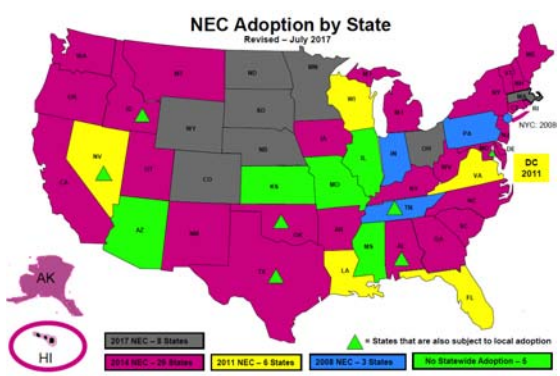
ECET 3000

Electrical Principles

Wires and Conductors

Design Standards

In the United States, the most widely adopted set of standards relating to electric distribution systems is the <u>National Electric Code</u> (NEC). It is the official installation code used in almost all 50 states and all US territories.



National Electrical Code

- Sponsored by the National Fire Protection Association (NFPA) since 1911
- Updated every 3 years
- Provides a set of standards that:

  "cover the installation of electrical conductors, equipment and raceways for… public and private premises, including buildings, structures, mobile homes, recreational vehicles, and floating buildings… yards, lots, parking lots, carnivals, and industrial substations"

  NFPA 70 – National Electrical Code – Article 90.2

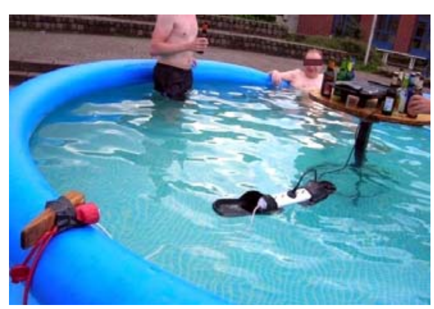
National Electrical Code

The purpose of the National Electrical Code (NEC) is:

"the practical safeguarding of persons and property from hazards arising from the use of electricity."

NFPA 70 – National Electrical Code – Article 90.1(A)

The standards presented in the National Electric Code have been developed over the past 100+ years in order to provide a minimum set of rules for designing, installing, and operating a safe electric distribution system.



National Electrical Code

It is important to note that the code is:

"<u>not</u> intended as a design specification or an instruction manual for untrained persons"

NFPA 70 – National Electrical Code – Article 90.1(A)

and that compliance results in an installation that is <u>safe</u>:

"but <u>not necessarily</u> efficient, convenient, or adequate for good service or future expansion of electrical use."

NFPA 70 – National Electrical Code – Article 90.1(B)

Note that the information that is provided in this presentation, although informative, is not meant to provide instruction regarding the design and/or implementation of electric distribution systems.

The design or implementation of these systems should be referred to either a registered <u>PROFESSIONAL ENGINEER</u> or a <u>LICENSED ELECTRICIAN</u>.

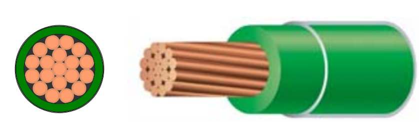
Wires and Conductors

A <u>wire</u> is a single, solid, cylindrical, flexible strand of metal through which charge can easily flow.

Note that the term "wire" is also used to refer to a bundle of individual conductive strands that are wrapped together to form a single entity. (I.e. – "stranded wire")

A <u>conductor</u> is a wire that is encased in one or more layers of insulation that provide electrical isolation and physical protection for the wire.

Conductor Constructed with Solid Wire



Conductor Constructed with Stranded Wire

Cable

Cable – a grouping of two or more insulated conductors that are either wound together or contained within a common protective sheath.

Wire Size

The sizes of wires used in electrical distribution systems are based on the American Wire Gauge (AWG).

The American Wire Gauge (AWG) is a standardized system used to define the size of solid, cylindrical wires based on their diameter.

Although defined for solid, cylindrical wires, the AWG standard can be extended to stranded or non-cylindrical conductors by maintaining a constant cross-sectional area.

American Wire Gauge (AWG)

The American Wire Gauge is based upon a standard set of 40 gauge sizes that relate to wires having diameters ranging exponentially from 0.005 inches to 0.46 inches.

The gauge sizes begin at #36 for a 0.005” wire and count up incrementally in size to #0 (zero), after which the sizes 00, 000 and 0000 are used.

