Electrical Tech Note — 212

Biosystems & Agricultural Engineering Department
Michigan State University

CONDUCTOR PROPERTIES

Electrical wire size in the United States is in American Wire Gage (**AWG**) with the cross-sectional area of the wire increasing as the AWG number decreases. The smallest wire size used for a power circuit is 14 AWG* copper which in most cases is permitted to be protected with a fuse or circuit breaker rated not more than 15 amperes. The actual cross-sectional area of the wire is given in square inches or square millimeters, but *for the purpose of determining conductor ampere rating, wires have a cross-sectional area in a unit called* ***circular mils (cmil)****.* The circular mil area of a wire is determined by converting the diameter of the wire given in inches to mils and then squaring the number. A mil is one thousandth of an inch. *Table 212.1* gives the approximate cross-sectional area and dc resistance of standard sizes of electrical wire. In the past wire was marked **MCM** rather than **kcmil.** **M** is the Roman numeral for one thousand followed by **CM** for circular mils. The approximate diameter of a wire in mils can be determined by finding the square root of the cross-sectional area in circular mils.
*(See page 8)

Table 212.1 *Cross-sectional area and resistance of standard sizes of stranded wire.*

Size	**Area**		**dc Resistance at 75°C**			
AWG or			copper		aluminum	
kcmil	mm^2	cmil	Ω/km	Ω/kft	Ω/km	Ω/kft
18	0.82	1,620	26.1	7.95	42.8	13.1
16	1.31	2,580	16.4	4.99	26.9	8.21
14	2.08	4,110	10.3	3.14	16.9	5.17
12	3.31	6,530	6.50	1.98	10.6	3.25
10	5.26	10,380	4.07	1.24	6.67	2.04
8	8.37	16,510	2.55	0.778	4.20	1.28
6	13.3	26,240	1.61	0.491	2.65	0.808
4	21.2	41,740	1.01	0.308	1.67	0.508
3	26.7	52,620	0.802	0.245	1.32	0.403
2	33.6	66,360	0.634	0.194	1.05	0.319
1	42.4	83,690	0.505	0.154	0.829	0.253
1/0	53.5	105,600	0.399	0.122	0.660	0.201
2/0	67.4	133,100	0.317	0.0967	0.523	0.159
3/0	85.0	167,800	0.251	0.0766	0.413	0.126
4/0	107	211,600	0.200	0.0608	0.328	0.100
250	127	250,000	0.169	0.0515	0.278	0.0847
300	152	300,000	0.141	0.0429	0.232	0.0707
350	177	350,000	0.121	0.0367	0.198	0.0605
400	203	400,000	0.105	0.0321	0.174	0.0529
500	253	500,000	0.085	0.0258	0.139	0.0424

The best conductors of electricity are silver, copper, gold, and aluminum. Silver is sometimes added to a metal alloy to improve the conductivity. Gold is a hard metal that is very stable and does not corrode and is sometimes used as a coating for electrical contact devices. Copper and aluminum are the common metals used for power conductors. When used for long spans overhead, both of these conductors must be supported by a material with a higher tensile strength. The conductors can be supported by a steel strand in the overhead support cable. Aluminum conductors will oxidize and can fail if exposed to moisture. It is not uncommon for a small moisture leak to develop in a direct burial aluminum cable that ultimately leads to failure.

Small sizes of wires may be solid or they may consist of many strands. The purpose of the strands is to make the conductor flexible. Solid wires larger than 10 AWG are very difficult to install. Stranded conductors have more surface area which can result in corrosion problems if exposed to corrosive conditions such as direct burial in the earth.

Conductor Resistance: Resistance (ohms) is the opposition to electrical current flow. The symbol for resistance is the letter "**R**". The amount of current a conductor can carry depends upon the resistance of the conductor. The resistance depends upon the type of material, it's length and it's cross-sectional area. The unit of measure of resistance is the ohm. Sometimes the term conductance is used when making reference to electrical conductors. *Conductance* is the opposite (reciprocal) of resistance and is in units of ***Siemens*** **(S).** . The resistance of a conductor can be determined using *Equation 212.1*

$$\text{Resistance (ohms)} = \frac{K \times L}{A} \qquad \textbf{\textit{Eq. 212.1}}$$

K is resistivity of the material in units of ohm•cmil per ft. Resistivity is temperature sensitive and decreases as temperature decreases. Typical values are given in *Table 212.3.*
L length of the conductor is usually in feet.
A cross-sectional area of the conductor is usually in **circular mils (cmil)**.

Scientists and engineers use the same equation but they usually use metric dimensions. They use the Greek letter rho (ρ) for resistivity which is in units of ohm•centimeters. Length will be in centimeters and cross-sectional area will be in square centimeters.

