Copper Development Association Inc.
Copper Alliance

Recommended Practices for Designing and Installing Copper Building Wire Systems

CDA - CWIS Committee

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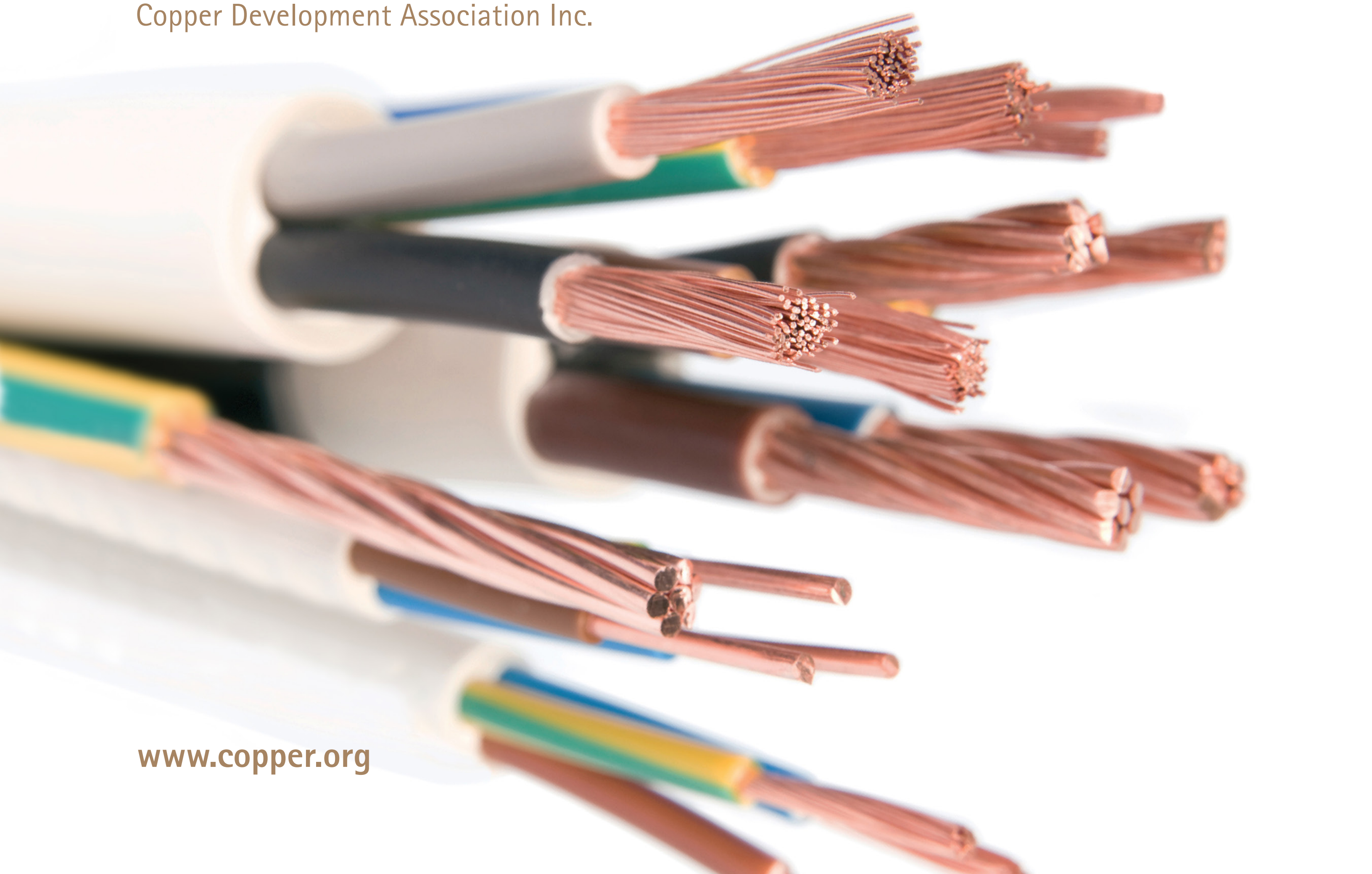
Developed by the
Copper Development Association Inc.



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Foreword

This document is intended to provide basic facts about copper wire and its use. It is not intended to be a comprehensive design guide; however, many features of design are explained herein.

Copper wire systems are the most widely used of all electrical systems and are often found whenever reliability and connectability are important.

Subsequent versions of this document will be expanded to include information on current trends and to update reference materials.

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1. Scope

1.1 Included

This document covers many of the considerations in the installation and maintenance of copper building wire permanently installed in building premises wiring systems for residential, commercial, institutional, and industrial applications. The reference materials are based on the 2011 edition of the National Electrical Code®, although the recommendations will not be materially affected. This document is not intended to be a comprehensive design guide.

1.2 Excluded

This document does not cover aluminum, or mixed metal building wire and cable in residential, commercial, institutional, and industrial applications. It also does not cover aluminum alloy conductors and cables used in electric utility applications.

1.3 Regulatory and Other Requirements

(a) All information in this publication is intended to conform to the National Electrical Code® (ANSI/NFPA Standard 70). Installers should always follow, but may certainly exceed the NEC®, applicable state and local codes, and manufacturers' instructions when installing and maintaining copper building wire systems.
(b) Only qualified persons as defined in the NEC familiar with the construction and operation of copper building wiring should perform the technical work described in this publication. Administrative functions such as receiving, handling, and storing and other tasks can be performed under the supervision of a qualified person. All work should be performed in accordance with NFPA 70E, *Standard for Electrical Safety in the Workplace*.

2. Definitions

This chapter contains definitions of most but not all technical terms used in this publication. Many of these definitions are taken directly from Article 100 of the NEC and are referenced [1] below. If the definition is taken from the text of the NEC it is referenced [2].

Ambient Temperature. The environmental temperature surrounding the object under consideration. (*Source: IEEE 100-2000)*

American Wire Gage (AWG). A standard system used in North America for designating the size of an electrical conductor based on a geometric progression between two conductor sizes. Based on the Brown & Sharpe Gage, the AWG system contains 40 sizes from 36 through 0000 (or 4/0), with smaller numbers designating larger sizes. A change of three AWG sizes approximately doubles (or halves) the cross-sectional area. Beyond 4/0, cross-sectional areas are usually expressed in North America in thousands of circular mils (kcmil).

Ampacity. The maximum current, in amperes, that a conductor can carry continuously under the conditions of use without exceeding its temperature rating. [1]

Armored Cable, Type AC. A fabricated assembly of insulated conductors in a flexible interlocked metallic armor. Type AC cable has an armor of flexible metal tape and an internal bonding strip of copper or aluminum in intimate contact with the armor for its entire length. [2]

AWG. See American Wire Gage.

