Electrical Tech Note — 212

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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 was 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.

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 simetimes 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 messenger cable, or sometimes one strand of a multiplex cable is actually steel to provide the needed strength. 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: 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

$$\text{Resistance (ohms)} = \frac{K \times L}{A}$$ **Equation 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 feet 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.

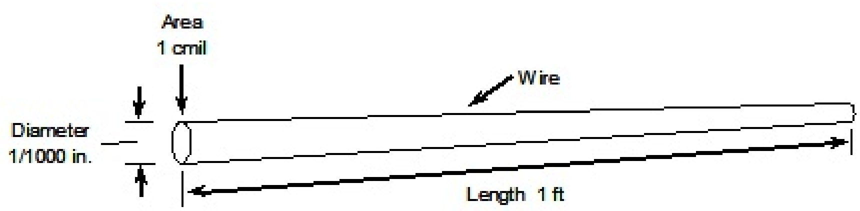

Figure 212.1 When wire resistivity is given in ohm•cmil/ft, the value represents the resistance of a one foot length of wire with a cross-sectional area of one circular mil.

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 25°C change in wire temperature.*

$$R_2 = R_1 \times [1 + \alpha \times (T_2 - T_1)]$$ **Equation 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 (1/1000) of an inch. *To convert inches to mils simply multiply the length in inches by 1000.* 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 4096 circular mils (cmil). For wires with a large diameter other factors come into play that also have an effect upon the current capacity of the wire. Even though the current capacity of large diameter conductors increases as the cross-sectional area increases, the relationship is no longer directly proportional.

Resistance of Earth, Water, and 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.

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

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

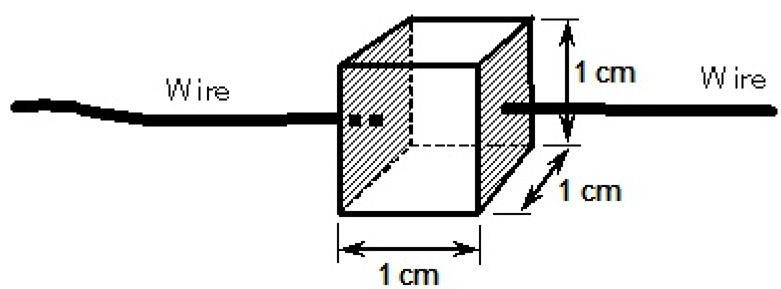

Figure 212.2 Unit resistivity of a material is generally given in ohm•centimeters which is the resistance through a one centimeter cube of the material.

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 4000 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 1524 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 the resistance of the water in the pipe has a value of 4,800,000 ohms.

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

$$\text{Resistance of water in pipe} = \frac{4000\ \Omega\text{•cm} \times 1524\ \text{cm}}{1.27\ \text{cm}^2} = 4{,}800{,}000\ \text{ohms.}$$

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 1990s 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 a 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.*

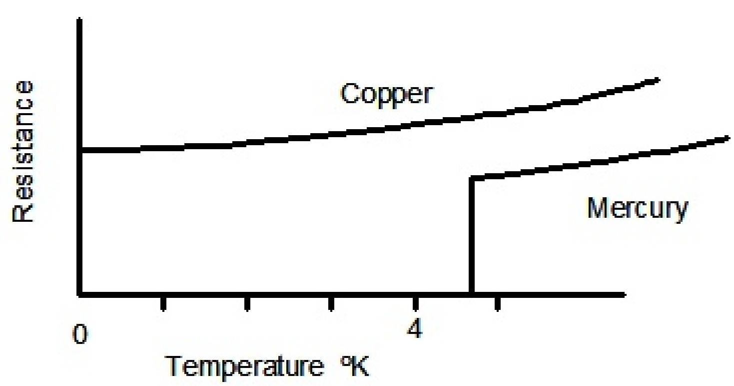

Figure 212.3 The resistance of some materials such as copper will decrease but never reach zero as the conductor is cooled to absolute zero, but some materials such as mercury will lose all resistance below some critical temperature. (This is a representation of the resistance of mercury and copper near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

Determine Resistance of Electrical Wire: 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 1000 ft (Ω/kft) or in ohms per kilometer (Ω/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.

$$\text{Resistance of wire} = \frac{\text{Length of wire}}{\text{1000 ft}} \times (\text{Resistance from Table}) \qquad \textbf{Equation 212.4}$$