Metals have a different electrical resistivity at different temperatures. *Table 212.2* gives the resistivity of some common metals at a temperature of 25°C. The lower the resistivity the better the conductor of electrical current. Silver is the best, and copper is next best. The unit of resistivity in this table is in ohm•circular mils per foot which is the resistance of a one foot long conductor with a cross-sectional area of one circular mil. This is illustrated in *Figure 212.1.* This value of resistivity can be used in *Equation 212.1* to determine the resistance of a wire.

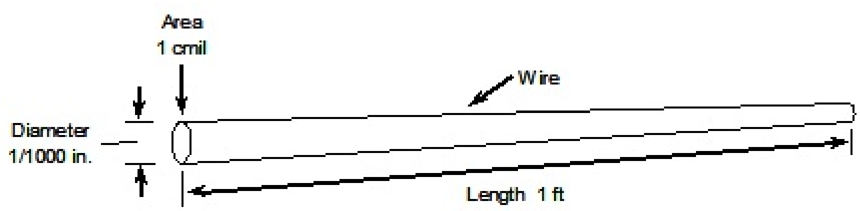


Figure 212.1 *When wire resistivity is given in ohm•cmil/ft, the value represents the resistance of a one foot length of wire with a cross-sectional area of one circular mil.*

Table 212.2 *Electrical resistivity of different metals compared to copper. Values of resistivity for metals in second column are at a temperature of 25°C. In an actual operating circuit the resistance of these conductors most likely will be higher.*

Material	**Resistivity** Ω-cmil/ft	**Resistance relative** to copper
silver	9.92	0.92
copper	10.79	1.00
gold	14.89	1.38
aluminum	18.02	1.67
brass	48.66	4.51
iron	66.57	6.17
platinum	73.80	6.84
steel	93.01	8.62

The unit *resistivity of metal conductors changes significantly with a change in temperature*. If a splice or termination becomes corroded, some resistance will develop. This *resistance results in heating when current flows.* The heating raises the temperature which further increases the resistance. Defective conductor splices and terminations are a common cause of fires. *Table 212.3* gives the resistivity of copper and aluminum conductors at several temperatures. These values can be substituted into *Equation 212.1* to determine the resistance of a conductor. Choose a value of resistivity from the *Table 212.3* for the approximate operating temperature of the wire. A good value to use for conductors operating in buildings is 50°C. If the resistance of a conductor is known at one temperature, the resistance can be determined at another temperature using *Equation 212.2.* Note the temperatures in the formula are in degrees Celsius. The symbol alpha (α) is the temperature coefficient of resistivity. These values given are for the typical operating range of conductors. This value will change as the temperature changes. *The resistance of copper and aluminum wire will change by about* ***8% (****0.08)* ***for a 25ºC change in wire temperature****.*

$$R_2 = R_1 \times [1 + \alpha \times (T_2 - T_1)] \qquad \textbf{\textit{Eq. 212.2}}$$

$$\alpha_{cu} = 0.00323$$
$$\alpha_{al} = 0.00330$$

Table 212.3 *Resistivity of copper and aluminum conductors at different temperatures.*

Temperature	**Resistivity (K)**			
	copper		aluminum	
°C	Ω cmil/ft	Ω mm^2/m	Ω cmil/ft	Ω mm^2/m
25	10.79	0.0180	17.69	0.0294
50	11.83	0.0197	19.43	0.0323
75	12.87	0.0214	21.18	0.0352

Circular Mil Area and Current Rating of a Wire: The electrical current rating of smaller sizes of electrical conductors is proportional to the cross-sectional area of the conductor. A conductor with a large cross-sectional area has a higher current capacity than a conductor with a smaller cross-sectional area. Cross-sectional area of electrical wires is given as a quantity called circular mils (cmil). The diameter of the wire in inches is first converted to mils. A mill is one-thousandth (1/1,000) of an inch. *To convert inches to mils simply multiply the diameter in inches by 1'000.* An example would be a wire with a diameter of 0.064 in. is equivalent to a diameter of 64 mils. ***Circular mil area** is simply the diameter in mils multiplied by itself or squared.* An example would be a wire with a diameter of 64 mils has a cross-sectional area of 4,096 circular mils (cmil).

