(1-0.003\ 870t+0.000\ 009\ 009\ t^2)$. λ_t and λ_0=reciprocal of resistance at t° and 0° C, respectively.
[12] At 15.6° C.
[13] This is the density at 20° C. It corresponds to 8.90 at 0° C.

Table 3. *Temperature coefficients of copper for different initial Celsius (Centigrade) temperatures and different conductivities*

Ohm-gram/meter^2 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 21	97. 5	. 004 15	. 003 91	. 003 83	. 003 76	. 003 69	. 003 44	241. 0
. 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
. 150 27	102	. 004 36	. 004 09	. 004 01	. 003 93	. 003 85	. 003 58	229. 5

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 Celisus temperatures. (n is considered to be expressed decimally; e. g., if percent conductivity=99 percent, 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:

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

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

Table 4. *Reduction of observations to standard temperature*

Temperature ° C.	Corrections to change resistivity to 20° C.				Factors to change resistance to 20° C.			Temperature ° C.
	Ohm-gram/meter²	Microhm—cm	Ohm-pound/mile²	Microhm—inch	For 96 percent conductivity	For 98 percent conductivity	For 100 percent 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

TABLE 5. *Wire table, standard annealed copper*

American Wire Gage. English units. Values at 20° C.

Gage	Diameter in mils	Cross section		Ohms per 1,000 feet	Feet per ohm	Pounds per 1,000 feet	Feet per pound	Ohms per pound	Pounds per ohm
		Circular mils	Square inches						
0000	460.0	211 600	0.1662	0.049 01	20 400	640.5	1.561	0.000 076 52	13 070
000	409.6	167 800	.1318	.061 82	16 180	507.8	1.969	.000 121 7	8215
00	364.8	133 100	.1045	.077 93	12 830	402.8	2.482	.000 193 5	5169
0	324.9	105 600	.082 91	.098 25	10 180	319.5	3.130	.000 307 5	3252
1	289.3	83 690	.065 73	.1239	8070	253.3	3.947	.000 489 1	2044
2	257.6	66 360	.052 12	.1563	6398	200.9	4.978	.000 778 1	1285
3	229.4	52 620	.041 33	.1971	5074	159.3	6.278	.001 237	808.3
4	204.3	41 740	.032 78	.2485	4024	126.3	7.915	.001 967	508.5
5	181.9	33 090	.025 99	.3134	3190	100.2	9.984	.003 130	319.5
6	162.0	26 240	.020 61	.3952	2530	79.44	12.59	.004 975	201.0
7	144.3	20 820	.016 35	.4981	2008	63.03	15.87	.007 902	126.5
8	128.5	16 510	.012 97	.6281	1592	49.98	20.01	.012 57	79.58
9	114.4	13 090	.010 28	.7925	1262	39.62	25.24	.020 00	49.99
10	101.9	10 380	.008 155	.9988	1001	31.43	31.82	.031 78	31.47
11	90.7	8230	.006 46	1.26	793	24.9	40.2	.0506	19.8
12	80.8	6530	.005 13	1.59	629	19.8	50.6	.0804	12.4
13	72.0	5180	.004 07	2.00	500	15.7	63.7	.127	7.84
14	64.1	4110	.003 23	2.52	396	12.4	80.4	.203	4.93
15	57.1	3260	.002 56	3.18	314	9.87	101	.322	3.10
16	50.8	2580	.002 03	4.02	249	7.81	128	.514	1.94
17	45.3	2050	.001 61	5.05	198	6.21	161	.814	1.23
18	40.3	1620	.001 28	6.39	157	4.92	203	1.30	0.770
19	35.9	1290	.001 01	8.05	124	3.90	256	2.06	.485
20	32.0	1020	.000 804	10.1	98.7	3.10	323	3.27	.306
21	28.5	812	.000 638	12.8	78.3	2.46	407	5.19	.193
22	25.3	640	.000 503	16.2	61.7	1.94	516	8.36	.120
23	22.6	511	.000 401	20.3	49.2	1.55	647	13.1	.0761
24	20.1	404	.000 317	25.7	39.0	1.22	818	21.0	.0476
25	17.9	320	.000 252	32.4	30.9	0.970	1030	33.4	.0300
26	15.9	253	.000 199	41.0	24.4	.765	1310	53.6	.0187
27	14.2	202	.000 158	51.4	19.4	.610	1640	84.3	.0119
28	12.6	159	.000 125	65.3	15.3	.481	2080	136	.007 36
29	11.3	128	.000 100	81.2	12.3	.387	2590	210	.004 76
30	10.0	100	.000 078 5	104	9.64	.303	3300	343	.002 92
31	8.9	79.2	.000 062 2	131	7.64	.240	4170	546	.001 83
32	8.0	64.0	.000 050 3	162	6.17	.194	5160	836	.001 20
33	7.1	50.4	.000 039 6	206	4.86	.153	6550	1350	.000 742
34	6.3	39.7	.000 031 2	261	3.83	.120	8320	2170	.000 460
35	5.6	31.4	.000 024 6	331	3.02	.0949	10 500	3480	.000 287
36	5.0	25.0	.000 019 6	415	2.41	.0757	13 200	5480	.000 182
37	4.5	20.2	.000 015 9	512	1.95	.0613	16 300	8360	.000 120
38	4.0	16.0	.000 012 6	648	1.54	.0484	20 600	13 400	.000 074 7
39	3.5	12.2	.000 009 62	847	1.18	.0371	27 000	22 800	.000 043 8
40	3.1	9.61	.000 007 55	1080	0.927	.0291	34 400	37 100	.000 027 0
41	2.8	7.84	.000 006 16	1320	.756	.0237	42 100	55 700	.000 017 9
42	2.5	6.25	.000 004 91	1660	.603	.0189	52 900	87 700	.000 011 4
43	2.2	4.84	.000 003 80	2140	.467	.0147	68 300	146 000	.000 006 84
44	2.0	4.00	.000 003 14	2590	.386	.0121	82 600	214 000	.000 004 67
45	1.8	3.24	.000 002 54	3200	.312	.009 81	102 000	326 000	.000 003 06
46	1.6	2.56	.000 002 01	4050	.247	.007 75	129 000	523 000	.000 001 91
47	1.4	1.96	.000 001 54	5290	.189	.005 93	169 000	892 000	.000 001 12
48	1.2	1.44	.000 001 13	7200	.139	.004 36	229 000	1 650 000	.000 000 605
49	1.1	1.21	.000 000 950	8570	.117	.003 66	273 000	2 340 000	.000 000 427
50	1.0	1.00	.000 000 785	10 400	.0964	.003 03	330 000	3 430 000	.000 000 292

NOTE 1.—The fundamental resistivity used in calculating the tables is the International Annealed Copper Standard, viz, 0.153 28 ohm-g/m² at 20° C. The temperature coefficient, for this particular resistivity, is $\alpha_{20}=0.003\ 93$ per ° C. or $\alpha_0=0.004\ 27$. However, the temperature coefficient is proportional to the conductivity, and hence the change of resistivity per ° C. is a constant, 0.000 597 ohm-g/m². The "constant mass" temperature coefficient of any sample is

$$\alpha_t=\frac{0.000\ 597+0.000\ 005}{\text{resistivity in ohm-g/m}^2\text{ at }t°\text{ C}}$$

The density is 8.89 g/cm³ at 20° C.

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 2.5 percent higher resistivity than annealed copper.

TABLE 6. *Wire table, standard annealed copper*

American Wire Gage. English units.

Ohms per 1,000 feet, 0° to 200° C.

Gage	Diameter at 20° C. mils	Cross section at 20° C.		Ohms per 1,000 feet [14] at the temperature of—						
		Circular mils	Square inch	0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
0000	460.0	211 600	0.1662	0.045 16	0.049 01	0.049 98	0.054 79	0.059 61	0.064 42	0.083 68
000	409.6	167 800	.1318	.056 96	.061 82	.063 03	.069 11	.075 18	.081 25	.1055
00	364.8	133 100	.1045	.071 81	.077 93	.079 46	.087 12	.094 78	.1024	.1331
0	324.9	105 600	.0829 1	.090 53	.098 25	.1002	.1098	.1195	.1291	.1678
1	289.3	83 690	.065 73	.1142	.1239	.1264	.1385	.1507	.1629	.2116
2	257.6	66 360	.052 12	.1440	.1563	.1594	.1747	.1901	.2054	.2669
3	229.4	52 620	.041 33	.1816	.1971	.2010	.2203	.2397	.2590	.3365
4	204.3	41 740	.032 78	.2289	.2485	.2534	.2778	.3022	.3266	.4243
5	181.9	33 090	.025 99	.2888	.3134	.3196	.3504	.3812	.4120	.5352
6	162.0	26 240	.020 61	.3641	.3952	.4029	.4418	.4806	.5194	.6747
7	144.3	20 820	.016 35	.4589	.4981	.5079	.5568	.6057	.6547	.8504
8	128.5	16 510	.012 97	.5787	.6281	.6404	.7021	.7639	.8256	1.072
9	114.4	13 090	.010 28	.7302	.7925	.8080	.8859	.9637	1.042	1.353
10	101.9	10 380	.008 155	.9203	.9988	1.018	1.117	1.215	1.313	1.705
11	90.7	8230	.006 46	1.16	1.26	1.29	1.41	1.53	1.66	2.15
12	80.8	6530	.005 13	1.46	1.59	1.62	1.78	1.93	2.09	2.71
13	72.0	5180	.004 07	1.84	2.00	2.04	2.24	2.43	2.63	3.42
14	64.1	4110	.003 23	2.33	2.52	2.57	2.82	3.07	3.32	4.31
15	57.1	3260	.002 56	2.93	3.18	3.24	3.56	3.87	4.18	5.43
16	50.8	2580	.002 03	3.70	4.02	4.10	4.49	4.89	5.28	6.86
17	45.3	2050	.001 61	4.66	5.05	5.15	5.65	6.15	6.64	8.63
18	40.3	1620	.001 28	5.88	6.39	6.51	7.14	7.77	8.39	10.9
19	35.9	1290	.001 01	7.41	8.05	8.21	9.00	9.79	10.6	13.7
20	32.0	1020	.000 804	9.33	10.1	10.3	11.3	12.3	13.3	17.3
21	28.5	812	.000 638	11.8	12.8	13.0	14.3	15.5	16.8	21.8
22	25.3	640	.000 503	14.9	16.2	16.5	18.1	19.7	21.3	27.7
23	22.6	511	.000 401	18.7	20.3	20.7	22.7	24.7	26.7	34.7
24	20.1	404	.000 317	23.7	25.7	26.2	28.7	31.2	33.7	43.8
25	17.9	320	.000 252	29.8	32.4	33.0	36.2	39.4	42.6	55.3
26	15.9	253	.000 199	37.8	41.0	41.8	45.9	49.9	53.9	70.0
27	14.2	202	.000 158	47.4	51.4	52.4	57.5	62.6	67.6	87.8
28	12.6	159	.000 125	60.2	65.3	66.6	73.0	79.4	85.9	112
29	11.3	128	.000 100	74.8	81.2	82.8	90.8	98.8	107	139
30	10.0	100	.000 078 5	95.6	104	106	116	126	136	177
31	8.9	79.2	.000 062 2	121	131	134	146	159	172	224
32	8.0	64.0	.000 050 3	149	162	165	181	197	213	277
33	7.1	50.4	.000 039 6	190	206	210	230	250	270	351
34	6.3	39.7	.000 031 2	241	261	266	292	318	343	446
35	5.6	31.4	.000 024 6	305	331	337	370	402	435	565
36	5.0	25.0	.000 019 6	382	415	423	464	505	545	708
37	4.5	20.2	.000 015 9	472	512	522	573	623	673	874
38	4.0	16.0	.000 012 6	597	648	661	725	788	852	1110
39	3.5	12.2	.000 009 62	780	847	863	946	1030	1110	1450
40	3.1	9.61	.000 007 55	994	1080	1100	1210	1310	1420	1840
41	2.8	7.84	.000 006 16	1220	1320	1350	1480	1610	1740	2260
42	2.5	6.25	.000 004 91	1530	1660	1690	1860	2020	2180	2830
43	2.2	4.84	.000 003 80	1970	2140	2180	2400	2610	2820	3660
44	2.0	4.00	.000 003 14	2390	2590	2640	2900	3150	3410	4430
45	1.8	3.24	.000 002 54	2950	3200	3260	3580	3890	4210	5470
46	1.6	2.56	.000 002 01	3730	4050	4130	4530	4930	5320	6920
47	1.4	1.96	.000 001 54	4880	5290	5400	5920	6440	6960	9030
48	1.2	1.44	.000 001 13	6640	7200	7340	8050	8760	9470	12 300
49	1.1	1.21	.000 000 950	7900	8570	8740	9580	10 400	11 300	14 600
50	1.0	1.00	.000 000 785	9560	10 400	10 600	11 600	12 600	13 600	17 700