Bonded (Bonding). Connected to establish electrical continuity and conductivity. [1]

Branch Circuit. The circuit conductors between the final overcurrent device protecting the circuit and the outlet(s). [1]

Branch Circuit, Individual. See Individual Branch Circuit.

Building Wire. 600 volt circuit conductors typically used for service entrances, feeders, and branch circuits in residential, commercial, institutional, and industrial buildings.

Bundled Cables. Cables installed without maintaining spacing. The effect on temperature rise is similar to that of multiple conductors installed in conduits.

Cable. Typically one or more conductors enclosed in a common sheath with or without a metallic or nonmetallic outer protective covering. See definitions of specific wiring types.

Cable Tray System. A unit or assembly of units or sections and associated fittings forming a structural system used to securely fasten or support cables and raceways. [2]

Circuit. A complete electrical path through which electricity may flow. Typically, two or more conductors providing an electrical path from the source through some device using electricity and back to the source.

Circuit Breaker. A device designed to open and close a circuit by non-automatic means and to open the circuit automatically on a predetermined overcurrent without damage to itself when properly applied within its rating. [1]

Circular mil. The area of a circle one mil (0.001 in.) in diameter. One circular mil equals 0.0000007854 (7.854 X 10^{-7}) sq. in. The area in circular mils, A, of a circle with a diameter of d mils, is given by the formula: $A = d^2$

Conductor. For the purposes of this standard, a solid or stranded annealed copper wire. In the context of the standard the term often is taken to include the attached insulation.

Conduit. A channel for holding and protecting conductors and cables, made of metal or an insulating material, usually circular in cross section like a pipe.

Continuous Load. A load where the maximum current is expected to continue for 3 hours or more. [1]

Copper. A noble metal that is highly conductive and resistant to corrosion from moisture, humidity, industrial pollution, and other atmospheric influences.

Dedicated Branch Circuit. See Individual Branch Circuit.

Demand Factor. The ratio of the maximum demand of a system, or part of a system, to the total connected load of a system or the part of the system under consideration. [1] See also Diversity.

Derating. Calculations that reduce standard tabulated ampacities for different conditions of use based on ambient temperature, bundling of conductors, and other factors.

Diversity. Also known as Load Diversity. The principle that, when multiple loads are connected to a power source, not all loads are on at the same time, not all loads are at full intensity, and not all loads are on for a long period of time. This may permit the use of assumed demand factors less than 100% when designing building wire systems.

Electrical Energy Efficiency. Percentage of total energy input to a piece of equipment that is consumed in useful work and not wasted as useless heat. Definition does not apply to resistance-heating systems.

Equipment Grounding Conductor (EGC). The conductive path(s) installed to connect normally non-current-carrying metal parts of equipment together and to the system grounded conductor or to the grounding electrode conductor, or both. [1]

Feeder. All circuit conductors between the service equipment, the source of a separately derived system, or other power supply source and the final branch-circuit overcurrent device. [1]

Fuse. An overcurrent protective device with a circuit-opening fusible part that is heated and severed by the passage of overcurrent through it. [1]

Ground. The earth. [1]

Grounded (Grounding). Connected (connecting) to ground or to a conductive body that extends the ground connection. [1]

Grounded Conductor. A system or circuit conductor that is intentionally grounded. [1]

Grounding Conductor. No longer used by the NEC. See Equipment Grounding Conductor.

Grounding Electrode. A conducting object through which a direct connection to earth is established. [1]

Grounding Electrode Conductor. A conductor used to connect the system grounded conductor or the equipment to a grounding electrode or to a point on the grounding electrode system. [1]

Ground Loop. A different voltage potential at two or more points along the grounding system caused by improper grounding and bonding that results in objectionable current flow over the grounding system. Ground loop currents can contain frequencies extending into the radio frequency range and are a common source of electrical interference in the form of background noise.

Ground Ring. A grounding electrode comprised of a bare conductor buried outdoors in direct contact with the earth that completely encircles a building or structure. Ground rings provide a low impedance path from the grounding system to the earth itself, and a convenient means to connect various grounding conductors to the grounding electrode system. Ground rings are required to be a minimum of 20 feet in length, not smaller than 2 AWG, and buried not less than 30 inches in depth.

Ground Rod. See Grounding Electrode.

Harmonics. A sinusoidal component of a periodic wave or quantity having a frequency that is an integer multiple of the fundamental frequency. For a 60-Hz operating system, for example, the second harmonic is 120 Hz, the third harmonic is 180 Hz, etc. For a three-phase power system, typically only odd harmonics are present due to the half-wave symmetry of the fundamental waveform. The load current for arcing devices, such as welders, arc furnaces, arc discharge lighting, etc., however, will contain some even-harmonic components.

Hot Conductor. See Ungrounded Conductor.
Individual Branch Circuit. A branch circuit that supplies only one utilization equipment. [1]

Insulation. A nonconductive material used on a conductor to separate conducting materials in a circuit.

I^2R Losses. The rate at which heat is internally generated when a current passes through a conductor. The heat losses are directly proportional both to the conductor's resistance and to the square of the current. Normally measured in watts.

Jacketing. In the case of Type NM or SEU cable, the protective outer covering of the insulated and bare conductors. Considered to have minimal electrical insulating properties.

kcmil. Thousands of circular mils. Formerly referred to as MCM.

Load Diversity. See Diversity.

MCM. See kcmil.

Metal Clad Cable, Type MC. A factory assembly of one or more insulated circuit conductors with or without optical fiber members enclosed in an armor of interlocking metal tape, or a smooth or corrugated metallic sheath. [2]

National Electrical Code (NEC). A set of rules governing safe wiring methods, drafted by the National Fire Protection Association with significant public input. The NEC does not become law until adopted by federal, state, or local laws and regulations. The regulations of a legal jurisdiction may differ somewhat from the NEC and take precedence over it.

Neutral Conductor. The conductor connected to the neutral point of a system that is intended to carry current under normal conditions. [1]

Nonlinear Load. A load where the wave shape of the steady-state current does not follow the wave shape of the applied voltage. Electronic equipment, electronic/electric-discharge lighting, adjustable-speed drive systems, and similar equipment may be nonlinear loads. [1]

Nonmetallic-Sheathed Cable, Type NM. A factory assembly of two or more insulated conductors enclosed within an overall nonmetallic jacket. Includes Types NM-B, NMC-B (corrosion resistant version), and NMS-B (containing signaling, data, or communications conductors). [2]

OCPD. See Overcurrent Protective Device.