Resistance of Earth, Water, & Biological Materials: There are many materials that will conduct electricity even though the resistivity of the material is quite high. Unit resistivity of materials is typically given in ohm•centimeters. This is the resistance from one side to the other of a cube of the material that is one centimeter on each side as illustrated in *Figure 212.2.* If the cross-sectional area and length of a material is known along with the resistivity, the resistance of the material can be determined using *Equation 212.1*, however, **rho (ρ)** is substituted for **K** and has units of ohm•centimeters. Length (L) will be in centimeters and cross-sectional area will be in square centimeters.

$$\text{Cross-sectional area of a circle} = \frac{\pi \times d^2}{4} \qquad \textbf{\textit{Eq. 212.3}}$$

where: π = 3.14
feet × 30.48 = centimeters
inches × 2.54 = centimeters

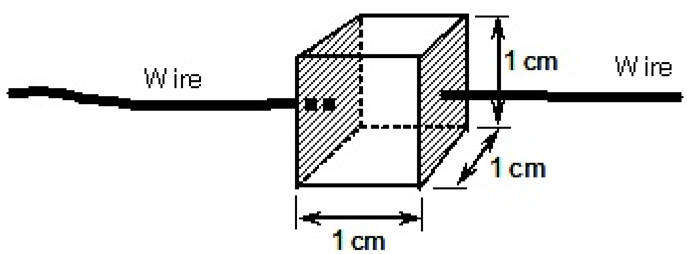


Figure 212.2 *Unit resistivity of a material is generally given in ohm•centimeters which is the resistance through a one centimeter cube of the material.*

Example: Here is an example using tap water. What is the danger of feeling a shock from electricity conducted through a plastic water pipe that is 50 ft long and has a ½ in. inside diameter if the resistivity of the water is 4,000 ohm•cm.

Solution: Before the resistance of the pipe full of water can be determined, it is necessary to convert the length from feet to centimeters and the diameter from inches to centimeters. It is also necessary to determine the cross-sectional area of the wire by using *Equation 212.3.* The inside pipe diameter is 1.27 cm. The pipe length is 1,524 cm. The inside cross-sectional area of the plastic pipe is 1.27 cm^2 using *Equation 212.3.* Now use *Equation 212.1* to determine that resistance of the water in the pipe has a value of 4,800,000 ohms.

$$\text{Area of pipe} = \frac{3.14 \times 1.27\text{cm} \times 1.27\text{cm}}{4} = 1.27\ \text{cm}^2$$

$$\text{Resistance of water in pipe} = \frac{4{,}000\ \text{ohm•cm} \times 1{,}524\ \text{cm}}{1.27\ \text{cm}^2} = 4{,}800{,}000\ \text{ohms.}$$

Superconductivity: Experiments were conducted in the early part of the 20th Century to determine what would happen to the resistance of a conductor as it was cooled to a very low temperature. Some researchers believed the resistance would decrease to zero, while others felt it would decrease to some finite value. Indeed that was true for a copper conductor as seen in *Figure 212.3.* The same was also true for silver and gold the other two best conductors of electricity at room temperature. A conductor was made from mercury and cooled to a temperature as low as possible. When the conductor was at about 5°K the resistance of the conductor suddenly dropped to zero, also illustrated in *Figure 212.3.* It was possible to pass electrical current through the conductor with no loss of energy. This condition was called superconductivity. Investigations continued and many more materials were identified that exhibited superconductivity near absolute zero. For most applications this phenomena was of little value because of the extreme difficulty of cooling the conductor to near absolute zero.

In the 1980s researchers discovered that some ceramic materials that acted as insulators at room temperature would become superconductors at temperatures well above absolute zero. Several materials will become superconducting above 90°K and one as high as 138°K. With these materials critical superconductivity temperature can be reached using liquid nitrogen as the coolant which has a boiling point of 77°K. This made superconductivity much more practical, except these materials were brittle and could not be easily formed into conductors. This problem was solved in the 1,990s and now experiments are underway to utilize superconductivity for everyday applications. *The **advantage of superconductivity** is that very high current levels can flow through extremely small conductors because the conductor resistance is zero.* Superconducting motors rated at thousands of horsepower can be fitted into small frame sizes which reduces weight and space requirements. In the electric power industry, transmission lines installed underground can transport huge amounts of bulk power with little or no losses of energy. High voltage is required to minimize current flow to reduce energy losses. *With no resistance in the wires, the energy losses will be low even with high currents.*

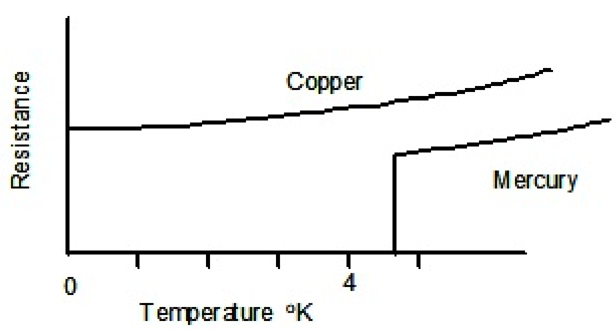


Figure 212.3 *The resistance of some materials such as copper will decrease but never reach zero as the conductor is cooled to absolute zero, but some materials such as mercury will lose all resistance below some critical temperature. (This is a representation of the resistance of mercury and copper near absolute zero not the actual values.)*