[14] Resistance at the stated temperatures of a wire whose length is 1,000 feet at 20° C.

Table 7. *Wire table, standard annealed copper*

American Wire Gage. English units

Feet per pound. Pounds per 1,000 ft.

Feet per ohm, 0° to 200° C.

Gage	Diameter at 20° C. mils	Pounds per 1,000 ft	Feet per pound	Feet per ohm [15] at—						
				0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
0000	460. 0	640. 5	1. 561	22 140	20 400	20 010	18 250	16 780	15 520	11 950
000	409. 6	507. 8	1. 969	17 560	16 180	15 870	14 470	13 300	12 310	9475
00	364. 8	402. 8	2. 482	13 930	12 830	12 580	11 480	10 550	9762	7515
0	324. 9	319. 5	3. 130	11 050	10 180	9982	9105	8369	7744	5961
1	289. 3	253. 3	3. 947	8758	8070	7914	7219	6636	6140	4726
2	257. 6	200. 9	4. 978	6944	6398	6275	5723	5261	4868	3747
3	229. 4	159. 3	6. 278	5507	5074	4976	4539	4172	3860	2972
4	204. 3	126. 3	7. 915	4368	4024	3947	3600	3309	3062	2357
5	181. 9	100. 2	9. 984	3462	3190	3129	2854	2623	2427	1869
6	162. 0	79. 44	12. 59	2746	2530	2482	2264	2081	1925	1482
7	144. 3	63. 03	15. 87	2179	2008	1969	1796	1651	1527	1176
8	128. 5	49. 98	20. 01	1728	1592	1561	1424	1309	1211	932. 5
9	114. 4	39. 62	25. 24	1370	1262	1238	1129	1038	960. 1	739. 1
10	101. 9	31. 43	31. 82	1087	1001	981. 9	895. 6	823. 3	761. 7	586. 4
11	90. 7	24. 9	40. 2	861	793	778	710	652	603	465
12	80. 8	19. 8	50. 6	683	629	617	563	518	479	369
13	72. 0	15. 7	63. 7	542	500	490	447	411	380	293
14	64. 1	12. 4	80. 4	430	396	389	354	326	301	232
15	57. 1	9. 87	101	341	314	308	281	258	239	184
16	50. 8	7. 81	128	270	249	244	223	205	189	146
17	45. 3	6. 21	161	215	198	194	177	163	151	116
18	40. 3	4. 92	203	170	157	154	140	129	119	91. 7
19	35. 9	3. 90	256	135	124	122	111	102	94. 5	72. 8
20	32. 0	3. 10	323	107	98. 7	96. 8	88. 3	81. 2	75. 1	57. 8
21	28. 5	2. 46	407	85. 0	78. 3	76. 8	70. 1	64. 4	59. 6	45. 9
22	25. 3	1. 94	516	67. 0	61. 7	60. 5	55. 2	50. 7	47. 0	36. 1
23	22. 6	1. 55	647	53. 4	49. 2	48. 3	44. 1	40. 5	37. 5	28. 8
24	20. 1	1. 22	818	42. 3	39. 0	38. 2	34. 8	32. 0	29. 6	22. 8
25	17. 9	0. 970	1030	33. 5	30. 9	30. 3	27. 6	25. 4	23. 5	18. 1
26	15. 9	. 765	1310	26. 5	24. 4	23. 9	21. 8	20. 0	18. 5	14. 3
27	14. 2	. 610	1640	21. 1	19. 4	19. 1	17. 4	16. 0	14. 8	11. 4
28	12. 6	. 481	2080	16. 6	15. 3	15. 0	13. 7	12. 6	11. 6	8. 97
29	11. 3	. 387	2590	13. 4	12. 3	12. 1	11. 0	10. 1	9. 37	7. 21
30	10. 0	. 303	3300	10. 5	9. 64	9. 46	8. 63	7. 93	7. 34	5. 65
31	8. 9	. 240	4170	8. 29	7. 64	7. 49	6. 83	6. 28	5. 81	4. 47
32	8. 0	. 194	5160	6. 70	6. 17	6. 05	5. 52	5. 07	4. 69	3. 61
33	7. 1	. 153	6550	5. 28	4. 86	4. 77	4. 35	4. 00	3. 70	2. 85
34	6. 3	. 120	8320	4. 15	3. 83	3. 75	3. 42	3. 15	2. 91	2. 24
35	5. 6	. 0949	10 500	3. 28	3. 02	2. 97	2. 70	2. 49	2. 30	1. 77
36	5. 0	. 0757	13 200	2. 62	2. 41	2. 36	2. 16	1. 98	1. 83	1. 41
37	4. 5	. 0613	16 300	2. 12	1. 95	1. 91	1. 75	1. 61	1. 49	1. 14
38	4. 0	. 0484	20 600	1. 67	1. 54	1. 51	1. 38	1. 27	1. 17	0. 904
39	3. 5	. 0371	27 000	1. 28	1. 18	1. 16	1. 06	0. 971	0. 899	. 692
40	3. 1	. 0291	34 400	1. 01	0. 927	0. 909	0. 829	. 762	. 705	. 543
41	2. 8	. 0237	42 100	0. 820	. 756	. 741	. 676	. 622	. 575	. 443
42	2. 5	. 0189	52 900	. 654	. 603	. 591	. 539	. 496	. 458	. 353
43	2. 2	. 0147	68 300	. 506	. 467	. 458	. 417	. 384	. 355	. 273
44	2. 0	. 0121	82 600	. 419	. 386	. 378	. 345	. 317	. 293	. 226
45	1. 8	. 009 81	102 000	. 339	. 312	. 306	. 279	. 257	. 238	. 183
46	1. 6	. 007 75	129 000	. 268	. 247	. 242	. 221	. 203	. 188	. 145
47	1. 4	. 005 93	169 000	. 205	. 189	. 185	. 169	. 155	. 144	. 111
48	1. 2	. 004 36	229 000	. 151	. 139	. 136	. 124	. 114	. 106	. 0813
49	1. 1	. 003 66	273 000	. 127	. 117	. 114	. 104	. 0959	. 0888	. 0683
50	1. 0	. 003 03	330 000	. 105	. 0964	. 0946	. 0863	. 0793	. 0734	. 0565

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

Table 8. *Wire tables, standard annealed copper*

American Wire Gage. English units.

Ohms per pound, 0° to 200° C.