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

Solution: Look up the resistance of a 1000 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.

$$\text{Resistance of 450 ft of Size 2 aluminum wire} = \frac{\text{450 ft} \times 0.319\ \Omega}{\text{1000 ft}} = 0.144\ \Omega$$

Understanding proportions can be a very useful tool when working with electrical circuits and wiring. Lets assume the resistance of a length of wire is known. For example the resistance of a 150 ft length of size 10 AWG aluminum wire is 0.306 ohms. Any size 10 AWG aluminum wire longer than 150 ft will have a greater resistance. Any length shorter than 150 ft will have a smaller resistance. Resistance of a wire and length are direct proportions, so divide the length desired by the length known to find the proportion. Then multiply that proportion by the known resistance to determine the resistance of the length of wire desired. Equation 212.5 is similar to the previous equation.

$$\text{Resistance of wire} = \frac{\text{Length desired}}{\text{Length known}} \times (\text{Resistance of known length}) \qquad \textbf{Equation 212.5}$$

Example: The resistance of a 150 ft length of size 10 AWG aluminum wire is 0.306 ohms. Determine the resistance of a 450 ft length of the wire.

Solution: Use Equation 212.5 and divide 450 ft by 150 ft to determine the desired length of wire is three time as long, so the resistance will be three times as much as the original wire.

$$\text{Resistance of 450 ft} = \frac{\text{450 ft}}{\text{150 ft}} \times 0.306\ \Omega = \frac{3}{1} \times 0.306\ \Omega = 0.918\ \Omega$$

Refer back to Equation 212.1 and note that to determine the resistance of an electrical conductor the resistivity (K) is multiplied by the length and divided by the cross-sectional area. The cross-sectional area is in the denominator of the equation. This means that the larger the cross-sectional area of the wire, the smaller the resistance of the wire. So if the resistance of a given length of wire is too high, replace it with a wire with a larger cross-sectional area and the resistance will be smaller. This is called an inverse proportion. The larger one value gets, the smaller the other quantity becomes. For example assume a wire has a resistance of 4 ohms. A wire of the same length with twice the cross-sectional area will have half the resistance. One quantity will go down by the same proportion the other quantity goes up. Equation 212.6 can be used to determine the resistance of a wire with the same length but different size or cross-sectional area. The cross-sectional area of common sizes of electrical wire is given in Table 212.1. Note in Equation 212.6 that the cross-sectional area of the desired wire is now in the denominator.

$$\text{Resistance of wire} = \frac{\text{Area known}}{\text{Area desired}} \times (\text{Resistance of known area}) \qquad \textbf{Equation 212.6}$$

Example: A size 4 AWG copper wire has a cross-sectional area of 41,740 cmil, and a 250 ft length of the wire has a resistance of 0.077 ohms. Determine the resistance of a 250 ft length of size 2 AWG copper wire that has a cross-sectional area of 66,360 cmil.

Solution: Notice that the size 2 AWG wire has a larger cross-sectional area than the size 4 AWG wire, so the resistance of the size 2 AWG wire will be smaller than the resistance of the size 4 AWG wire. In this case the resistance of the size 2 AWG copper wire will be smaller than 0.077 ohms. Put the values into Equation 212.6 and find the actual resistance of the size 2 AWG copper wire to be 0.0484 ohm.

$$\text{Resistance of wire} = \frac{41{,}740 \text{ cmil}}{66{,}360 \text{ cmil}} \times 0.077\ \Omega = 0.629 \times 0.077\ \Omega = 0.0484\ \Omega$$

Ampere Rating of Conductors: The ampere rating of a conductor when used in electrical installations is determined based upon a safe operating temperature. Because the conductor has a finite resistance, *the temperature of the conductor will rise when it carries electrical current.* The amount of current a conductor can safely carry depends upon it’s ability to dissipate heat. Wires are insulated and that insulation slows heat dissipation. Wires may be installed in open free air, or they may be assembled into cables with an outer jacket for protection that slows heat dissipation. Wires may be placed in pipes called raceway. Wires may be buried in the earth. The *National Electrical Code*® is used in most areas of the United States as a standard for determining the size and installing electrical wires. In the *Code* are several tables that give the ampere rating of wires for common installations. Those wire allowable ampere tables are somewhat complex to apply and are used by electricians and engineers to determine the conductor size needed for various applications. Abnormal heating conditions frequently occur that require experienced personnel to make adjustments in the allowable ampere rating of conductors. Training is required to know how and when to apply the adjustment factors. Table 212.4 is intended only as a general guide to electrical wire selection and gives the allowable ampere rating of electrical wires for typical applications assuming adjustment factors are not required.