Outlet. A point on the wiring system at which current is taken to supply utilization equipment. [1]

Overcurrent Protective Device, Branch Circuit (OCPD). A device capable of providing protection for service, feeder, and branch circuits and equipment over the full range of overcurrent conditions between its rated current and its interrupting rating. Branch-circuit overcurrent protective devices are provided with interrupting ratings appropriate for the intended use but no less than 5000 amperes. [1]

Panelboard. A single panel or group of panel units designed for assembly in the form of a single panel, including buses and automatic overcurrent devices, and equipped with or without switches for the control of light, heat, or power circuits; designed to be placed in a cabinet or cutout box placed in or against a wall, partition, or other support; and accessible only from the front. [1]

Phase Conductor. See Ungrounded Conductor.

Power Quality. The concept of powering and grounding sensitive electronic equipment in a manner that is suitable for the operation of the equipment.

Raceway. An enclosed channel of metal or nonmetallic materials designed expressly for holding wires, cables, or busbar, with additional functions as permitted by the NEC. Raceways include, but are not limited to, rigid metal conduit, rigid nonmetallic conduit, intermediate metal conduit, liquidtight flexible conduit, flexible metallic tubing, flexible metal conduit, electrical nonmetallic tubing, electrical metallic tubing, underfloor raceways, cellular concrete floor raceways, cellular metal floor raceways, surface raceways, wireways, and busways. [1]

Receptacle. A contact device installed at the outlet for the connection of an attachment plug. A single receptacle is a single contact device with no other contact device on the same yoke. A multiple receptacle is two or more contact devices on the same yoke. [1]

Service Conductors, Overhead. The overhead conductors between the service point and the first point of connection to the service-entrance conductors at the building or other structure. [1]

Service Conductors, Underground. The underground conductors between the service point and the first point of connection to the service-entrance conductors in a terminal box, meter, or other enclosure, inside or outside the building wall. [1]

Service Drop. The overhead conductors between the utility electric supply system and the service point. [1]

Service-Entrance Cable, Type SE and Type USE. A single conductor or multi-conductor assembly provided with or without an overall covering, primarily used for services. Type SE has a flame-retardant, moisture-resistant covering, while Type USE, identified for underground use, has a moisture-resistant covering but is not required to have a flame-retardant covering. [2]

Service-Entrance Conductors, Overhead System. The service conductors between the terminals of the service equipment and a point usually outside the building, clear of building walls, where joined by tap or splice to the service drop or overhead service conductors. [1]

Service-Entrance Conductors, Underground System. The service conductors between the terminals of the service equipment and the point of connection to the service lateral or underground service conductors. [1]

Service Equipment. The necessary equipment, usually consisting of a circuit breaker(s) or switch(es) and fuse(s) and their accessories, connected to the load end of service conductors to a building or other structure, or an otherwise designated area, and intended to constitute the main control and cutoff of the supply. [1]

Skin Effect. In an alternating current system, the tendency of the outer portion of a conductor to carry more of the current as the frequency of the ac increases.

Thermoplastic. Insulation that will soften and melt with sufficient heat.

Thermosetting. Insulation that will not re-melt.

THHN. A thermoplastic-insulated, nylon-jacketed conductor used in dry locations up to 90°C.

THW. A thermoplastic-insulated, moisture-resistant conductor used in wet or dry locations up to 75° C.

THWN-2. a thermoplastic-insulated, moisture-resistant conductor used in wet or dry locations up to 90°C.

TW. A thermoplastic-insulated, moisture-resistant conductor used in wet or dry locations up to 60°C.

Underground Feeder and Branch-Circuit Cable, Type UF. A factory assembly of one or more insulated conductors with an integral or an overall covering of nonmetallic material suitable for direct burial in the earth. [2]

Ungrounded Conductor. Also commonly referred to as Phase Conductor or Hot Conductor. The conductor carrying electrical current forward from the source. Usually identified by black, red, or blue insulation in a cable, but may be any color other than white, gray or green.

Voltage Drop. The loss of voltage in a circuit when current flows.

Wiring Device. Equipment, typically mounted in a device box, that aids in the use of electricity but does not itself use an appreciable amount. Includes switches, receptacles, thermostats, timers, dimmers, and free-standing sensors, but excludes lighting and heating equipment.

XHHW-2. A thermosetting-insulated, moisture-resistant conductor used in wet or dry locations up to 90° C.

3. Purpose

In the Introduction to NFPA 70®, the National Electrical Code®, or the NEC®, the following wording appears in Article 90.1(B): “This *Code* contains provisions that are considered necessary for safety. Compliance therewith and proper maintenance results in an installation that is essentially free from hazard but not necessarily efficient, convenient, or adequate for good service or future expansion of electrical use.”

The purpose of this document is to establish design and installation practices for copper conductors that not only adhere to the NEC, but also supplement and expand it to make such systems efficient, convenient, serviceable, and expandable, in addition to being safe. It addresses such concerns as temperature effects on wiring systems, voltage drop, conductors for grounding, future electrical capacity, electrical energy efficiency, and good installation practices. The scope is limited to “building wire.” Conductors such as bus-duct conductors are not included. *This document is not intended to be a comprehensive design manual.*

Temperature Effects on Wiring Systems. The ampacity of building wire type conductors is limited by the temperature rating of the conductor insulation. This publication recommends methods of calculating the ampacity of conductors, taking into consideration ambient temperature, the number of current-carrying conductors in a raceway or cable(s), bundling of conductors or cables and exposure to sunlight, in compliance with the NEC.

Voltage Drop. The NEC recommends, but does not require, maximum voltage drops for general use feeder and branch circuit conductors. This publication expands those recommendations, addressing conductor sizing, supply voltage, circuit loading, and the power quality needs of sensitive electronic equipment.

Conductors for Grounding. The grounding of conductive, but not normally current-carrying, components of an electrical system is vital to the safe and effective performance of the system. An adequate system will safely carry fault currents from the failure point to the earth and allow overcurrent protective devices to operate. The NEC covers grounding from a safety standpoint, but not necessarily adequately for power quality. This document expands on the NEC requirements for grounding and recommends design and installation practices that address equipment operation and power quality.

Future Electrical Capacity. Although provisions for future expansion are recommended by Article 90.8, electrical wiring is often installed without consideration for changes in use or occupancy. While applicable to all types of construction, this is particularly the case in residential construction, where rewiring for additions, alterations, or changes in use is often difficult to implement and is costly. This publication recommends wiring practices that meet the NEC and provide for future flexibility and load growth in residential and nonresidential construction.

Electrical Energy Efficiency. Though not covered in the NEC, electrical energy efficiency should be considered to achieve higher reliability, lower energy costs, and longer equipment life, all as a result of running cooler. In addition to high-efficiency motors and transformers (where applicable), larger-than-minimum wire gauge is often cost-justified by the attendant energy savings, due to the lower I^2R losses. Payback times of 3 years or less are often achievable.