Gage	Diameter at 20° C. mils	Ohms per pound at—						
		0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
0000	460.0	0.000 070 51	0.000 076 52	0.000 078 03	0.000 085 54	0.000 093 06	0.000 100 6	0.000 130 7
000	409.6	.000 112 2	.000 121 7	.000 124 1	.000 136 1	.000 148 0	.000 160 0	.000 207 8
00	364.8	.000 178 3	.000 193 5	.000 197 3	.000 216 3	.000 235 3	.000 254 3	.000 330 3
0	324.9	.000 283 3	.000 307 5	.000 313 5	.000 343 7	.000 373 9	.000 404 2	.000 525 0
1	289.3	.000 450 7	.000 489 1	.000 498 7	.000 546 8	.000 594 9	.000 642 9	.000 835 1
2	257.6	.000 716 9	.000 778 1	.000 793 4	.000 869 8	.000 946 3	.001 023	.001 329
3	229.4	.001 140	.001 237	.001 262	.001 383	.001 505	.001 626	.002 112
4	204.3	.001 812	.001 967	.002 005	.002 199	.002 392	.002 585	.003 358
5	181.9	.002 884	.003 130	.003 191	.003 499	.003 806	.004 114	.005 343
6	162.0	.004 584	.004 975	.005 072	.005 561	.006 050	.006 539	.008 494
7	144.3	.007 281	.007 902	.008 057	.008 834	.009 610	.010 39	.013 49
8	128.5	.011 58	.012 57	.012 81	.014 05	.015 28	.016 52	.021 46
9	114.4	.018 43	.020 00	.020 40	.022 36	.024 33	.026 29	.034 15
10	101.9	.029 28	.031 78	.032 40	.035 52	.038 65	.041 77	.054 26
11	90.7	.0466	.0506	.0516	.0566	.0616	.0665	.0864
12	80.8	.0741	.0804	.0820	.0899	.0978	.106	.137
13	72.0	.117	.127	.130	.143	.155	.168	.218
14	64.1	.187	.203	.207	.227	.247	.267	.347
15	57.1	.297	.322	.329	.360	.392	.424	.550
16	50.8	.474	.514	.525	.575	.626	.676	.878
17	45.3	.750	.814	.830	.910	.989	1.07	1.39
18	40.3	1.20	1.30	1.32	1.45	1.58	1.71	2.22
19	35.9	1.90	2.06	2.10	2.31	2.51	2.71	3.52
20	32.0	3.01	3.27	3.33	3.65	3.97	4.29	5.58
21	28.5	4.79	5.19	5.30	5.81	6.32	6.83	8.87
22	25.3	7.71	8.36	8.53	9.35	10.2	11.0	14.3
23	22.6	12.1	13.1	13.4	14.7	16.0	17.3	22.4
24	20.1	19.3	21.0	21.4	23.5	25.5	27.6	35.8
25	17.9	30.8	33.4	34.0	37.3	40.6	43.9	57.0
26	15.9	49.4	53.6	54.7	59.9	65.2	70.5	91.5
27	14.2	77.6	84.3	85.9	94.2	102	111	144
28	12.6	125	136	139	152	165	179	232
29	11.3	194	210	214	235	256	276	359
30	10.0	316	343	349	383	417	450	585
31	8.9	503	546	557	610	664	718	932
32	8.0	771	836	853	935	1020	1100	1430
33	7.1	1240	1350	1370	1510	1640	1770	2300
34	6.3	2000	2170	2220	2430	2650	2860	3710
35	5.6	3210	3480	3550	3890	4240	4580	5950
36	5.0	5050	5480	5590	6130	6670	7210	9360
37	4.5	7700	8360	8520	9340	10 200	11 000	14 300
38	4.0	12 300	13 400	13 600	15 000	16 300	17 600	22 900
39	3.5	21 000	22 800	23 300	25 500	27 800	30 000	39 000
40	3.1	34 200	37 100	37 800	41 500	45 100	48 800	63 300
41	2.8	51 400	55 700	56 800	62 300	67 800	73 300	95 200
42	2.5	80 800	87 700	89 400	98 100	107 000	115 000	150 000
43	2.2	135 000	146 000	149 000	164 000	178 000	192 000	250 000
44	2.0	197 000	214 000	218 000	239 000	260 000	281 000	366 000
45	1.8	301 000	326 000	333 000	365 000	397 000	429 000	557 000
46	1.6	482 000	523 000	533 000	584 000	636 000	687 000	893 000
47	1.4	822 000	892 000	909 000	997 000	1 080 000	1 170 000	1 520 000
48	1.2	1 520 000	1 650 000	1 680 000	1 850 000	2 010 000	2 170 000	2 820 000
49	1.1	2 160 000	2 340 000	2 390 000	2 620 000	2 850 000	3 080 000	4 000 000
50	1.0	3 160 000	3 430 000	3 490 000	3 830 000	4 170 000	4 500 000	5 850 000

Table 9. *Wire tables, standard annealed copper*

American Wire Gage. English units.

Pounds per ohm, 0° to 200° C.

Gage	Diameter at 20° C. mils	Pounds per ohm at—						
		0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
0000	460. 0	14 180	13 070	12 820	11 690	10 750	9942	7654
000	409. 6	8916	8215	8057	7349	6755	6250	4812
00	364. 8	5610	5169	5069	4624	4250	3933	3027
0	324. 9	3530	3252	3190	2909	2674	2474	1905
1	289. 3	2219	2044	2005	1829	1681	1555	1197
2	257. 6	1395	1285	1260	1150	1057	977. 8	752. 7
3	229. 4	877. 2	808. 3	792. 7	723. 0	664. 6	614. 9	473. 4
4	204. 3	551. 8	508. 5	498. 7	454. 8	418. 1	386. 8	297. 8
5	181. 9	346. 8	319. 5	313. 4	285. 8	262. 7	243. 1	187. 1
6	162. 0	218. 2	201. 0	197. 1	179. 8	165. 3	152. 9	117. 7
7	144. 3	137. 3	126. 5	124. 1	113. 2	104. 1	96. 28	74. 12
8	128. 5	86. 37	79. 58	78. 05	71. 19	65. 44	60. 54	46. 61
9	114. 4	54. 26	49. 99	49. 03	44. 72	41. 11	38. 03	29. 28
10	101. 9	34. 15	31. 47	30. 86	28. 15	25. 88	23. 94	18. 43
11	90. 7	21. 4	19. 8	19. 4	17. 7	16. 2	15. 0	11. 6
12	80. 8	13. 5	12. 4	12. 2	11. 1	10. 2	9. 46	7. 29
13	72. 0	8. 51	7. 84	7. 69	7. 02	6. 45	5. 97	4. 59
14	64. 1	5. 35	4. 93	4. 83	4. 41	4. 05	3. 75	2. 89
15	57. 1	3. 37	3. 10	3. 04	2. 78	2. 55	2. 36	1. 82
16	50. 8	2. 11	1. 94	1. 91	1. 74	1. 60	1. 48	1. 14
17	45. 3	1. 33	1. 23	1. 21	1. 10	1. 01	0. 935	0. 720
18	40. 3	0. 836	0. 770	0. 755	0. 689	0. 633	. 586	. 451
19	35. 9	. 526	. 485	. 475	. 434	. 399	. 369	. 284
20	32. 0	. 332	. 306	. 300	. 274	. 252	. 233	. 179
21	28. 5	. 209	. 193	. 189	. 172	. 158	. 146	. 113
22	25. 3	. 130	. 120	. 117	. 107	. 0983	. 0910	. 0700
23	22. 6	. 0826	. 0761	. 0747	. 0681	. 0626	. 0579	. 0446
24	20. 1	. 0517	. 0476	. 0467	. 0426	. 0392	. 0362	. 0279
25	17. 9	. 0325	. 0300	. 0294	. 0268	. 0246	. 0228	. 0175
26	15. 9	. 0202	. 0187	. 0183	. 0167	. 0153	. 0142	. 0109
27	14. 2	. 0129	. 0119	. 0116	. 0106	. 009 76	. 009 03	. 006 95
28	12. 6	. 007 98	. 007 36	. 007 21	. 006 58	. 006 05	. 005 60	. 004 31
29	11. 3	. 005 16	. 004 76	. 004 67	. 004 26	. 003 91	. 003 62	. 002 79
30	10. 0	. 003 17	. 002 92	. 002 86	. 002 61	. 002 40	. 002 22	. 001 71
31	8. 9	. 001 99	. 001 83	. 001 80	. 001 64	. 001 51	. 001 39	. 001 07
32	8. 0	. 001 30	. 001 20	. 001 17	. 001 07	. 000 983	. 000 910	. 000 700
33	7. 1	. 000 805	. 000 742	. 000 727	. 000 663	. 000 610	. 000 564	. 000 434
34	6. 3	. 000 499	. 000 460	. 000 451	. 000 411	. 000 378	. 000 350	. 000 269
35	5. 6	. 000 312	. 000 287	. 000 282	. 000 257	. 000 236	. 000 218	. 000 168
36	5. 0	. 000 198	. 000 182	. 000 179	. 000 163	. 000 150	. 000 139	. 000 107
37	4. 5	. 000 130	. 000 120	. 000 117	. 000 107	. 000 098 4	. 000 091 1	. 000 070 1
38	4. 0	. 000 081 1	. 000 074 7	. 000 073 3	. 000 066 8	. 000 061 4	. 000 056 8	. 000 043 8
39	3. 5	. 000 047 5	. 000 043 8	. 000 043 0	. 000 039 2	. 000 036 0	. 000 033 3	. 000 025 7
40	3. 1	. 000 029 3	. 000 027 0	. 000 026 4	. 000 024 1	. 000 022 2	. 000 020 5	. 000 015 8
41	2. 8	. 000 019 5	. 000 017 9	. 000 017 6	. 000 016 0	. 000 014 8	. 000 013 6	. 000 010 5
42	2. 5	. 000 012 4	. 000 011 4	. 000 011 2	. 000 010 2	. 000 009 37	. 000 008 67	. 000 006 68
43	2. 2	. 000 007 42	. 000 006 84	. 000 006 71	. 000 006 12	. 000 005 62	. 000 005 20	. 000 004 00
44	2. 0	. 000 005 07	. 000 004 67	. 000 004 58	. 000 004 18	. 000 003 84	. 000 003 55	. 000 002 74
45	1. 8	. 000 003 33	. 000 003 06	. 000 003 00	. 000 002 74	. 000 002 52	. 000 002 33	. 000 001 79
46	1. 6	. 000 002 08	. 000 001 91	. 000 001 88	. 000 001 71	. 000 001 57	. 000 001 46	. 000 001 12
47	1. 4	. 000 001 22	. 000 001 12	. 000 001 10	. 000 001 00	. 000 000 922	. 000 000 853	. 000 000 657
48	1. 2	. 000 000 657	. 000 000 605	. 000 000 594	. 000 000 541	. 000 000 498	. 000 000 460	. 000 000 354
49	1. 1	. 000 000 464	. 000 000 427	. 000 000 419	. 000 000 382	. 000 000 351	. 000 000 325	. 000 000 250
50	1. 0	. 000 000 317	. 000 000 292	. 000 000 286	. 000 000 261	. 000 000 240	. 000 000 222	. 000 000 171

TABLE 10. *Complete wire table, standard annealed copper, 20° C*

American Wire Gage. Metric units.