The *National Electrical Code* has a rule that a fuse or circuit breaker is required to be installed with a rating not higher than the allowable ampere rating of the wire after any adjustment factors have been applied. Wire ampere ratings less than those listed in Table 212.4 may be required if adjustment factors apply. Never install a circuit where the fuse or circuit breaker rating exceeds the allowable ampere rating of the wire. The result could be a fire. The following example will show how to determine the size of wire for a circuit.

Example: Power is to be supplied to one building from another building. The wires originate at a 100 ampere circuit breaker in the first building. Determine the minimum size of wire required for this circuit.

Solution: Before the wire size can be determined, it is necessary to decide if the wire will be copper or aluminum. Next it will be necessary to determine how the circuit is to be installed. For example, will the wire be run underground as a direct burial cable or in raceway. Will it be run overhead in air as single wires on insulators or as a multiplex cable. Once this decision has been made, the wire size can be selected form Table 212.4. When wires are run overhead, frequently aluminum is selected to minimize the weight. Here are several wiring methods with the minimum wire size selected from Table 212.4. Aluminum wire has a lower tensile strength than copper wire and sometimes requires a steel strand for strength.

Copper wire run underground in raceway	3 AWG
Aluminum wire run underground as direct burial cable	1 AWG
Aluminum wire run overhead in air as multiplex cable	2 AWG
Aluminum wire run overhead as single conductors on insulators	4 AWG

Insulation Temperature: Individual wires are coated with an insulation to prevent the wire from making contact with other objects or other wires. Insulation materials have a maximum operating withstand temperature rating. So the operating temperature rating of an insulated electrical wire is determined by the type of insulation. If this maximum temperature withstand rating is exceeded the insulation will likely be damaged and eventually will become ineffective thus creating a dangerous condition. *Standard electrical wire insulation ratings are in degrees Celsius (^oC) with 60^oC as the base value or minimum.* The next higher standard insulation temperature rating is 75^oC, and the next higher than that is 90^oC. 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 does not contain an H the wire temperature rating is assumed to be 60^oC unless otherwise marked on the wire. An example of a 60^oC rated wire is type TW. Typical code lettering that applies to electrical wires commonly used for construction are listed in *Table 310.104(A)* of the *National Electrical Code*. (*Table 310.13* in Codes dated earlier than 2011) The first one or two code letters usually designates the type of insulating material used such as T for thermoplastic. The letter H is reserved for designating the temperature rating with one H used to indicate a temperature rating of 75^oC and HH used to designate 90^oC. (*Each letter H adds 15^oC to the base value of 60^oC)* 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^oC 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^oC 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 presently designated in units called circular mils. 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 1000. 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 1000 (k) is used. For example, rather than giving a wire size as 500,000 cmil it is given as 500 kcmil. Some years ago a different designation was used to indicate thousands of circular mils and even though manufacturers do not mark wire with that designation, many wires presently in used are marked MCM. The first letter M is the Roman numeral for 1000 and the CM designates circular mils. A wire installed many years ago may be marked 500 MCM which is the same as 500 kcmil.

Summary: Electrical conductors are not necessarily required to be wires. Metal bars of various sizes and shapes and supported by insulating materials are permitted to be used as electrical conductors. When the conductors are wires the smaller sizes are indicated by an AWG number. Wire sizes larger than 4/0 AWG have the size indicated in thousands of circular mils (kcmil). For circuits of high capacity several wires may be installed in parallel to carry the current. Excessive current on a conductor can result in excessive heating and possibly a fire. A fuse or circuit breaker as an overcurrent cutoff device will limit current to the allowable rating of the conductor. When the distance the wire must carry current to get to the intended load is very long, the resistance of the wire may use up an excessive amount of the voltage before the current reaches the load. This condition is called voltage drop and in many cases can be reduced by increasing the size of the wires. *Tech Note 227* discusses this condition and explains how to determine the wire size needed to compensate for excessive voltage drop.

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**					
AWG or	Cable, conduit or direct burial		Multiplex cable in open air		Single conductor on insulators in open air	
kcmil	copper	aluminum	copper	aluminum	copper	aluminum
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.