Installing Copper Building Wire. Since copper wire is the standard against which other electrical wiring materials are compared, many publications and training activities address the proper installation of copper building wire systems. This publication does not attempt to replicate these many excellent sources, but offers a brief overview of good installation practices. Copper building wire systems are reliable, with minimal or no maintenance. They generally do not require wire brushing, conductive grease or periodic re-tightening.

4. Temperature Effects on Wiring Systems

4.1 Heat and Conductor Insulations

One factor that has to be considered in applying building wire is the temperature limitation of the conductor insulation. Building wire conductor insulation is rated 90°C (194°F), 75°C (167°F), and 60°C (140°F). This is significantly lower than the melting point of copper, 1083°C (1981°F).

Thermoplastic or thermoset electrical insulation and jacketing are not as resistant to elevated temperature as the copper conductor. The ability of electrical systems to withstand elevated temperatures is essentially the temperature resistance of the electrical insulation protecting it, along with the temperature rating of terminations. Consequently, conductors and cables must be limited to an operating temperature within the temperature rating of their insulation system in accordance with NEC 310.15(A)(3), which states, in part, "No conductor shall be used in such a manner that its operating temperature exceeds that designated for the type of insulated conductor involved."

Electrical conductors are exposed to internal and external heating effects. Internally, conductors are heated by I^2R losses from the load current passing through the inherent resistance within the conductor.

Externally, conductors are exposed to elevated temperatures in the surrounding space, such as in an attic, to heat generated by other conductors in close proximity, and to the heating effects of sunlight. Any of these factors may result in a high *ambient temperature*, the temperature of the air in immediate proximity to the conductor.

High ambient temperatures limit the cooling of the conductors. Cooling occurs by thermal conduction, by convection currents of the surroundings (usually air), and by infrared heat radiation. These processes may be seriously affected by the conditions of installation. When combined with the heat generated internally, within the conductor, the temperature limit of the insulation can be exceeded.

The effects of internal and external conductor heating are taken into account by the NEC in ampacity tables. Ampacity is the maximum amount of current a conductor can carry continuously under conditions of use without exceeding its temperature rating. For NEC Table 310.15(B)(16) (Table 4.1 below), conductor ampacity is provided using an ambient temperature of 30°C (86°F), and not more than three current-carrying conductors in close proximity in raceway, cable, or earth (directly buried).

Examples of commonly encountered conditions affecting conductor operating temperature that necessitate adjusting or correcting conductor ampacity are:

- conductors in high ambient temperatures,
- more than three current-carrying conductors in a single raceway or cable,

- cables installed without maintaining spacing, whether or not encased in thermal insulation,
- conductors in raceways exposed to sunlight on or above rooftops, and
- conductors serving continuous loads.

Table 4.1. NEC Table 310.15(B)(16) (part) 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)* (copper only)

	Temperature Rating of Copper Conductors [See Table 310.104(A).]			
	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, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Size AWG or kcmil
18	--	--	14	18
16	--	--	18	16
14**	15	20	25	14**
12**	20	25	30	12**
10**	30	35	40	10**
8	40	50	55	8
6	55	65	75	6
4	70	85	95	4
3	85	100	115	3
2	95	115	130	2
1	110	130	145	1
1/0	125	150	170	1/0
2/0	145	175	195	2/0
3/0	165	200	225	3/0
4/0	195	230	260	4/0
250	215	255	290	250
300	240	285	320	300
350	260	310	350	350
400	280	335	380	400
500	320	380	430	500
600	350	420	475	600
700	385	460	520	700
750	400	475	535	750
800	410	490	555	800
900	435	520	585	900
1000	455	545	615	1000
1250	495	590	665	1250
1500	525	625	705	1500
1750	545	650	735	1750
2000	555	665	750	2000

* Refer to 310.15(B)(2) for the ampacity correction factors where the ambient temperature is other than 30°C (86°F).
** Refer to 240.4(D) for conductor overcurrent protection limitations.

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4.2 Elevated Ambient Temperatures

The ampacity of a conductor must be corrected when the conductor is exposed to ambient operating temperatures above the 30°C (86°F) upon which Table 310.15(B)(16) is based. The concern is about elevated temperatures because of the inherent danger in exceeding the temperature limit of the insulation. This correction should be in accordance with Table 310.15(B)(2)(a) (shown as Table 4.2). As an example, the ampacity of 500 kcmil THWN conductors rated 75°C (167°F) with an ampacity of 380 amps that are installed in a space with an ambient temperature of 57°C (135°F) must be reduced to 58% of their ampacity in the 75°C column, or 220 amps (380 amps x 0.58 = 220 amps).

Table 4.2 NEC Table 310.15(B)(2)(a) 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	
10 or less	1.29	1.20	1.15	50 or less
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
76-80	—	—	0.41	168-176
81-85	—	—	0.29	177-185

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4.3 More Than Three Current-Carrying Conductors in a Raceway or Cable

Heat is generated when current passes through a conductor. The ability of an insulated conductor to dissipate heat to its surroundings is hampered when more than three current-carrying conductors are installed in a single raceway or cable or are installed without maintaining spacing. Each heat-producing conductor increases the temperature of adjacent conductors and increases the temperature of the environment in which the conductors operate. Non-current-carrying neutrals and equipment grounding conductors should not be counted, as their effect on the system is not considered significant. Consequently, the ampacity of conductors must be adjusted when more than three current-carrying conductors are contained within a single raceway or cable in accordance with NEC Table 310.15(B)(3)(a) (Table 4.3 below):

Table 4.3 NEC 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 Tables 310.15(B)(16) through 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).

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As an example, Table 310.15(B)(16) shows that 8 AWG copper wire with 90°C (194°F) insulation has an ampacity of 55 amps when operated in an ambient of 30°C (86°F) and there are three or fewer current-carrying conductors contained within a common raceway or cable. When there are 4 to 6 conductors in a common raceway or cable, the ampacity of the 8 AWG 90°C (194°F) conductor must be adjusted or reduced in accordance with Table 310.15(B)(3)(a) to 80%, or 44 amps.

When there are 7 to 9 current-carrying 8 AWG 90°C (194°F) conductors in a common raceway or cable, their ampacity must be adjusted or reduced to 70%, or 38.5 amps.

When there are 10 to 20 current-carrying conductors in a common raceway or cable, the ampacity must be adjusted or reduced to 50%, resulting in an ampacity of 27.5 amps for each 8 AWG 90°C (194°F) insulated conductor.