Gage	Diameter	Cross-section	Ohms per kilometer	Meters per ohm	Kilograms per kilometer	Meters per gram	Ohms per kilogram	Grams per ohm
	mm	*mm*²						
0000	11.68	107.2	0.160 8	6 219	953.2	0.001 049	0.000 168 7	5 928 000
000	10.40	85.01	.202 8	4 931	755.8	.001 323	.000 268 4	3 726 000
00	9.266	67.43	.255 7	3 911	599.5	.001 668	.000 426 5	2 345 000
0	8.252	53.49	.322 3	3 102	475.5	.002 103	.000 677 9	1 475 000
1	7.348	42.41	.406 6	2 460	377.0	.002 652	.001 078	927 400
2	6.543	33.62	.512 8	1 950	298.9	.003 345	.001 715	583 000
3	5.827	26.67	.646 6	1 547	237.1	.004 218	.002 728	366 600
4	5.189	21.15	.815 2	1 227	188.0	.005 319	.004 336	230 600
5	4.620	16.77	1.028	972.4	149.0	.006 709	.006 900	144 900
6	4.115	13.30	1.297	771.3	118.2	.008 459	.010 97	91 180
7	3.665	10.55	1.634	612.0	93.80	.010 66	.017 42	57 400
8	3.264	8.367	2.061	485.3	74.38	.013 44	.027 70	36 100
9	2.906	6.632	2.600	384.6	58.95	.016 96	.044 10	22 680
10	2.588	5.261	3.277	305.2	46.77	.021 38	.070 06	14 270
11	2.30	4.17	4.14	242	37.1	.027 0	.112	8 960
12	2.05	3.31	5.21	192	29.4	.034 0	.177	5 640
13	1.83	2.63	6.56	152	23.4	.042 8	.281	3 560
14	1.63	2.08	8.28	121	18.5	.054 0	.447	2 240
15	1.45	1.65	10.4	95.8	14.7	.068 1	.711	1 410
16	1.29	1.31	13.2	75.8	11.6	.086 0	1.13	882
17	1.15	1.04	16.6	60.3	9.24	.108	1.79	557
18	1.02	0.823	21.0	47.7	7.32	.137	2.86	349
19	0.912	.653	26.4	37.9	5.81	.172	4.55	220
20	.813	.519	33.2	30.1	4.61	.217	7.20	139
21	.724	.412	41.9	23.9	3.66	.273	11.4	87.3
22	.643	.324	53.2	18.8	2.88	.347	18.4	54.2
23	.574	.259	66.6	15.0	2.30	.435	29.0	34.5
24	.511	.205	84.2	11.9	1.82	.549	46.3	21.6
25	.455	.162	106	9.42	1.44	.693	73.6	13.6
26	.404	.128	135	7.43	1.14	.878	118	8.46
27	.361	.102	169	5.93	0.908	1.10	186	5.38
28	.320	.080 4	214	4.67	.715	1.40	300	3.34
29	.287	.064 7	266	3.75	.575	1.74	463	2.16
30	.254	.050 7	340	2.94	.450	2.22	755	1.32
31	.226	.040 1	430	2.33	.357	2.80	1 200	0.831
32	.203	.032 4	532	1.88	.288	3.47	1 840	.542
33	.180	.025 5	675	1.48	.227	4.40	2 970	.336
34	.160	.020 1	857	1.17	.179	5.59	4 790	.209
35	.142	.015 9	1 090	0.922	.141	7.08	7 680	.130
36	.127	.012 7	1 360	.735	.113	8.88	12 100	.082 7
37	.114	.010 3	1 680	.595	.091 2	11.0	18 400	.054 3
38	.102	.008 11	2 130	.470	.072 1	13.9	29 500	.033 9
39	.089	.006 21	2 780	.360	.055 2	18.1	50 300	.019 9
40	.079	.004 87	3 540	.282	.043 3	23.1	81 800	.012 2
41	.071	.003 97	4 340	.230	.035 3	28.3	123 000	.008 14
42	.063	.003 17	5 440	.184	.028 2	35.5	193 000	.005 17
43	.056	.002 45	7 030	.142	.021 8	45.9	322 000	.003 10
44	.051	.002 03	8 510	.118	.018 0	55.5	472 000	.002 12
45	.046	.001 64	10 500	.095 2	.014 6	68.5	720 000	.001 39
46	.041	.001 30	13 300	.075 2	.011 5	86.7	1 150 000	.000 868
47	.036	.000 993	17 400	.057 6	.008 83	113	1 970 000	.000 509
48	.030	.000 730	23 600	.042 3	.006 49	154	3 640 000	.000 275
49	.028	.000 613	28 100	.035 6	.005 45	183	5 160 000	.000 194
50	.025	.000 507	34 000	.029 4	.004 50	222	7 550 000	.000 132

Table 11. *Wire table, standard annealed copper*

American Wire Gage. Metric units.

Ohms per kilometer, 0° to 200° C.

Gage	Diameter at 20° C.	Cross section at 20° C.	Ohms per Kilometer [16] at—						
			0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
	mm	*mm²*							
0000	11.68	107.2	0.1482	0.1608	0.1640	0.1798	0.1956	0.2114	0.2746
000	10.40	85.01	.1869	.2028	.2068	.2267	.2466	.2666	.3463
00	9.266	67.43	.2356	.2557	.2607	.2858	.3110	.3361	.4366
0	8.252	53.49	.2970	.3223	.3287	.3603	.3920	.4237	.5504
1	7.348	42.41	.3746	.4066	.4145	.4545	.4944	.5344	.6941
2	6.543	33.62	.4725	.5128	.5228	.5732	.6236	.6740	.8755
3	5.827	26.67	.5958	.6466	.6593	.7228	.7863	.8499	1.104
4	5.189	21.15	.7511	.8152	.8312	.9113	.9914	1.072	1.392
5	4.620	16.77	.9475	1.028	1.049	1.150	1.251	1.352	1.756
6	4.115	13.30	1.195	1.297	1.322	1.449	1.577	1.704	2.214
7	3.665	10.55	1.506	1.634	1.666	1.827	1.987	2.148	2.790
8	3.264	8.367	1.899	2.061	2.101	2.304	2.506	2.709	3.518
9	2.906	6.632	2.396	2.600	2.651	2.906	3.162	3.417	4.439
10	2.588	5.261	3.019	3.277	3.341	3.663	3.985	4.307	5.595
11	2.30	4.17	3.81	4.14	4.22	4.62	5.03	5.44	7.06
12	2.05	3.31	4.80	5.21	5.31	5.83	6.34	6.85	8.90
13	1.83	2.63	6.05	6.56	6.69	7.34	7.98	8.63	11.2
14	1.63	2.08	7.63	8.28	8.44	9.26	10.1	10.9	14.1
15	1.45	1.65	9.62	10.4	10.6	11.7	12.7	13.7	17.8
16	1.29	1.31	12.1	13.2	13.4	14.7	16.0	17.3	22.5
17	1.15	1.04	15.3	16.6	16.9	18.5	20.2	21.8	28.3
18	1.02	0.823	19.3	21.0	21.4	23.4	25.5	27.5	35.8
19	0.912	.653	24.3	26.4	26.9	29.5	32.1	34.7	45.1
20	.813	.519	30.6	33.2	33.9	37.1	40.4	43.7	56.7
21	.724	.412	38.6	41.9	42.7	46.8	50.9	55.1	71.5
22	.643	.324	49.0	53.2	54.2	59.4	64.6	69.9	90.8
23	.574	.259	61.4	66.6	67.9	74.5	81.0	87.6	114
24	.511	.205	77.6	84.2	85.9	94.2	102	111	144
25	.455	.162	97.8	106	108	119	129	140	181
26	.404	.128	124	135	137	150	164	177	230
27	.361	.102	155	169	172	189	205	222	288
28	.320	.0804	197	214	219	240	261	282	366
29	.287	.0647	246	266	272	298	324	350	455
30	.254	.0507	314	340	347	380	414	447	581
31	.226	.0401	396	430	438	480	522	565	733
32	.203	.0324	490	532	542	594	647	699	908
33	.180	.0255	622	675	688	755	821	887	1150
34	.160	.0201	790	857	874	958	1040	1130	1460
35	.142	.0159	1000	1090	1110	1210	1320	1430	1850
36	.127	.0127	1250	1360	1390	1520	1650	1790	2320
37	.114	.0103	1550	1680	1710	1880	2040	2210	2870
38	.102	.008 11	1960	2130	2170	2380	2590	2800	3630
39	.089	.006 21	2560	2780	2830	3100	3380	3650	4740
40	.079	.004 87	3260	3540	3610	3960	4310	4650	6050
41	.071	.003 97	4000	4340	4430	4850	5280	5700	7410
42	.063	.003 17	5020	5440	5550	6090	6620	7160	9300
43	.056	.002 45	6480	7030	7170	7860	8550	9240	12 000
44	.051	.002 03	7840	8510	8670	9510	10 300	11 200	14 500
45	.046	.001 64	9680	10 500	10 700	11 700	12 800	13 800	17 900
46	.041	.001 30	12 200	13 300	13 500	14 900	16 200	17 500	22 700
47	.036	.000 993	16 000	17 400	17 700	19 400	21 100	22 800	29 600
48	.030	.000 730	21 800	23 600	24 100	26 400	28 700	31 100	40 300
49	.028	.000 613	25 900	28 100	28 700	31 400	34 200	37 000	48 000
50	.025	.000 507	31 400	34 000	34 700	38 000	41 400	44 700	58 100

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

TABLE 12. *Wire table, standard annealed copper*

American Wire Gage. Metric units.

Kilograms per kilometer, meters per gram. Meters per ohm, 0° to 200° C.