(36, 35, 34, … 2, 1, 0, 00, 000, 0000)
(0.005” → 0.46”)

Note that sizes 00, 000 and 0000 are often expressed as 2/0, 3/0 and 4/0 respectively.

American Wire Gauge (AWG)

The following tables show the diameter of solid, cylindrical wires ranging in size from #36 AWG to 4/0 AWG.

AWG	Diameter	
	(inch)	(mm)
36	0.00500	0.127
35	0.00561	0.143
34	0.00630	0.160
33	0.00708	0.180
32	0.00795	0.202
31	0.00893	0.227
30	0.0100	0.255
29	0.0113	0.286
28	0.0126	0.321
27	0.0142	0.361
26	0.0159	0.405
25	0.0179	0.455
24	0.0201	0.511
23	0.0226	0.573
22	0.0253	0.644
21	0.0285	0.723
20	0.0320	0.812
19	0.0359	0.912
18	0.0403	1.024
17	0.0453	1.150

AWG	Diameter	
	(inch)	(mm)
16	0.0508	1.291
15	0.0571	1.450
14	0.0641	1.628
13	0.0720	1.828
12	0.0808	2.053
11	0.0907	2.305
10	0.1019	2.588
9	0.1144	2.906
8	0.1285	3.264
7	0.1443	3.665
6	0.1620	4.115
5	0.1819	4.621
4	0.2043	5.189
3	0.2294	5.827
2	0.2576	6.544
1	0.2893	7.348
0 (1/0)	0.3249	8.252
00 (2/0)	0.3648	9.266
000 (3/0)	0.4096	10.404
0000 (4/0)	0.4600	11.684

Circular Mils

Wires <u>larger</u> in diameter than 4/0 AWG (0.46”) are typically defined in terms of their cross-sectional area (expressed in thousands of <u>circular mils</u>) instead of by a gauge number.

A <u>circular mil</u> (*cmil*) is a base unit of area equal to the area of a circle that has a $^{1}/_{1000}$ of an inch (i.e. – 1mil) diameter.

Since the area of a circle is defined by: $A_{circle} = \pi \cdot \left(\frac{d}{2}\right)^2$

the area of one circular mil is equivalent to:

$$A_{cmil} = \pi \cdot \left(\frac{0.001in}{2}\right)^2 = \underline{7.854x10^{-7}\ in^2} \quad or \quad 5.0671x10^{-4}\ mm^2$$

Standard Wire Sizes

The following table shows some of the standard AWG sized wires along with some larger wires whose sizes are defined by their cross-sectional area expressed in thousands of circular mils (kcmil).

AWG

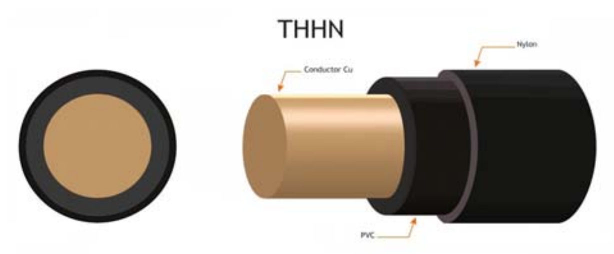
kcmil

Conductor (Wire) Size	Nominal Cross-Sectional Area (Bare Conductor)			Nominal Diameter (Bare Conductor)	
	cmil	in²	mm²	in	mm
AWG					
14	4110	0.00323	2.08	0.073	1.85
12	6530	0.00513	3.31	0.092	2.34
10	10 380	0.00815	5.26	0.116	2.95
8	16 510	0.01296	8.36	0.146	3.71
6	26 240	0.02060	13.29	0.184	4.67
4	41 740	0.03277	21.14	0.232	5.89
3	52 620	0.04131	26.65	0.260	6.60
2	66 360	0.05209	33.61	0.292	7.42
1	83 690	0.06570	42.38	0.332	8.43
0 or 1/0	105 600	0.08290	53.48	0.373	9.47
00 or 2/0	133 100	0.10448	67.41	0.419	10.64
000 or 3/0	167 800	0.13172	84.98	0.470	11.94
0000 or 4/0	211 600	0.16611	107.16	0.528	13.41
kcmil					
250	250 000	0.19625	126.61	0.575	14.61
300	300 000	0.23550	151.94	0.630	15.00
350	350 000	0.27475	177.26	0.681	17.30
400	400 000	0.31400	202.58	0.728	18.49
500	500 000	0.39250	253.23	0.813	20.65
600	600 000	0.47100	303.87	0.893	22.68
700	700 000	0.54950	354.52	0.964	24.49
750	750 000	0.58875	379.84	0.998	25.35
800	800 000	0.62800	405.16	1.030	26.16
900	900 000	0.70650	455.81	1.090	27.69
1000	1 000 000	0.78500	506.45	1.150	29.21
1500	1 500 000	1.17750	759.68	1.410	35.81
2000	2 000 000	1.57000	1012.90	1.630	41.40

Solid vs. Stranded Wire

The conductors utilized in electrical distribution systems can be constructed using either solid or stranded wire.