4.4 Cables Installed Without Maintaining Spacing

This section covers cables installed without maintaining spacing, also commonly referred to as "bundled" or "grouped" cables. For clarity, the term "bundled" is used in this document to describe this type of installation. Similar to the case of more than three current-carrying conductors in a single raceway or cable, bundling can also result in mutual heating and restricted air circulation, inhibiting the dissipation of heat generated within the conductors when carrying current. Thus bundling can cause the conductors to run hotter. NEC 310.15(B)(3)(a) states in part

> “where single conductors or multi-conductor cables are installed without maintaining spacing for a continuous length longer than 600 mm (24 in.) and are not installed in raceways, the allowable ampacity of each conductor shall be reduced as shown in Table 310.15(B)(3)(a).”

Bundled Type NM cables that are in contact with thermal insulation are covered by NEC 334.80, which states

> “Where more than two NM cables containing two or more current-carrying conductors are installed in contact with thermal insulation without maintaining spacing between cables, the allowable ampacity of each conductor shall be adjusted in accordance with Table 310.15(B)(3)(a).”

Note that this provision applies to any length of Type NM cable installed in this manner. In essence, bundled cables must be treated similarly to individual conductors in a single raceway, and derated when more than three current-carrying conductors are in close proximity. The small-conductor rule in NEC 240.4(D) may also come into play in bundling situations, but only for conductors 10 AWG and smaller.

For both conductors in raceways and bundled cables, non-current-carrying conductors used for equipment grounding are not included in the count when applying Table 310.15(B)(3)(a). In the case of neutral (grounded) conductors in 3-phase systems, the installer may not know whether the load will consist of harmonic components or whether loads might change over time. Therefore, careful consideration should be taken to decide if the neutral conductors should be counted as current-carrying conductors when applying the table.

Another provision of NEC 334.80 refers to more than two Type NM cables, each containing two or more current-carrying conductors, passing through openings in wood framing that are to be sealed with thermal insulation, caulk, or sealing foam. If the cables are installed without maintaining spacing between them, Table 310.15(B)(3)(a) must be applied to adjust the ampacity of the conductors. This provision demonstrates that even quite short bundle lengths can exhibit excess heating.

4.5 Conductors in Raceways Above Rooftops

In addition to solar heat gain, the ability of an insulated conductor to dissipate heat to its surroundings is hampered when conductors are installed in circular raceways that are mounted in direct sunlight on roofs. Consequently, the ampacity of roof-mounted conductors in circular raceways must be adjusted in accordance with NEC Table 310.15(B)(3)(c) (Table 4.5 below):

Table 4.5. NEC Table 310.15(B)(3)(c). Ambient Temperature Adjustment for Circular Raceways Exposed to Sunlight on or Above Rooftops.

Distance Above Roof to Bottom of Conduit	Temperature Adder	
	ºC	ºF
0 – 13 mm (1/2 in.)	33	60
Above 13 mm (1/2 in.) – 90 mm (3-1/2 in.)	22	40
Above 90 mm (3-1/2 in.) – 300 mm (12 in.)	17	30
Above 300 mm (12 in.) – 900 mm (36 in.)	14	25

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The ambient temperature adder from Table 310.15(B)(3)(c) must be added to the appropriate outdoor temperature for the geographical area in which the conductors are located. That resulting ambient temperature should then be used in applying Table 310.15(B)(2)(a) to determine adjustments to the ampacity values in Table 310.15(B)(16). It is good engineering practice to apply these temperature adjustments to all conductors, irrespective of minimal Code requirements.

One way to determine the appropriate outdoor temperatures to use for various North American locations is using data compiled by the American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). The 2% design temperature, averaged for the months of June, July, and August, was determined to be an appropriate measure of outdoor temperature. This means that 2% of the hourly summer readings (day and night) were higher than that design temperature for a given location.

Annex B is a shortened version of the complete data for 791 U.S. and 27 Canadian locations which can be found at www.copper.org/rooftop. Table B.1 lists the 2% design outdoor temperatures for the largest 50 metropolitan statistical areas (MSAs) in North America, arranged by decreasing population, encompassing 52% of the North American population. It also provides the recommended design temperatures inside raceways, based on Table 310.15(B)(3)(c).

4.6 Conductors Serving Continuous Loads

Though technically not an ampacity correction for temperature, continuous loads – those expected to last for at least three hours – can be considered in this category, because the corrections made for them are as a result of the possibility of the buildup of heat over a period of time. The relevant rules for branch circuits are contained in NEC 210.19(A)(1) for conductors and NEC 210.20(A) for overcurrent protective devices (OCPDs). Both state that the continuous portion of a given load must be multiplied by 125%, then added to the noncontinuous load, to determine the final calculated load. Appropriate adjustments must be made in both conductors and OCPDs to allow for this. Similar rules exist for feeders and services.

4.7 Summary

The NEC articles that apply to corrections for temperature effects are quite extensive, going well beyond those mentioned above. To aid those who have to apply these rules, Table 4.7 is given to summarize the most important rules that must be considered to arrive at a design that is in full compliance with the NEC.

Table 4.7. Summary of Selected NEC Sections Used in Determining Conductor Size and Overcurrent Protective Device (OCPD) Ratings, Where Temperature or Voltage Drop Are Involved.

NEC Section	Summary (1)	Further Explanation
110.14(C)	Temperature rating associated with conductor ampacity must be coordinated with the lowest temperature rating of any connected termination (e.g. circuit breakers).	Terminations may be rated 60°C, 60ºC/75°C or only 75ºC.
110.14(C)(1)(a)	For circuits ≤100 amps (or 14 AWG thru 1 AWG), conductor ampacities based on 60ºC column of Table 310.15(B)(16).	For Type NM cable, the 60ºC column must be used even if the OCPD is rated 75ºC.
110.14(C)(1)(b)	For circuits >100 amps (or larger than 1 AWG), conductor ampacities based on 75ºC column of Table 310.15(B)(16).	
210.3	Branch circuits are rated in accordance with the ampere rating of the OCPD.	Therefore, the circuit's rating *is* the rating of the OCPD.
210.19(A)(1)	A branch circuit shall have an ampacity not less than the maximum load to be served. A branch circuit's conductor size, before the application of any adjustment or correction factors, shall have an allowable ampacity of the noncontinuous load plus 125% of the continuous load.	Continuous loads are those where the maximum current is expected to continue for 3 hours or more.
210.19(A)(1) IN No. 4	Voltage drop recommendations for branch circuits. No more than 3% in the branch circuit, or 5% in the branch circuit and feeder combined.	A lower voltage drop can be advantageous in many applications. See Chapter 5 of this document.
210.19(A)(2)	Conductors of branch circuits serving more than one receptacle shall have an ampacity not less than the branch circuit rating.	Since loading of receptacles is unpredictable. Also see 210.3.
210.20(A)	Where a branch circuit serves continuous loads, the rating of the OCPD shall be not less than the noncontinuous load plus 125% of the continuous load.	Same rule as 210.19(A)(1) for conductors.