Gage	Diameter at 20° C.	Kilograms per kilometer	Meters per gram	Meters per ohm [17] at—						
				0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
	mm									
0000	11.68	953.2	0.001 049	6749	6219	6099	5563	5113	4731	3642
000	10.40	755.8	.001 323	5351	4931	4836	4411	4054	3751	2888
00	9.266	599.5	.001 668	4245	3911	3836	3499	3216	2976	2291
0	8.252	475.5	.002 103	3367	3102	3043	2775	2551	2360	1817
1	7.348	377.0	.002 652	2670	2460	2412	2200	2023	1871	1441
2	6.543	298.9	.003 345	2117	1950	1913	1745	1604	1484	1142
3	5.827	237.1	.004 218	1679	1547	1517	1383	1272	1177	905.8
4	5.189	188.0	.005 319	1331	1227	1203	1097	1009	933.2	718.4
5	4.620	149.0	.006 709	1055	972.4	953.7	869.9	799.6	739.8	569.5
6	4.115	118.2	.008 459	837.1	771.3	756.4	689.9	634.2	586.8	451.7
7	3.665	93.80	.010 66	664.2	612.0	600.2	547.4	503.2	465.6	358.4
8	3.264	74.38	.013 44	526.7	485.3	475.9	434.1	399.0	369.2	284.2
9	2.906	58.95	.016 96	417.4	384.6	377.2	344.1	316.3	292.6	225.3
10	2.588	46.77	.021 38	331.2	305.2	299.3	273.0	250.9	232.2	178.7
11	2.30	37.1	.0270	262	242	237	216	199	184	142
12	2.05	29.4	.0340	208	192	188	172	158	146	112
13	1.83	23.4	.0428	165	152	149	136	125	116	89.2
14	1.63	18.5	.0540	131	121	118	108	99.3	91.9	70.7
15	1.45	14.7	.0681	104	95.8	94.0	85.7	78.8	72.9	56.1
16	1.29	11.6	.0860	82.3	75.8	74.4	67.8	62.4	57.7	44.4
17	1.15	9.24	.108	65.5	60.3	59.1	53.9	49.6	45.9	35.3
18	1.02	7.32	.137	51.8	47.7	46.8	42.7	39.2	36.3	28.0
19	0.912	5.81	.172	41.1	37.9	37.1	33.9	31.1	28.8	22.2
20	.813	4.61	.217	32.7	30.1	29.5	26.9	24.7	22.9	17.6
21	.724	3.66	.273	25.9	23.9	23.4	21.4	19.6	18.2	14.0
22	.643	2.88	.347	20.4	18.8	18.4	16.8	15.5	14.3	11.0
23	.574	2.30	.435	16.3	15.0	14.7	13.4	12.3	11.4	8.79
24	.511	1.82	.549	12.9	11.9	11.6	10.6	9.76	9.03	6.95
25	.455	1.44	.693	10.2	9.42	9.24	8.42	7.74	7.16	5.52
26	.404	1.14	.878	8.06	7.43	7.29	6.65	6.11	5.65	4.35
27	.361	0.908	1.10	6.43	5.93	5.81	5.30	4.87	4.51	3.47
28	.320	.715	1.40	5.06	4.67	4.58	4.17	3.84	3.55	2.73
29	.287	.575	1.74	4.07	3.75	3.68	3.36	3.09	2.86	2.20
30	.254	.450	2.22	3.19	2.94	2.88	2.63	2.42	2.24	1.72
31	.226	.357	2.80	2.53	2.33	2.28	2.08	1.91	1.77	1.36
32	.203	.288	3.47	2.04	1.88	1.84	1.68	1.55	1.43	1.10
33	.180	.227	4.40	1.61	1.48	1.45	1.33	1.22	1.13	0.868
34	.160	.179	5.59	1.27	1.17	1.14	1.04	0.959	0.887	.683
35	.142	.141	7.08	1.00	0.922	0.904	0.824	.758	.701	.540
36	.127	.113	8.88	0.797	.735	.721	.657	.604	.559	.430
37	.114	.0912	11.0	.646	.595	.584	.532	.489	.453	.349
38	.102	.0721	13.9	.510	.470	.461	.421	.387	.358	.275
39	.089	.0552	18.1	.391	.360	.353	.322	.296	.274	.211
40	.079	.0433	23.1	.307	.282	.277	.253	.232	.215	.165
41	.071	.0353	28.3	.250	.230	.226	.206	.189	.175	.135
42	.063	.0282	35.5	.199	.184	.180	.164	.151	.140	.108
43	.056	.0218	45.9	.154	.142	.140	.127	.117	.108	.0833
44	.051	.0180	55.5	.128	.118	.115	.105	.0967	.0894	.0689
45	.046	.0146	68.5	.103	.0952	.0934	.0852	.0783	.0724	.0558
46	.041	.0115	86.7	.0817	.0752	.0738	.0673	.0619	.0572	.0441
47	.036	.008 83	113	.0625	.0576	.0565	.0515	.0474	.0438	.0337
48	.030	.006 49	154	.0459	.0423	.0415	.0379	.0348	.0322	.0248
49	.028	.005 45	183	.0386	.0356	.0349	.0318	.0292	.0271	.0208
50	.025	.004 50	222	.0319	.0294	.0288	.0263	.0242	.0224	.0172

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

TABLE 13. *Wire table, standard annealed copper*

American Wire Gage. Metric units.

Ohm per kilogram, 0° to 200° C.

Gage	Diameter at 20° C.	Ohms per kilogram at—						
		0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
	mm							
0000	11.68	0.000 155 4	0.000 168 7	0.000 172 0	0.000 188 6	0.000 205 2	0.000 221 7	0.000 288 0
000	10.40	.000 247 3	.000 268 4	.000 273 6	.000 300 0	.000 326 4	.000 352 7	.000 458 2
00	9.266	.000 393 0	.000 426 5	.000 434 9	.000 476 8	.000 518 7	.000 560 6	.000 728 2
0	8.252	.000 624 6	.000 677 9	.000 691 2	.000 757 8	.000 824 4	.000 891 0	.001 157
1	7.348	.000 993 6	.001 078	.001 100	.001 205	.001 311	.001 417	.001.841
2	6.543	.001 581	.001 715	.001 749	.001 918	.002 086	.002 255	.002 929
3	5.827	.002 513	.002 728	.002 781	.003 049	.003 317	.003 585	.004 657
4	5.189	.003 995	.004 336	.004 421	.004 847	.005 273	.005 699	.007 403
5	4.620	.006 357	.006 900	.007 035	.007 713	.008 391	.009 069	.011 78
6	4.115	.010 10	.010 97	.011 18	.012 26	.013 34	.014 42	.018 73
7	3.665	.016 05	.017 42	.017 76	.019 48	.021 19	.022 90	.029 75
8	3.264	.025 53	.027 70	.028 25	.030 97	.033 69	.036 41	.047 30
9	2.906	.040 63	.044 10	.044 97	.049 30	.053 63	.057 97	.075 30
10	2.588	.064 55	.070 06	.071 43	.078 32	.085 20	.092 08	.119 6
11	2.30	.103	.112	.114	.125	.136	.147	.191
12	2.05	.163	.177	.181	.198	.216	.233	.303
13	1.83	.259	.281	.287	.314	.342	.369	.480
14	1.63	.412	.447	.456	.500	.544	.588	.764
15	1.45	.655	.711	.725	.794	.864	.934	1.21
16	1.29	1.05	1.13	1.16	1.27	1.38	1.49	1.94
17	1.15	1.65	1.79	1.83	2.01	2.18	2.36	3.06
18	1.02	2.64	2.86	2.92	3.20	3.48	3.76	4.89
19	0.912	4.19	4.55	4.64	5.08	5.53	5.98	7.76
20	.813	6.64	7.20	7.35	8.05	8.76	9.47	12.3
21	.724	10.5	11.4	11.7	12.8	13.9	15.0	19.5
22	.643	17.0	18.4	18.8	20.6	22.4	24.2	31.5
23	.574	26.7	29.0	29.5	32.4	35.2	38.1	49.4
24	.511	42.6	46.3	47.2	51.7	56.3	60.8	79.0
25	.455	67.8	73.6	75.0	82.3	89.5	96.7	126
26	.404	109	118	121	132	144	155	202
27	.361	171	186	189	208	226	244	317
28	.320	276	300	306	335	364	394	512
29	.287	427	463	472	518	563	609	791
30	.254	696	755	770	844	919	993	1 290
31	.226	1 110	1 200	1 230	1 350	1 460	1 580	2 060
32	.203	1 700	1 840	1 880	2 060	2 240	2 420	3 150
33	.180	2 740	2 970	3 030	3 320	3 610	3 910	5 080
34	.160	4 420	4 790	4 890	5 360	5 830	6 300	8 190
35	.142	7 080	7 680	7 830	8 590	9 340	10 100	13 100
36	.127	11 100	12 100	12 300	13 500	14 700	15 900	20 600
37	.114	17 000	18 400	18 800	20 600	22 400	24 200	31 500
38	.102	27 200	29 500	30 100	33 000	35 900	38 800	50 400
39	.089	46 400	50 300	51 300	56 300	61 200	66 200	85 900
40	.079	75 400	81 800	83 400	91 400	99 500	108 000	140 000
41	.071	113 000	123 000	125 000	137 000	149 000	162 000	210 000
42	.063	178 000	193 000	197 000	216 000	235 000	254 000	330 000
43	.056	297 000	322 000	329 000	360 000	392 000	424 000	551 000
44	.051	435 000	472 000	481 000	528 000	574 000	621 000	806 000
45	.046	663 000	720 000	734 000	804 000	875 000	946 000	1 230 000
46	.041	1 060 000	1 150 000	1 180 000	1 290 000	1 400 000	1 510 000	1 970 000
47	.036	1 810 000	1 970 000	2 000 000	2 200 000	2 390 000	2 580 000	3 360 000
48	.030	3 360 000	3 640 000	3 710 000	4 070 000	4 430 000	4 790 000	6 220 000
49	.028	4 750 000	5 160 000	5 260 000	5 770 000	6 270 000	6 780 000	8 810 000
50	.025	7 000 000	7 550 000	7 700 000	8 400 000	9 200 000	9 930 000	12 900 000

TABLE 14. *Wire table, standard annealed copper*

American Wire Gage. Metric units.

Grams per ohm, 0° to 200° C.