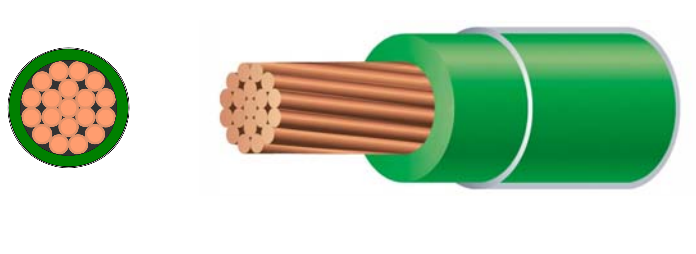
Solid – wire that is composed of a single, solid, cylindrical conductor.



Solid vs. Stranded Wire

The conductors utilized in electrical distribution systems can be constructed using either solid or stranded wire.

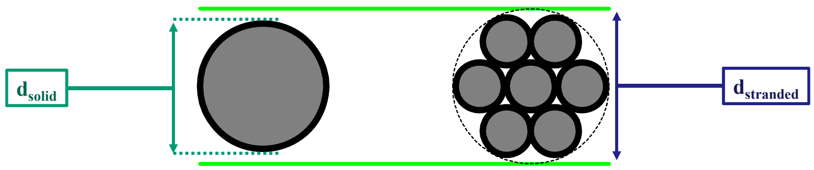
Stranded – wire that is composed of a set of small, conductive strands that are bundled together to form a single, larger conductor.



Solid vs. Stranded Wire

AWG wire sizes are extended from solid to stranded wire by keeping a constant, cross-sectional, (conductive) area.

Thus, a stranded wire will have a larger overall diameter than an equivalently-sized solid wire in order to compensate for the spacing between the individual strands.



Overall diameter of solid and stranded wires with the same conductive cross-sectional area.

Solid vs. Stranded Wire

Table 8 in the NEC shows the physical dimensions for both solid and stranded wire in a variety of sizes.

Solid → (first row of each size); Stranded → (second row)

Size (AWG or kcmil)	Area mm²	Area Circ. mils	Stranding Quantity	Stranding Diameter mm	Stranding Diameter in.	Overall Diameter mm	Overall Diameter in.	Overall Area mm²	Overall Area in.²
14	2.08	4110	1	—	—	1.63	0.064	2.08	0.003
14	2.08	4110	7	0.62	0.024	1.85	0.073	2.68	0.004
12	3.31	6530	1	—	—	2.05	0.081	3.31	0.005
12	3.31	6530	7	0.78	0.030	2.32	0.092	4.25	0.006
10	5.261	10380	1	—	—	2.588	0.102	5.26	0.008
10	5.261	10380	7	0.98	0.038	2.95	0.116	6.76	0.011
8	8.367	16510	1	—	—	3.264	0.128	8.37	0.013
8	8.367	16510	7	1.23	0.049	3.71	0.146	10.76	0.017
6	13.30	26240	7	1.56	0.061	4.67	0.184	17.09	0.027
4	21.15	41740	7	1.96	0.077	5.89	0.232	27.19	0.042
3	26.67	52620	7	2.20	0.087	6.60	0.260	34.28	0.053
2	33.62	66360	7	2.47	0.097	7.42	0.292	43.23	0.067
1	42.41	83690	19	1.69	0.066	8.43	0.332	55.80	0.087

Portion of "Table 8 – Conductor Properties" (NEC)

NEC ≡ National Electric Code

The column labeled "Diameter" under "Stranding" shows the diameter of the individual strands.

Solid vs. Stranded Wire

Note that only stranded wire information is provided for wire size #6 AWG and larger-diameter wires.