210.23	In no case shall the load exceed the branch circuit ampere rating. An individual branch circuit (supplies only one utilization equipment) shall be permitted to serve any load for which it is rated.	
215.2(A)(4) IN No. 2	Voltage drop recommendations for feeders. No more than 3% in the feeder and 5% in the feeder and branch circuit combined.	A lower voltage drop can be advantageous in many applications. See Chapter 5 of this document.
240.4(B)	The next higher standard overcurrent device rating (above the ampacity of the conductors being protected) shall be permitted to be used, provided conductors being protected are not part of a branch circuit supplying more than one receptacle for cord and plug connected loads.	While the overcurrent protective device may be permitted to exceed the conductor ampacity, the load being carried by the conductor is never permitted to exceed its ampacity. This “round-up” rule does not apply above 800 A.
240.4(D)	Overcurrent protection shall not exceed 15 amps for 14 AWG, 20 amps for 12 AWG, and 30 amps for 10 AWG after any correction factors for ambient temperature and number of conductors has been applied.	Branch circuit loads are difficult to predict or control, especially in residential settings. Some exceptions exist, such as certain motor loads.
240.6(A)	List of standard ampere ratings of fuses and fixed-trip circuit breakers.	Useful for applying the round-up provisions of 240.4(B)(1).
310.15(A)(2)	Where more than one ampacity applies for a given circuit length, the lowest value is used. Exception: Where two or more ampacities apply to a circuit, the higher ampacity may be used beyond the point of transition, a distance equal to 10 feet or 10% of the circuit length figured at the higher ampacity, whichever is less.	Different ampacities apply to a total length of conductors if a portion of the length operates in a higher ambient temperature or a portion of the length has more than three current-carrying conductors that are installed without maintaining spacing. It is also possible that a combination of these factors apply to a given length of conductor. It is presumed the longer length of cooler conductor acts as a heat sink for the shorter section operating at a hotter temperature.
310.15(A)(3)	No conductor shall be used in such a manner that its operating temperature exceeds that designated for the type of insulated conductor involved. In no case shall conductors be associated together in such a way, with respect to type of circuit, the wiring method employed, or the number of conductors, that the limiting temperature of any conductor is exceeded.	Five major determinants of operating temperature are: ambient temperature; internally generated heat; heat from adjacent conductors; dissipation of generated heat; and radiant energy.
310.15(B)	Tables 310.15(B)(16) thru 310.15(B)(21) are the source for allowable ampacities of insulated conductors rated from 0 to 2000 volts.	Table 310.15(B)(16) is by far the most important for building wiring.

310.15(B) Informational Note	For Table 310.15(B)(16) and those following, the tables take into account (1) temperature compatibility with connected equipment (2) coordination with OCPDs (3) compliance with product listings or certifications and (4) preservation of the safety benefits of established industry practices and procedures.	
310.15(B)(2)	Ampacities for ambient temperatures other than shown in the ampacity tables shall be corrected in accordance with Table 310.15(B)(2)(a) – based on 30°C – or Table 310.15(B)(2)(b) – based on 40°C.	Alternatively, the Neher-McGrath equation may be used under engineering supervision.
310.15(B)(3)(a)	If more than 3 current-carrying conductors are installed in a raceway or cable, or if single- or multi-conductor cables are installed for a distance greater than 24 inches without maintaining spacing, then the ampacity of the conductors must be adjusted in accordance with Table 310.15(B)(3)(a).	
0.15(B)(3)(c)	Where conductors or cables installed in circular raceways are exposed to direct sunlight on or above rooftops, the ambient temperature to be applied from Table 310.15(B)(2)(a), Correction Factors, shall be the outdoor design temperature for the area in question *plus* the temperature adders from Table 310.15(B)(3)(c).	Suggested outdoor design temperatures for the summer months, based on ASHRAE data, are available for many U.S. locations. See Annex B of this document.
310.15(B)(5)	When applying 310.15(B)(5), neutral (grounded) conductors that carry only the unbalanced current from other conductors of the same circuit shall not be required to be counted.	Note that 310.15(B)(5)(c) requires the neutral to be counted as a current-carrying conductor when the major portion consists of nonlinear loads.
310.15(B)(7)	Conductor sizes permitted to be used for single-phase services and feeders for dwelling units are given in Table 310.15(B)(7).	Diversity of loads in dwellings is the reason for these conductor sizes.
334.80	The ampacity of Types NM, NMC, and NMS cable shall be in accordance with the 60ºC conductor temperature rating. The 90ºC rating shall be permitted to be used for ampacity derating purposes, provided the final derated ampacity does not exceed that for a 60ºC rated conductor.	This restriction is for all sizes. Since 2 AWG is the largest size mentioned in 334.104, the rule has essentially the same effect as that for terminations in 110.14(C)(1)(a).
334.80	Where more than two Type NM cables containing two or more current-carrying conductors are installed without maintaining spacing through an opening in wood framing members to be sealed	Note that the 10 ft or 10 percent provisions of 310.15(A)(2) Exception are not permitted to apply.

	with thermal insulation, caulk, or sealing foam, use Table 310.15(B)(3)(a).	
334.80	Where more than two Type NM cables containing two or more current-carrying conductors are installed without maintaining spacing in contact with thermal insulation, use Table 310.15(B)(3)(a).	All thermal insulations restrict the dissipation of heat from embedded cables.

- The full text of the NEC Sections should be consulted because of possible exceptions, caveats, Informational Notes, etc.

4.8 Sample Calculations

A large number of sample calculations are given in Annex A, showing how these NEC provisions should be applied to determine conductor sizing and OCPD rating.

5. Voltage Drop

5.1 General

Voltage drop is an important subject that unfortunately gets little attention in the NEC since it is perceived to be more important to equipment performance than to safety.

Some manufacturers specify the minimum voltage to be supplied to their equipment. This becomes a requirement under NEC 110.3(B). In addition, special precautions must be taken to provide adequate voltage during startup of certain equipment utilizing a large motor. Completely ignored is energy efficiency, which is a major consideration today.

The NEC states in two Informational Notes that a maximum voltage drop of 3% for branch circuit or feeder conductors, and 5% for branch circuit and feeder conductors together, will provide reasonable efficiency of operation for general use circuits. For sensitive electronic equipment operating within its scope, NEC 647.4(D) *requires* that the voltage drop on any branch circuit shall not exceed 1.5%, and that the combined voltage drop of branch circuit and feeder conductors shall not exceed 2.5%. Note, however, that this section does not apply to general-use branch circuits which are often used to supply electronic equipment.