Gage	Diameter at 20° C.	Grams per ohm at—						
		0° C.	20° C.	25° C.	50° C.	75° C.	100° C.	200° C.
	mm							
0000	11.68	6 433 000	5 928 000	5 813 000	5 302 000	4 874 000	4 510 000	3 472 000
000	10.40	4 044 000	3 726 000	3 655 000	3 333 000	3 064 000	2 835 000	2 183 000
00	9.266	2 545 000	2 345 000	2 299 000	2 097 000	1 928 000	1 784 000	1 373 000
0	8.252	1 601 000	1 475 000	1 447 000	1 320 000	1 213 000	1 122 000	864 000
1	7.348	1 006 000	927 400	909 500	829 500	762 500	705 500	543 100
2	6.543	632 700	583 000	571 700	521 500	479 300	443 500	341 400
3	5.827	397 900	366 600	359 600	328 000	301 500	278 900	214 700
4	5.189	250 300	230 600	226 200	206 300	189 600	175 500	135 100
5	4.620	157 300	144 900	142 100	129 700	119 200	110 300	84 890
6	4.115	98 960	91 180	89 430	81 570	74 980	69 370	53 400
7	3.665	62 300	57 400	56 290	51 350	47 200	43 670	33 620
8	3.264	39 180	36 100	35 400	32 290	29 680	27 460	21 140
9	2.906	24 610	22 680	22 240	20 280	18 650	17 250	13 280
10	2.588	15 490	14 270	14 000	12 770	11 740	10 860	8360
11	2.30	9720	8960	8790	8010	7370	6820	5250
12	2.05	6120	5640	5530	5050	4640	4290	3300
13	1.83	3860	3560	3490	3180	2930	2710	2080
14	1.63	2430	2240	2190	2000	1840	1700	1310
15	1.45	1530	1410	1380	1260	1160	1070	824
16	1.29	957	882	865	789	725	671	516
17	1.15	605	557	547	499	458	424	327
18	1.02	379	349	342	313	287	266	205
19	0.912	239	220	216	197	181	167	129
20	.813	151	139	136	124	114	106	81.3
21	.724	94.8	87.3	85.7	78.1	71.8	66.5	51.2
22	.643	58.9	54.2	53.2	48.5	44.6	41.3	31.8
23	.574	37.5	34.5	33.9	30.9	28.4	26.3	20.2
24	.511	23.4	21.6	21.2	19.3	17.8	16.4	12.7
25	.455	14.8	13.6	13.3	12.2	11.2	10.3	7.96
26	.404	9.18	8.46	8.30	7.57	6.96	6.44	4.96
27	.361	5.84	5.38	5.28	4.82	4.43	4.10	3.15
28	.320	3.62	3.34	3.27	2.98	2.74	2.54	1.95
29	.287	2.34	2.16	2.12	1.93	1.77	1.64	1.26
30	.254	1.44	1.32	1.30	1.18	1.09	1.01	0.775
31	.226	0.901	0.831	0.815	0.743	0.683	0.632	.486
32	.203	.589	.542	.532	.485	.446	.413	.318
33	.180	.365	.336	.330	.301	.277	.256	.197
34	.160	.226	.209	.205	.187	.171	.159	.122
35	.142	.141	.130	.128	.116	.107	.0991	.0763
36	.127	.0898	.0827	.0811	.0740	.0680	.0630	.0485
37	.114	.0589	.0543	.0532	.0486	.0446	.0413	.0318
38	.102	.0368	.0339	.0332	.0303	.0279	.0258	.0198
39	.089	.0216	.0199	.0195	.0178	.0163	.0151	.0116
40	.079	.0133	.0122	.0120	.0109	.0100	.009 30	.007 16
41	.071	.008 83	.008 14	.007 98	.007 28	.006 69	.006 19	.004 77
42	.063	.005 61	.005 17	.005 07	.004 63	.004 25	.003 93	.003 03
43	.056	.003 37	.003 10	.003 04	.002 77	.002 55	.002 36	.001 82
44	.051	.002 30	.002 12	.002 08	.001 89	.001 74	.001 61	.001 24
45	.046	.001 51	.001 39	.001 36	.001 24	.001 14	.001 06	.000 814
46	.041	.000 942	.000 868	.000 851	.000 776	.000 713	.000 660	.000 508
47	.036	.000 552	.000 509	.000 499	.000 455	.000 418	.000 387	.000 298
48	.030	.000 298	.000 275	.000 269	.000 246	.000 226	.000 209	.000 161
49	.028	.000 210	.000 194	.000 190	.000 173	.000 159	.000 147	.000 114
50	.025	.000 144	.000 132	.000 130	.000 118	.000 109	.000 101	.000 078

TABLE 15. *Standard annealed copper wire, British Standard Wire Gage*

Gage	Diameter in mils	Cross section		Ohms per 1,000 feet[18]		Pounds per 1,000 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 75
49	1. 2	1. 440	. 000 001 131	7078	8476	. 004 36
50	1. 0	1. 000	. 000 000 785	10 190	12 210	. 003 03

[18] Resistance at the stated temperature of a wire whose length is 1,000 feet at the lower temperature.

Table 16. *Standard annealed copper wire, "millimeter" wire gage*

Diameter in mm	Cross section in mm²	Ohms per kilometer [19]		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	. 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 85	2195	2583	. 0698
. 05	. 001 96	8781	10 330	. 0175

[19] Resistance at the stated temperature of wire whose length is 1 km at 20° C.

Note 1.—The fundamental resistivity used in calculating the table is the International Annealed Copper Standard, viz, 0.153 28 ohm-g/m² 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-g/m². The "constant mass" temperature coefficient of any sample is

$$\alpha_t=\frac{0.000\ 597+0.000\ 005}{\text{resistivity in ohm-g/m}^2\text{ at } t\ ^\circ\text{ C.}}.$$

The density is 8.89 g/cm³ at 20° C.

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 2.5 percent higher resistivity than annealed copper.

TABLE 17. *Bare concentric-lay stranded conductors of standard annealed copper*

English units

Nominal size of conductor		Ohms per 1,000 feet		Standard concentric stranding (Class B)				Flexible concentric stranding (Class C)		
Circular mils	AWG	25° C. (=77° F.)	65° C. (=149° F.)	Pounds per 1000 feet	Number of wires	Diameter of wires	Outside diameter	Number of wires	Diameter of wires	Outside diameter
						Mils	*Mils*		*Mils*	*Mils*
5 000 000	----	0. 002 22	0. 002 56	15 890	217	151. 8	2580	271	135. 8	2580
4 500 000	----	. 002 47	. 002 85	14 300	217	144. 0	2450	271	128. 9	2450
4 000 000	----	. 002 75	. 003 17	12 600	217	135. 8	2310	271	121. 5	2310
3 500 000	----	. 003 14	. 003 63	11 020	169	143. 9	2160	217	127. 0	2160
3 000 000	----	. 003 63	. 004 19	9 349	169	133. 2	2000	217	117. 6	2000
2 500 000	----	. 004 36	. 005 03	7 794	127	140. 3	1820	169	121. 6	1820
2 000 000	----	. 005 39	. 006 22	6 176	127	125. 5	1630	169	108. 8	1630
1 900 000	----	. 005 68	. 006 55	5 865	127	122. 3	1590	169	106. 0	1590
1 800 000	----	. 005 99	. 006 92	5 562	127	119. 1	1550	169	103. 2	1450
1 700 000	----	. 006 34	. 007 32	5 249	127	115. 7	1500	169	100. 3	1500
1 600 000	----	. 006 74	. 007 78	4 936	127	112. 2	1460	169	97. 3	1460
1 500 000	----	. 007 19	. 008 30	4 632	91	128. 4	1410	127	108. 7	1410
1 400 000	----	. 007 70	. 008 89	4 320	91	124. 0	1360	127	105. 0	1360
1 300 000	----	. 008 30	. 009 58	4 012	91	119. 5	1310	127	101. 2	1320
1 200 000	----	. 008 99	. 010 4	3 703	91	114. 8	1260	127	97. 2	1260
1 100 000	----	. 009 81	. 011 3	3 394	91	109. 9	1210	127	93. 1	1210
1 000 000	----	. 010 8	. 012 4	3 086	61	128. 0	1150	91	104. 8	1150
950 000	----	. 011 4	. 013 1	2 933	61	124. 8	1120	91	102. 2	1120
900 000	----	. 012 0	. 013 8	2 780	61	121. 5	1090	91	99. 4	1090
850 000	----	. 012 7	. 014 6	2 622	61	118. 0	1060	91	96. 6	1060
800 000	----	. 013 5	. 015 6	2 469	61	114. 5	1030	91	93. 8	1030
750 000	----	. 014 4	. 016 6	2 316	61	110. 9	998	91	90. 8	1000
700 000	----	. 015 4	. 017 8	2 160	61	107. 1	964	91	87. 7	965
650 000	----	. 016 6	. 019 2	2 006	61	103. 2	929	91	84. 5	930
600 000	----	. 018 0	. 020 7	1 850	61	99. 2	893	91	81. 2	893
550 000	----	. 019 6	. 022 6	1 700	61	95. 0	855	91	77. 7	855
500 000	----	. 021 6	. 024 9	1 542	37	116. 2	813	61	90. 5	814
450 000	----	. 024 0	. 027 7	1 390	37	110. 3	772	61	85. 9	773
400 000	----	. 027 0	. 031 1	1 236	37	104. 0	728	61	81. 0	729
350 000	----	. 030 8	. 035 6	1 080	37	97. 3	681	61	75. 7	681
300 000	----	. 036 0	. 041 5	925	37	90. 0	630	61	70. 1	631
250 000	----	. 043 1	. 049 8	772	37	82. 2	575	61	64. 0	576
212 000	0000	. 050 9	. 058 7	653	19	105. 5	528	37	75. 6	529
168 000	000	. 064 2	. 074 1	518	19	94. 0	470	37	67. 3	471
133 000	00	. 081 1	. 093 6	411	19	83. 7	418	37	60. 0	420
106 000	0	. 102	. 117	326	19	74. 5	372	37	53. 4	374
83 700	1	. 129	. 149	259	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	162	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	208
26 300	6	. 410	. 473	80. 9	7	61. 2	184	19	37. 2	186
20 800	7	. 519	. 599	64. 2	7	54. 5	164	19	33. 1	166
16 500	8	. 654	. 755	51. 0	7	48. 6	146	19	29. 5	148

NOTE 1.—The fundamental resistivity used in calculating the table is the International Annealed Copper Standard, viz., 0.15328 ohm-g/m² at 20° C. The temperature coefficient is given in table 3. The density is 8.89 grams per cubic centimeter at 20° C.