Resistance of Electrical Wires: The resistance of a wire at a specific temperature depends upon the length of the wire and it's cross-sectional area. *The longer the wire the greater the resistance and the shorter the wire the smaller the resistance.* There are standard tables that give the resistance of different types of wire usually in ohms per 1,000 ft (ohm/kft) or in ohms per kilometer (ohm/km) of length. Here is how to determine the resistance of a wire of a particular size for any given length starting with a value from a standard table such as *Table 212.1.* Look up the resistance from the table for the type of wire (copper or aluminum) and the size desired. Using *Equation 212.4*, determine the resistance of the wire for the length desired.

$$\text{Resistance of wire} = \frac{\text{Length of wire}}{1{,}000\text{ ft}} \times (\text{Resistance from Table}) \qquad \textbf{\textit{Eq. 212.4}}$$

Example: Determine the resistance of a 450 ft length of size 2 AWG aluminum wire.

Solution: Look up the resistance of a 1,000 ft length of size 2 aluminum wire from Table 212.1 and find the value of 0.319 ohms. Next substitute this value along with 450 ft into Equation 212.4 to determine the resistance of this length of wire to be 0.144 ohms.

$$\text{Resistance of 450 ft of Size 2 aluminum wire} = \frac{450\text{ ft} \times 0.319\text{ ohm}}{1{,}000\text{ ft}} = 0.144\text{ ohm}$$

Electrical Wire Ratings & Markings: *Standard electrical wire insulation ratings are in degrees Celsius (°C) with* ***60°C as the minimum insulation temperature rating****.* The next higher standard insulation temperature rating is **75°C**, and the next higher than that is **90°C.** For typical building wires the temperature rating is coded with the **letter H.** Electricians are required to learn the meaning of the wire type code letters marked on the sides of each wire. If the code letter <u>does not contain an H the wire temperature rating is assumed to be 60°C</u>. An example of a 60°C rated wire is type TW. The first code letter usually designates the type of insulating material such as **T** for thermoplastic.

The **letter H** is reserved for designating the temperature rating of wire. **One H** is used to indicate a wire temperature insulation rating of **75°C**, and **HH designates 90°C** wire insulation temperature rating. **(*Each letter H adds 15°C to the base value of 60°C)*** The next letters generally designate the environmental conditions such as W indicating it is permitted to be installed in damp or wet locations. Sometimes the last letter indicates a type of outer coating applied to the wire such as N for neopreme which is a tough coating sometimes used to protect wires from damage during installation. Examples for wire type letters may be THHW which means a thermoplastic insulation with a 90°C rating suitable to be installed in damp or wet locations. An aluminum wire suitable for installation outside and overhead in air may be marked XHHW which means cross-linked polyethylene insulation with a 90°C temperature rating suitable for installation in damp or wet locations.

Electrical Conductor Size: The cross-sectional area of electrical wires in the *United States* is in units called <u>circular mils</u>. The diameter of typical wires is given in inches. *A **mil** is one thousandth of an inch*, therefore, the diameter in inches can be converted to mils by multiplying by 1,000. A wire that is 0.125 inches in diameter is 125 mils in diameter. Not considering environmental conditions, the current carrying capacity of a wire is generally proportional to the cross-sectional area of the wire. Circular mil area of a wire is simply the diameter of the wire in mils squared. So for a wire that has a diameter of 125 mils, it's circular mil area is 15,625 cmil. These numbers can get rather large so for the big sizes the metric designation for 1,000 (k) is used. For example, rather than giving a wire size as 500,000 cmil it is given as 500 kcmil.