However, under the present California Energy Code, voltage drop not exceeding the 3% and 5% requirements cited above is mandatory for all new construction. Good practice would dictate that the 3%/5% voltage drop rule be observed in most cases.

This publication expands those rules and recommendations, considering conductor sizing, supply voltage, and circuit loading, and the power quality needs of sensitive electronic equipment.

Correct voltage is critical for optimal load operation. Low operating voltage causes some equipment to draw higher than normal load current. For constant wattage loads, load current increases to make up the difference from low voltage to maintain the power output. Consequently, low voltage can cause motors and certain equipment and components to run hotter than normal, and can cause components to fail prematurely. In addition, significant voltage drop across phase and neutral conductors can result in incorrect operation of computers and other sensitive electronic equipment.

Manufacturers of air conditioning and refrigeration equipment, fire pumps, submersible pumps, and many other types of motor-driven equipment specify acceptable ranges of operating voltages. During startup, motors typically draw several times their operating currents. Sizing conductors based only on operating currents may not provide sufficient voltage to allow motors to start. Sensitive electronic equipment is also particularly susceptible to mis-operation or failure if voltage drop is excessive.

Many of these problems can be reduced or eliminated by considering the impact of voltage drop on circuit design. The following sections explain how to calculate voltage drop and provide various techniques to optimize circuit design by limiting voltage drop.

5.2 Calculating Voltage Drop

Current flowing through a conductor with a finite resistance causes a voltage drop over the length of the conductor. Voltage drop can be calculated using a variation of the familiar Ohm's Law (E = IR), as follows:

$$\mathbf{V_D = kIR}$$

Where V_D is the voltage drop across the length of the conductor in volts,
"k" is a constant depending upon whether the system is single-phase or three-phase,
I is the load current flowing through the conductor in amperes, and
R is the direct-current resistance of uncoated copper conductors at 75^{o}C (167^{o}F).

R is calculated by multiplying ohms per 1,000 feet (the value given in Table 5.2 below, which is excerpted from NEC Chapter 9, Table 8) by the one-way circuit length in thousands of feet. For single-phase loads, the constant "k" is 2. For three-phase loads, the constant "k" is the square root of 3, or 1.732.

For simplicity, the examples in this chapter use direct current resistance R values, as shown in Table 5.2 below. For alternating current systems which are found in practice, the values are slightly different, and for loads that are not purely resistive, impedance values Z should be used, taking power factor into consideration. This is covered in NEC Chapter 9, Table 9. Calculations based on impedance are more complicated and beyond the scope of this publication. The reader is referred to the sample calculations accompanying NEC Chapter 9, Table 9 in the 2011 NEC Handbook, as well as to the Institute of Electrical and Electronic Engineers (IEEE) Gray Book.

Table 5.2. NEC Chapter 9, Table 8 (part). Conductor Properties (copper only).

Size (AWG or kcmil)	Area		Conductors							Direct-Current Resistance at 75° C (167° F)			
			Stranding			Overall				Copper			
				Diameter		Diameter		Area		Uncoated		Coated	
	mm^2	Circ mils	Quantity	mm	in.	mm	in.	mm^2	$in.^2$	ohm/km	ohm/kFT	ohm/km	ohm/kFT
18	0.823	1620	1	--	--	1.02	0.040	0.823	0.001	25.5	7.77	26.5	8.08
18	0.823	1620	7	0.39	0.015	1.16	0.046	1.06	0.002	26.1	7.95	27.7	8.45
16	1.31	2580	1	--	--	1.29	0.051	1.31	0.002	16.0	4.89	16.7	5.08
16	1.31	2580	7	0.49	0.019	1.46	0.058	1.68	0.003	16.4	4.89	17.3	5.29
14	2.08	4110	1	--	--	1.63	0.064	2.08	0.003	10.1	3.07	10.4	3.19
14	2.08	4110	7	0.62	0.024	1.85	0.073	2.68	0.004	10.3	3.14	10.7	3.26
12	3.31	6530	1	--	--	2.05	0.081	3.31	0.005	6.34	1.93	6.57	2.01
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	5.261	10380	1	--	--	2.588	0.102	5.26	0.008	3.984	1.21	4.148	1.26
10	5.261	10380	7	0.98	0.038	2.95	0.116	6.76	0.011	4.070	1.24	4.226	1.29
8	8.367	16510	1	--	--	3.264	0.128	8.37	0.013	2.506	0.764	2.579	0.786
8	8.367	16510	7	1.23	0.049	3.71	0.146	10.76	0.017	2.551	0.778	2.653	0.809
6	13.30	26240	7	1.56	0.061	4.67	0.184	17.09	0.027	1.608	0.491	1.671	0.510
4	21.15	41740	7	1.96	0.077	5.89	0.232	27.19	0.042	1.010	0.308	1.053	0.321
3	26.67	52620	7	2.20	0.087	6.60	0.260	34.28	0.053	0.802	0.245	0.833	0.254
2	33.62	66360	7	2.47	0.097	7.42	0.292	43.23	0.067	0.634	0.194	0.661	0.201
1	42.41	83690	19	1.69	0.066	8.43	0.332	55.80	0.087	0.505	0.154	0.524	0.160
1/0	53.49	105600	19	1.89	0.074	9.45	0.372	70.41	0.109	0.399	0.122	0.415	0.127
2/0	67.43	133100	19	2.13	0.084	10.62	0.418	88.74	0.137	0.3170	0.0967	0.329	0.101
3/0	85.01	167800	19	2.39	0.094	11.94	0.470	111.9	0.173	0.2512	0.0766	0.2610	0.0797
4/0	107.2	211600	19	2.68	0.106	13.41	0.528	141.1	0.219	0.1996	0.0608	0.2050	0.0626
250	127	--	37	2.09	0.082	14.62	0.575	168	0.260	0.1687	0.0515	0.1753	0.0535
300	152	--	37	2.29	0.090	16.00	0.630	201	0.312	0.1409	0.0429	0.1463	0.0446
350	177	--	37	2.47	0.097	17.30	0.681	235	0.364	0.1205	0.0367	0.1252	0.0382
400	203	--	37	2.64	0.104	18.49	0.728	268	0.416	0.1053	0.0321	0.1084	0.0331
500	253	--	37	2.95	0.116	20.65	0.813	336	0.519	0.0845	0.0258	0.0869	0.0265
600	304	--	61	2.52	0.099	22.68	0.893	404	0.626	0.0704	0.0214	0.0732	0.0223
700	355	--	61	2.72	0.107	24.49	0.964	471	0.730	0.0603	0.0184	0.0622	0.0189
750	380	--	61	2.82	0.111	25.35	0.998	505	0.782	0.0563	0.0171	0.0579	0.0176
800	405	--	61	2.91	0.114	26.16	1.030	538	0.834	0.0528	0.0161	0.0544	0.0166
900	456	--	61	3.09	0.122	27.79	1.094	606	0.940	0.0470	0.0143	0.0481	0.0147
1000	507	--	61	3.25	0.128	29.26	1.152	673	1.042	0.0423	0.0129	0.0434	0.0132
1250	633	--	91	2.98	0.117	32.74	0.289	842	1.305	0.0388	0.0103	0.0347	0.106
1500	760	--	91	3.26	0.128	35.86	1.412	1011	1.566	0.02814	0.00858	0.02814	0.00883
1750	887	--	127	2.98	0.117	38.76	1.526	1180	1.829	0.02410	0.00735	0.02410	0.00756
2000	1013	--	127	3.19	0.126	41.45	1.632	1349	2.092	0.02109	0.00643	0.02109	0.00662