NOTE 2.—The values given for "Ohms per 1,000 feet" and "Pounds per 1,000 feet" are 2 to 5 percent greater than for a solid rod of cross section equal to the total cross section of the wires of the stranded conductor. See p. 12. The values of "pounds per 1,000 feet" are correct for Class B stranding and approximate for Class C stranding. The "ohms per 1,000 feet" are approximate for either stranding.

Table 18. *Bare concentric-lay stranded conductors of standard annealed copper*

Metric units

Size of cable, "circular mils" (or gage No.)	Total cross section in mm ^{2}	Ohms per kilometer		Kilograms per kilometer	Standard concentric stranding (Class B)			Flexible concentric stranding (Class C)		
		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
5 000 000	2530	0. 007 29	0. 008 41	236 00	217	3. 86	65. 6	271	3. 45	65. 5
4 500 000	2280	. 008 09	. 009 34	213 00	217	3. 66	62. 2	271	3. 27	62. 2
4 000 000	2030	. 009 02	. 0104	187 00	217	3. 45	58. 6	271	3. 09	58. 6
3 500 000	1770	. 0103	. 0119	164 00	169	3. 66	54. 8	217	3. 23	54. 8
3 000 000	1520	. 0119	. 0137	139 00	169	3. 38	50. 7	217	2. 99	50. 8
2 500 000	1270	. 0143	. 0165	116 00	127	3. 56	46. 3	169	3. 09	46. 3
2 000 000	1010	. 0177	. 0204	9190	127	3. 19	41. 5	169	2. 76	41. 5
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
AWG										
0000	107	. 167	. 193	972	19	2. 68	13. 4	37	1. 92	13. 4
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. 28
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. 76

Note 1.—The fundamental resistivity used in calculating the table is the International Annealed Copper Standard, viz., 0.15328 ohm-g/m ^{2} at 20°C. The temperature coefficient is given in table 3. The density is 8.89 g/cm ^{3} at 20° C.

Note 2.—The values given for "Ohms per kilometer" and "Kilograms per kilometer" are 2 to 5 percent greater than for a solid rod of cross section equal to the total cross section of the wires of the stranded conductor. See p. 12.

Table 19. *Conversion table for electrical resistivities*

Standard annealed copper

Given values at 20° C in	To obtain values in—						
	Ohm g/m²	Ohm lb/mile²	Ohm mm²/m	Microhm-cm	Microhm-in.	Ohm-cir mil/ft	% conductivity
	multiply by	multiply by	multiply by	multiply by	multiply by	multiply by	divide into
Ohm g/m²	------------	5709.8	0.112 48	11.248	4.4284	67.660	15.328
Ohm lb/mi²	0.000 175 14	------------	.000 019 700	0.001 970 0	0.000 775 6	0.011 850	87 520
Ohm mm²/m	8.8900	50 763	------------	100	39.371	601.53	1.7241
Microhm-cm	0.088 900	507.63	0.010 000	------------	0.393 71	6.0153	172.41
Microhm-in.	.225 81	1289.4	.025 400	2.5400	------------	15.279	67.879
Ohm-cir mil/ft	.014 780	84.389	.001 662 4	0.166 24	.065 451	------------	1037.1
	divide into	divide into	divide into	divide into	divide into	divide into	
% conductivuty	15.328	87 520	1.7241	172.41	67.879	1037.1	------------

PART III. APPENDIXES

1. Expression of Resistivity

In the experimental work that led to the formulation of his law, Ohm found that the resistance, R, of a uniform conductor is directly proportional to its length, l, and inversely proportional to its cross-sectional area, s. These experimental facts may be written in the form of an equation as

$$R=\rho\frac{l}{s}, \qquad (12)$$

where ρ is a constant of proportionality whose value depends upon the material of the conductor and upon the units used in measuring l and s. This constant of proportionality is called *resistivity*.

The above equation, which defines resistivity may be written

$$\rho=R\frac{s}{l}. \qquad (13)$$

No name has been assigned to the unit of resistivity, and consequently the unit is specified by stating the units used in measuring R, s, and l. This has resulted in the use of a large number of units for resistivity, as R, s, and l may each be expressed in more than one unit or subunit. From the above equation for ρ, it is seen that the value of ρ is numerically equal to that of R for a conductor having unit length and unit cross-sectional area. A cube is such a conductor, and this has led to the rather common expressions for the unit of resistivity "ohms per inch cube" or "microhms per centimeter cube". These expressions are undesirable, because they imply that resistivity is the ratio of resistance to volume. It is logically better to say "ohms times square inches per inch", "microhms times square centimeters per centimeter".

The above expression for resistivity involves the cross-sectional area of the conductor, which is often difficult to measure to a sufficient accuracy. It is therefore convenient to express the area in terms of other quantities that are more easily measured. For a uniform conductor the cross-sectional area, s, equals the ratio of volume to length, V/l, and from the definition of density, D, $V=M/D$ where M is the mass, hence

$$s=\frac{V}{l}=\frac{M}{l}\cdot\frac{1}{D} \qquad (14)$$

and equation (13) may be written

$$\rho=\frac{R}{l}\cdot\frac{M}{l}\cdot\frac{1}{D} \qquad (15)$$

For most commercial purposes the density of copper may be assumed, and the measurement of resistivity requires only determinations of resistance per unit length and mass per unit length, determinations which usually may be readily made. In fact, since D is nearly constant it is customary to specify the quality of copper wires for use as electrical conductors merely by specifying the product of R/l and M/l. This product is called "mass resistivity" and is usually designated by the symbol δ. When mass resistivity is divided by density the ordinary resistivity, "volume resistivity", is obtained; i. e., $\rho=\delta/D$.

For either volume or mass resistivity the unit is specified by stating the units used in measuring the several quantities involved. These expressions should, if possible, be given in such a way as to show how the quantities enter into the expression for resistivity, and as a result the units are apt to be rather involved. In the first edition of this Circular the author shortened the units somewhat by adopting expressions which in effect merely listed the component units, without showing how they entered into the expression for resistivity. While these expressions have been copied in other tables, they have not been universally accepted. In this edition, therefore, expressions have been used that more nearly meet the requirement of showing the relation between the component units. These are as follows:

For mass resistivity {ohm-gram/meter² ; ohm-pound/mile²}

For volume resistivity {ohm-circular mil/ft ; ohm-mm²/meter ; microhm-cm ; microhm-inch}

While some of these expressions may be misinterpreted, they are all exact dimensionally and are of reasonable lengths. From the point of view of clarity the units for mass resistivity should be (ohm/meter)(grams/meter) and (ohm/mile) × (pounds/mile). Moreover, the expressions microhm-cm and microhm-inch should be microhm-cm²/cm and microhm-inch²/inch, but the expressions listed have been chosen because of their brevity, or because they are already in current use.

2. 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:

$$\delta = MR/l^2$$

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

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

For 100 percent conductivity, using ohm-gram/meter²

$$\delta_t = 0.153\ 28\ (1+[0.003\ 930-0.000\ 034]\ [t-20])$$

$$= 0.153\ 28 + 0.000\ 597\ (t-20)$$

This "resistivity-temperature constant," 0.000 597, is 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:

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

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

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

For 100 percent conductivity, using microhm-cms,

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

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:

$$\alpha_\delta = \alpha_R - 2\gamma \qquad (16)$$

$$\alpha_\rho = \alpha_R + \gamma \qquad (17)$$

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 percent 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 (16) 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 potential terminals rigidly attached to the wire), we have

$$\alpha_t = \frac{0.000\ 597 + 0.000\ 005}{\text{ohm-gram/meter}^2 \text{ at } t°\text{C}}$$

$$\text{also, } \alpha_t = \frac{0.006\ 81 - 0.000\ 03}{\text{microhm-cm at } t°\text{C}}$$

$$\text{also, } \alpha_t = \frac{3.41 + 0.03}{\text{ohm-pound/mile}^2}$$

$$\text{also, } \alpha_t = \frac{0.002\ 68 - 0.000\ 01}{\text{microhm-inch at } t°\text{C}}$$

$$\text{also, } \alpha_t = \frac{0.0409 - 0.0002}{\text{ohm-circular mil/ft}}$$

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

3. Density of Copper

As stated in appendix 1, 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 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 g/cm^3 (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 for ordinary conductivity tests by various companies. During the 3 years, 1908–1910, the density of 36 such samples was determined. These samples had been submitted by 7 companies, as follows: 3 smelters, 3 electrolytic refiners, and 1 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 percent, except one of the samples in the fourth group, for which the conductivity was 94.6 percent 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 George L. Heath, of the Calumet & Hecla Smelting Works, on 18 samples of copper, a number of which were included in the Bureau's 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 percent.

The third group of data is that obtained at the Physikalisch-Technische Reichsanstalt, of Germany, by Prof. Lindeck,[20] and given in the appendix 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 5 years, 1905–1909. The mean value of the density for the 48 samples is

8.890.

[20] Bul. BS 7, pp. 97–101 (1910).

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 percent, 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:

NBS tests	8. 887
NBS 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 percent, we have:

NBS tests	8. 887
NBS investigation	8. 893
Reichsanstalt	8. 881
Final average	8. 887

Or, if we consider the Calumet & 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 percent, we have:

NBS tests	8. 887
NBS investigation	8. 892
Calumet & 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 at 20°C is

$$8.89 \text{ g/cm}^3.$$

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 percent.

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 AWG). 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 at 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 cannot 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 g/cm³ at 20° C.

4. Calculation of the Resistance and Mass Per Unit Length of Concentric-Lay Stranded Conductors

In the first place, it is proposed to show that the percent increase of resistance of a concentric-lay stranded conductor, 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 such a conductor 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 stranded conductor (taking the cross section of each wire prependicular to the axis of the wire),

R_1=resistance of a stranded conductor with the individual wires perfectly insulated from one another.

R_2=resistance of a hypothetical stranded conductor with the wires distorted into such shape that they make contact throughout their length (the layers all being twisted in the same direction), it will be shown that

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

Now, $R_1>R_s$, because, on account of the stranding, the path of the current is longer than it would be if parallel to the axis of the stranded conductor. Also, $R_2 < R_s$, because the path of the current is in this case parallel to the axis of the conductor, 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; or length of "equivalent solid rod",
s=total cross section of the wires of the conductor, 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 stranded conductor due to twisting.