Stranded only

Size (AWG or kcmil)	Area mm²	Area Circ. mils	Stranding Quantity	Stranding Diameter mm	Stranding Diameter in.	Overall Diameter mm	Overall Diameter in.	Overall Area mm²	Overall Area in.²
14	2.08	4110	1	—	—	1.63	0.064	2.08	0.003
14	2.08	4110	7	0.62	0.024	1.85	0.073	2.68	0.004
12	3.31	6530	1	—	—	2.05	0.081	3.31	0.005
12	3.31	6530	7	0.78	0.030	2.32	0.092	4.25	0.006
10	5.261	10380	1	—	—	2.588	0.102	5.26	0.008
10	5.261	10380	7	0.98	0.038	2.95	0.116	6.76	0.011
8	8.367	16510	1	—	—	3.264	0.128	8.37	0.013
8	8.367	16510	7	1.23	0.049	3.71	0.146	10.76	0.017
6	13.30	26240	7	1.56	0.061	4.67	0.184	17.09	0.027
4	21.15	41740	7	1.96	0.077	5.89	0.232	27.19	0.042
3	26.67	52620	7	2.20	0.087	6.60	0.260	34.28	0.053
2	33.62	66360	7	2.47	0.097	7.42	0.292	43.23	0.067
1	42.41	83690	19	1.69	0.066	8.43	0.332	55.80	0.087

Portion of "Table 8 – Conductor Properties" (NEC)

Although solid wire is typically chosen for the smaller conductor sizes, <u>stranded wire</u> is used almost exclusively when <u>#6 AWG or larger-sized</u> conductors are utilized in a distribution system.

Material Type

Although wires can be made from any conductive material, distribution system wires are typically constructed from:

- **Copper**
- **Aluminum**

Aluminum is typically reserved for #6 AWG and larger wires.

Copper (Cu)
- lower resistance (higher current limits)
- higher weight
- higher cost
- easier to splice

Aluminum (Al)
- higher resistance (lower current limits)
- lower weight
- lower cost
- requires extra care when splicing/terminating

Coated vs. Uncoated Wire

Due to the corrosive chemicals contained in the insulating materials that were used in the past, a tin coating was added to copper wires to protect them from corrosion.

Many people mistakenly associate coated wire with insulated wire, and uncoated wire with bare wire.

Almost all currently manufactured wire (bare or insulated) is uncoated wire due to advances in the insulating materials.

Table 8 Conductor Properties (partial)

Size (AWG or kcmil)	Area		Conductors: Stranding			Conductors: Overall				Direct-Current Resistance at 75°C (167°F): Copper				Aluminum	
				Diameter		Diameter		Area		Uncoated		Coated			
	mm²	Circular mils	Quantity	mm	in.	mm	in.	mm²	in.²	ohm/km	ohm/kFT	ohm/km	ohm/kFT	ohm/km	ohm/kFT
12	3.31	6530	1	—	—	2.05	0.081	3.31	0.005	6.34	1.93	6.57	2.01	10.45	3.18
12	3.31	6530	7	0.78	0.030	2.32	0.092	4.25	0.006	6.50	1.98	6.73	2.05	10.69	3.25

Insulated Conductors

Insulated wires or conductors are almost exclusively utilized in (non-aerial) electric distribution systems.

Insulated conductors consist of wires that are surrounded by one or more layers of (non-conductive) materials in order to electrically isolate the conductors from other conductors or grounded objects.

An outer jacket may be used to provide physical protection for the insulation.

Additional material layers may also be included to provide further physical qualities to the conductor such as water resistance, flame retardancy, and axial pull strength

Conductor Voltage Rating

The voltage rating of a conductor specifies the maximum voltage for which the conductor is designed to operate, and is based on the amount of electrical isolation provided by the conductor's insulation.

In general, the higher the voltage rating of the conductor, the larger the overall diameter of the conductor due to the thickness of the insulation layer required to provide the necessary electrical isolation.

Conductor Temperature Rating

Conductors are assigned a base temperature rating by their manufacturer.

The base temperature rating of a conductor is a maximum temperature (at any location along its length) that the conductor can withstand for a prolonged period of time without serious degradation its insulating materials.

The most common temperature ratings for conventional building conductors and cable are 60°C, 75°C and 90°C.

The base temperature rating of a conductor must be greater than or equal to the operational temperature rating of the system (or portion thereof) in which it is used.

Conductor Heating

The temperature rating of a conductor has a direct effect on the amount of current that can be allowed to flow continuously through the conductor.