Wire Ampere Ratings: There are three columns of ampere ratings for each wire size in *Table 212.4.* The top of each wire ampere column is the actual table from the *NEC* where these ampere values were taken. For wires to be installed inside buildings or buried below the ground, use *Table 310.16.* Multiplex cable consists of a bare conductor with a steel strand for strength around which will be wound one to four insulated wires. Multiplex cable is installed outside in the air between buildings or between poles, use *Table 310.20.* Sometimes individual insulated wires are installed outdoors as single wires each connected to separate insulators and exposed to the weather. The ampere rating of these wires is found in *Table 310.17.*

Table 212.4 *Ampere rating of electrical wire with 75°C insulation and terminations where no abnormal heating conditions exist that would require derating of conductors.*

Size	**Allowable Ampere Rating**					
	Cable, conduit or direct burial		Multiplex cable in open air		Single conductor on insulators in open air	
AWG or kcmil	copper	aluminum	copper	aluminum	copper	aluminum
	Table 310.16		**Table 310.20**		**Table 310.17**	
18	7	—	—	—	—	—
16	10	—	—	—	—	—
14	15	—	—	—	—	—
12	20	15	—	—	—	—
10	30	20	—	—	—	—
8	50	40	57	44	70	55
6	65	50	76	59	95	75
4	85	65	101	78	125	100
3	100	75	118	92	145	115
2	115	90	135	106	170	135
1	130	100	158	123	195	155
1/0	150	120	183	143	230	180
2/0	175	135	212	165	265	210
3/0	200	155	245	192	340	240
4/0	230	180	287	224	360	280
250	255	205	320	251	405	315
300	285	230	359	282	455	350
350	310	250	397	312	505	395
400	335	270	430	339	545	425
500	380	310	496	392	620	485

References: *A copy of the latest edition of the National Electrical Code can be obtained from most any electrical wholesale distributor in all major cities, through an on-line book seller, or by contacting the National Fire Protection Association, One Batterymarch park, Quincy, MA 02269.*

Understanding Wire Size Designations: Examine *Table 212.1* and notice that as the AWG number gets smaller the cross-sectional area of the wire increases. Now examine *Table 212.4* and notice that as the AWG number gets smaller the ampere rating of the wire increases.

Notice in *Table 212.1* and *Table 212.4* there are four AWG wire sizes listed as 1/0 through 4/0. These are size 0, 00, 000, and 0000. The more zeros the larger the cross-sectional area and the greater the ampere rating of the wire. Counting the number of zeros can result in an error so AWG 0 is shown as AWG 1/0 pronounced “one aught.” Size AWG 0000 is shown as 4/0 and pronounced “four aught.”

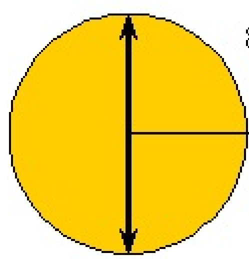
AWG 4/0 is the largest wire diameter using an *American Wire Gage (AWG)* designation. Wires with a larger cross-sectional area are simply listed according to the wire cross-sectional area in *“thousands of circular mils”* such as 250 kcmil. The lower case **“k”** represents 1,000. So 250 kcmil is 250,000 cmil. In this case a “mil” is one-thousandth of an inch. *Square the diameter of the wire in **“mils”** and the result is **“circular mils.”*** *Figure 212.4* illustrates how circular mil area of a wire is determined. Common wire sizes installed by electricians with a “kcmil” designation are shown in *Table 212.1* and *Table 212.4.* An electrician may encounter non-standard “kcmil” wire sizes.

Electrical Wire Size Dimensions: Just like a water pipe the size *(inside area)* determines the water flow quantity. Pressure is also a factor. Pressure of an electrical circuit is the voltage. Knowing the wire cross-sectional area is necessary to determine the maximum current flow (amperes) of an electrical wire. Most commonly used wires have a small area so area in square inches ($in.^2$) is a big number. For electrical wires the cross-sectional area is listed in mils where one mil is 1/1000 inch. A size 12 electrical wire has a cross-sectional area of 6,530 square mils. The electrical codes do not use square mils instead the designation is 6,530 cmil. The designation "cmil" is known as "circular mils." The method of how to determine the circular mils (cmil) is described in *Figure 212.4.* *Table 212.1* lists the circular mil area for the common sizes of electrical wires.

Figure 212.4 *Electrical wire circular mil area is determined by converting the diameter of the wire from inches to mils (multiply inches by 1,000) and then squaring the mils ($mils^2$).*

Example: Determine the circular mil area of an 8 AWG solid copper or aluminum electrical wire. The diameter of an 8 AWG electrical wire is 0.1285 in.

1. Convert 0.1285 inches to mils. 0.1285 x 1,000 = 128.5 mils
2. Square diameter in mils. Circular mil area = 128.5^2 = 16,512 cm.
3. Electrical circular mil area can be found in *Table 212.8* of the *NEC*.



* *As of 2025, 14 AWG is the smallest size electrical wire permitted for circuits in dwellings. The NEC has permitted 16 AWG copper wire and 14 AWG copper-clad aluminum wire to be installed for 10 ampere circuits. These new wire sizes will be permitted for use when a jurisdiction adopts the 2026 NEC electrical code.*