We have:

$$R_s = \frac{\rho l}{s}, \qquad (18)$$

$$R_1 = \frac{\rho(l+\Delta l)}{s}, \qquad (19)$$

$$R_2 = \frac{\rho l}{s+\Delta s}. \qquad (20)$$

The following diagram shows a side view of one wire of the stranded conductor. 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.

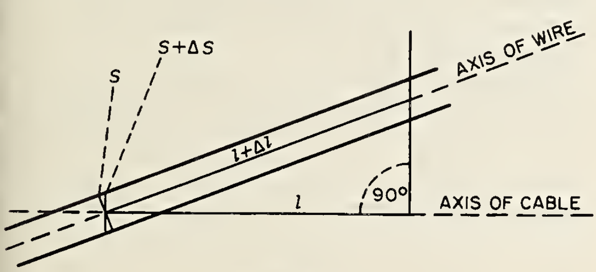

FIGURE 1.

By similar triangles,

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

$$s+\Delta s = s\left(1+\frac{\Delta l}{l}\right) \qquad (21)$$

$$\therefore R_2 = \frac{\rho l}{s\left(1+\frac{\Delta l}{l}\right)} = \frac{\rho l}{s}\left(1-\frac{\Delta l}{l}\right), \qquad (22)$$

since $\frac{\Delta l}{l}$ is small.

From (19),

$$R_1 = \frac{\rho l}{s}\left(1+\frac{\Delta l}{l}\right) \qquad (23)$$

$$\therefore R_1 + R_2 = \frac{2\rho l}{s}. \qquad (24)$$

From (18) and (24),

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

The resistance of an actual stranded conductor 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 stranded conductors increases with age, which may be considered to be due to contamination of the wire surfaces. Hence the resistance 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 eq (18) and (23),

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

The resistance of a stranded conductor is therefore taken to be greater than R_s by a fractional amount equal to $\Delta l/l$. Also, the mass of a stranded conductor is greater than the mass of the "equivalent solid rod" by a fractional amount exactly equal to $\Delta l/l$. 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 percent in calculating the tables of this Circular for conductors up to 2,000,000 circular mils in area. This involves the assumption of a definite value for the "lay ratio." The method of computing this fraction from the lay ratio of the concentric-lay stranded conductor is given herewith. Let

d=diameter of the helical path of one wire.
L=length along axis of conductor for one complete revolution of this wire about axis, i. e., "length of lay."
$n=\frac{L}{d}$=number of times the diameter d is contained in the length L, i. e., the "lay ratio."

The lay ratio is sometimes expressed as $1/n$ or "1 in n"; thus we may speak of a lay ratio of 1/20, or 1 in 20, although it is usual to say "a lay ratio of 20."

Consider a wire of length $(L+\Delta L)$, developed in a plane containing the axis of the stranded conductor, of length L. The developed wire and the axis make with each other the angle θ, in figure 2. The third side of the triangle equals in length the circumference of the helical path of the wire.

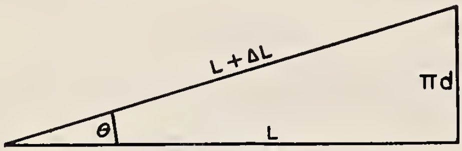

FIGURE 2.

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

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

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

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

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 stranded conductor 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 ratio is different for different layers of the conductor. If L is the same for each layer of the conductor, the lay ratio varies because of the change of d. It should not be forgotten that usually the central wire is untwisted.

The lay ratio corresponding to a correction of 2 percent is calculated thus:

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

$$n=15.7.$$

This means that for sizes up to and including 2,000,000 circular mils the values given in tables 17 and 18 for resistance and mass per unit length correspond to stranded conductors having a lay ratio of 15.7. If the lay ratio is known and is different from 15.7, resistance or mass may be calculated by multiplying these values in tables 17 and 18 by

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

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

Manufacturers have found it practicable to produce concentric-lay stranded conductors of sizes up to 2,000,000 circular mils for which the weight and resistance per unit length do not exceed that of an equivalent solid rod by more than 2 percent. However, for still larger sizes this is not considered feasible, and the allowable increase rises about 1 percent for each additional million circular mils of area.

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5. Publication 28 of International Electrotechnical Commission, "International Standard of Resistance for Copper"

Preface to First Edition

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. 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.

Preface to Second Edition

The purpose of this edition is not to change in any way the substance of the original recommendations but only to re-state them in a manner which renders them free from ambiguity or the possibility of misconstruction.

The recommendations as given in this report have been approved by the Directors of the National Laboratories of London, Paris and Washington. Through the good offices of the President of the Swiss Committee this revised report has been reviewed by Prof. Dr. E. Warburg.

London, March, 1925.

INTERNATIONAL ELECTROTECHNICAL COMMISSION

International Standard of Resistance for Copper

Definitions:

(a) A metal being taken in the form of a wire of any length and of uniform section, the volume resistivity of this metal is the product of its resistance and its section divided by its length.

(b) The mass resistivity of this metal is the product of its resistance per unit length and its mass per unit length.

(c) The volume resistivity, ρ; mass resistivity, δ; and density, d, are interrelated by the formula: $\delta=\rho d$.

Units adopted:

For this publication, where not otherwise specified, the gramme shall be taken as the unit of mass, the metre as the unit of length, the square millimetre as the unit of area, and the cubic centimetre as the unit of volume. Hence the unit of volume resistivity here used is the ohm square millimetre per metre $\left(\frac{\text{ohm mm}^2}{\text{m}}\right)$ and the unit of mass resistivity is the ohm gramme per metre per metre $\left(\frac{\text{ohm g}}{\text{m}^2}\right)$.

I. STANDARD ANNEALED COPPER

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

(1) At a temperature of 20° C the volume resistivity of standard annealed copper is 1/58=0.017241 . . . ohm square millimetre per metre $\left(\frac{\text{ohm mm}^2}{\text{m}}\right)$.

(2) At a temperature of 20° C the density of standard annealed copper is 8.89 grammes per cubic centimetre $\left(\frac{\text{g}}{\text{cm}^3}\right)$.

(3) At a temperature of 20° C the coefficient of linear expansion of standard annealed copper is 0.000017 per degree Centigrade.

(4) At a temperature of 20° C, the coefficient of variation of the resistance with temperature of standard annealed copper, measured between two potential points rigidly fixed to the wire, the metal being allowed to expand freely, is:

$$0.00393=\frac{1}{254.45\ .\ .\ .}\text{ per degree Centigrade.}$$

(5) As a consequence, it follows from (1) and (2) that at a temperature of 20° C the mass resistivity of standard annealed copper is $1/58\times8.89=$ 0.15328 . . . ohm gramme per metre per metre.

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 percent.

(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 volume resistivity of commercial copper increases by 0.000068 ohm square millimetre per metre per degree Centigrade.

(c) The mass resistivity of commercial copper increases by 0.00060 ohm gramme per metre per metre per degree Centigrade.

(d) The density of commercial annealed copper at a temperature of 20°C is 8.89 grammes per cubic centimetre.

This value of the density shall be employed in calculating the percentage conductivity of commercial annealed copper.

From these assumptions it follows that, if at a temperature of t°C, R is the resistance, in ohms, of a wire "l" metres in length weighing "m" grammes, the volume resistivity of the same copper is·

$$\text{at } t^\circ\text{C}\quad \frac{Rm}{l^2\times8.89}\text{ ohm square millimetre per metre, and}$$

$$\text{at } 20^\circ\text{C}\quad \frac{Rm}{l^2\times8.89}+0.000068\ (20-t)\text{ ohm square millimetre per metre.}$$

The percentage 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 mass resistivity of a wire of the same copper is:

at t°C $\frac{Rm}{l^2}$ ohm gramme per metre per metre, and

at 20°C $\frac{Rm}{l^2}+0.00060\ (20-t)$ ohm gramme per metre per metre.

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 percent, plus or minus, and the temperature coefficient of resistance may differ from the standard by 1 percent, plus or minus; 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 constants at 0°C of standard annealed copper deduced from the values given above for 20°C are the following:

Density at 0°C .... 8.90 $\frac{g}{cm^3}$.

Coefficient of linear expansion per degree Centigrade 0.000017

Volume resistivity at 0°C ...... 1.588_1 microhm centimetres.

Coefficient at 0°C of variation of volume resistivity 0.00428_2 per degree Centigrade.

Coefficient at 0°C of variation of resistance (at constant mass and free expansion) measured between two potential points rigidly fixed to the wire .... $\frac{1}{234.45}=0.00426_5$ per degree Centigrade.

Note III. EXPLANATION OF TEMPERATURE COEFFICIENTS.

1. Coefficient of variation of resistance at constant mass and free expansion with the temperature.

If R_1 and R_2 are the resistances measured at the temperatures t_1 and t_2 of a uniform wire, between two potential points rigidly fixed to the wire when the current flows parallel to the axis of the wire, the coefficient of variation of resistance at constant mass and free expansion for the temperature t_1, α_1 is defined by the formula:

$$R_2=R_1\ [1+\alpha_1\ (t_2-t_1)]$$

2. Coefficient of variation of the volume resistivity with the temperature.

If ρ represents the volume resistivity of the wire, i. e., if the resistance R of the wire is equal to $\rho\frac{l}{s}$ (l=length of wire, s=section) and if, for the temperature t_1 the coefficient of variation of volume resistivity with the temperature is represented by β_1, the same notation being used as before, the following is obtained:

$$\rho_2=\rho_1\ [1+\beta_1\ (t_2-t_1)].$$

If γ represents the coefficient of linear expansion of the metal, the following is approximately correct:

$$\beta_1=\alpha_1+\gamma.$$

3. Coefficient of variation of the mass resistivity with the temperature.

If δ represents the mass resistivity, i. e., if the resistance R of the wire is equal to $\delta\frac{l^2}{m}$, l being its length and m its mass, and if the coefficient of the variation of the mass resistivity with the temperature for the temperature t_1 is represented by β_1', the following is obtained:

$$\delta_2=\delta_1\ [1+\beta_1'\ (t_2-t_1)]$$

giving the approximate formula:

$$\beta_1'=\alpha_1-2\gamma.$$

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