During normal operation, heat is generated within an electrical conductor at a rate that is equal to:

$$P_{heat} = \left| I \right|^2 \cdot R_{conductor}$$

If heat is generated at a rate that is greater than the conductor's ability to dissipate that heat, then the temperature of the conductor will increase. Over time, this may cause the conductor to exceed its temperature rating.

Conductor Resistance

The resistance of a conductor is a function of the conductor's length, cross-sectional area, and material type (conductivity):

$$R_{conductor} = \frac{l}{\sigma \cdot A}$$

Table 8 of the NEC also provides information regarding the DC resistance of both copper and aluminum, standard-sized conductors. **(Note – AC Resistances are shown in Table 9)**

Table 8 Conductor Properties (partial)

Size (AWG or kcmil)	Area		Conductors							Direct-Current Resistance at 75°C (167°F)					
			Stranding			Overall				Copper				Aluminum	
				Diameter		Diameter		Area		Uncoated		Coated			
	mm²	Circular mils	Quantity	mm	in.	mm	in.	mm²	in.²	ohm/km	ohm/kFT	ohm/km	ohm/kFT	ohm/km	ohm/kFT
12	3.31	6530	1	—	—	2.05	0.081	3.31	0.005	6.34	1.93	6.57	2.01	10.45	3.18
12	3.31	6530	7	0.78	0.030	2.32	0.092	4.25	0.006	6.50	1.98	6.73	2.05	10.69	3.25

Conductor Ampacity

<u>Conductor Ampacity</u> – the maximum current, in amperes, that a conductor can carry CONTINUOUSLY under the conditions of use without exceeding its temperature rating.

Although the base temperature rating for a specific conductor is provided by the manufacturer, the conditions of use may require that a lower <u>operational temperature rating</u> be applied to that conductor.

The concept of operational temperature ratings, along with all of the factors that may be taken into account when sizing conductors, can be very complicated.

In terms of both industrial and residential installations, laws (that are typically based on the NEC) may be in place regarding the proper sizing of conductors.

Seek the advice of a <u>licensed electrician</u>.

Conductor Ampacity

The following NEC ampacity table is for insulated conductors rated up to 2000V, based on a <u>30°C ambient temperature</u> and a limit of <u>up to three current-carrying conductors</u> within the same raceway.

Table 310.15(B)(16) (partial) Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

	Temperature Rating of Conductor						
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
Size AWG or kcmil	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, XHHW	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW	
	COPPER			ALUMINUM			Size AWG or kcmil
14**	15	20	25	—	—	—	—
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	55	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	195	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500

Conductor Ampacity

A footnote at the bottom of the table refers the reader to an additional table that provides correction factors that can be applied to the ampacities for ambient temperatures that are other than 30°C.

Table 310.15(B)(16) (partial) Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

Size AWG or kcmil	Temperature Rating of Conductor						Size AWG or kcmil
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, XHHW	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW	
	COPPER			ALUMINUM			
14**	15	20	25	—	—	—	—
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	55	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	195	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500

Table 310.15(B)(2)(a) (partial) Ambient Temperature Correction Factors Based on 30°C (86°F)

For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities specified in the ampacity tables by the appropriate correction factor shown below.

Ambient Temperature (°C)	Temperature Rating of Conductor			Ambient Temperature (°F)
	60°C	75°C	90°C	
11–15	1.22	1.15	1.12	51–59
16–20	1.15	1.11	1.08	60–68
21–25	1.08	1.05	1.04	69–77
26–30	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	132–140
61–65	—	0.47	0.65	141–149
66–70	—	0.33	0.58	150–158
71–75	—	—	0.50	159–167

Conductor Ampacity

A separate table provides additional correction factors for cases where more than three current-carrying conductors are located within the same raceway.

Table 310.15(B)(16) (partial) Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

Size AWG or kcmil	Temperature Rating of Conductor						Size AWG or kcmil
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, XHHW	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW	
	COPPER			ALUMINUM			
14**	15	20	25	—	—	—	—
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	55	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	195	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500

Table 310.15(B)(3)(a) Adjustment Factors for More Than Three Current-Carrying Conductors in a Raceway or Cable

Number of Conductors[1]	Percent of Values in Table 310.15(B)(16) through Table 310.15(B)(19) as Adjusted for Ambient Temperature if Necessary
4–6	80
7–9	70
10–20	50
21–30	45
31–40	40
41 and above	35

[1]Number of conductors is the total number of conductors in the raceway or cable adjusted in accordance with 310.15(B)(5) and (6).