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5.2.1 Single-Phase Voltage Drop Example. The direct-current resistance of uncoated 4/0 AWG copper conductors is 0.0608 ohms per 1,000 feet, as given by Table 5.2 above. The voltage drop of a circuit with a one-way measurement of 250 feet, comprised of 4/0 AWG copper conductors supplying a 190 ampere, 240 volt single-phase load, is given by:

$$\text{Voltage Drop} = 2 \times 190 \times 0.0608 \times (250/1000) = 5.8 \text{ volts}$$

A voltage drop of 5.8 volts is a 2.4% voltage drop for a 240 volt single-phase circuit.

5.2.2 Three-Phase Voltage Drop Example. The direct-current resistance of uncoated 350 kcmil copper conductors is 0.0367 ohms per 1,000 feet. The voltage drop of a circuit with a one-way measurement of 475 feet, comprised of 350 kcmil copper conductors supplying a 285 ampere, 480 volt three-phase load, is given by:

$$\text{Voltage Drop} = 1.732 \times 285 \times 0.0367 \times (475/1000) = 8.6 \text{ volts}$$

A voltage drop of 8.6 volts is a 1.8% voltage drop for a 480 volt three-phase circuit.

5.2.3 Calculating Maximum Circuit Length. The maximum circuit length (one-way) for a given conductor size and voltage drop is calculated by reorganizing the voltage drop equation and solving for distance:

$$\mathbf{D_{max} = V_D / (k \times I \times R_{PF})}$$

Where D_{max} is the *one-way* distance from source to load; V_D is the maximum allowable voltage drop in volts; "k" is a constant depending upon whether the system is single-phase or three-phase; I is the current in amperes; and R_{PF} is the resistance per foot derived by dividing the values taken from Table 5.2 by 1,000.

The maximum one-way circuit length for 4/0 AWG copper conductors that supply a 190 ampere, 480 volt, three-phase load with a maximum desired voltage drop of 1.5%, or 7.2 volts, is given by:

$$D_{max} = 7.2 / (1.732 \times 190 \times (0.0608/1000)) = 360 \text{ feet}$$

The maximum one-way circuit length for 4/0 AWG copper conductors, the conductors of this circuit not to exceed 1.5% voltage drop, is 360 feet.

5.3 Recommended Practices to Limit Voltage Drop

The NEC states in an Informational Note that a maximum voltage drop of 3% for branch circuit conductors, and 5% for feeder and branch circuit conductors together, will provide reasonable efficiency of operation for general use circuits. For sensitive electronic loads, circuits should be designed for a maximum of 1.5% voltage drop for branch circuits at full load, and 2.5% voltage drop for feeder and branch circuits combined at full load. Four practical approaches can be used to minimize voltage drop problems: increasing the number or size of conductors, reducing the load current on the circuit, decreasing conductor length, and decreasing conductor temperature.

5.3.1 Increase the Number or Size of Conductors. Parallel or oversized conductors have lower resistance per unit length than the Code-required minimum-sized conductors, reducing voltage drop and increasing energy efficiency with lower losses than using the Code-required minimum-sized conductor. In data centers and other sensitive installations, it is not uncommon to find conductor gauges for phase, neutral, and ground exceeding Code minimums, and a separate branch circuit installed for each large or sensitive load. To limit neutral-to-ground voltage drop, install a separate, full-sized neutral conductor for each phase conductor in single-phase branch circuit applications. For three-phase feeder circuits, do not downsize the grounded conductor or neutral. For three-phase circuits where significant non-linear loads are anticipated, it is recommended to install grounded or neutral conductors with at least double the ampacity of each phase conductor.

5.3.2 Decrease Load Current. Limiting the amount of equipment that can be connected to a single circuit will limit the load current on the circuit. Limit the number of receptacles on each branch circuit to three to six. Install individual branch circuits to sensitive electronic loads or loads with a high inrush current. For residential applications, install outdoor receptacles not to exceed 50 linear feet between receptacles, with a minimum of one outdoor receptacle on each side of the house, and with individual branch circuits with a minimum of 12 AWG to each receptacle.

5.3.3 Decrease Conductor Length. Decreasing conductor length reduces the resistance of the conductor, which reduces voltage drop. Circuit lengths are usually fixed, but some control can be exercised at the design stage if panels or subpanels are located as close as possible to the loads, especially for sensitive electronic equipment.

5.3.4 Adjust Conductor Temperature. The conductor temperature is in turn dependent on each of the three factors above, since more heavily loaded circuits will run hotter. Conductor temperature is a major factor in conductor resistance, and therefore in voltage drop. The temperature coefficient of electrical resistance for copper, $\boldsymbol{\alpha}$, is 0.00323/°C, or a resistance change of about 0.3% for each °C of temperature change. The effect of temperature can be determined by the following equation:

$$\mathbf{R_2 = R_1\,[1 + \alpha(T_2 - T_1)]}$$

Where R_1 is the resistance (Ω) at temperature T_1 and R_2 is the resistance at temperature T_2. Temperature T_1 is often referenced at 75°C.

As noted, voltage drop is a particular concern at high conductor loadings, where conductor temperatures will also be high.

5.3.5 Examples. The interactions between conductor sizes, load currents, and conductor lengths at various supply voltages are shown in Table 5.3.5.

The combinations of various load currents – from 8 to 30 amperes – and supply voltages – from 120 to 480 volts – are shown in the left two columns of the table. The next four columns show the maximum circuit lengths (one-way) for four different conductor sizes to attain a 3% voltage drop. The last four columns are maximum lengths for an allowable 1.5% voltage drop.

For example, a 12 ampere load in a 120 volt circuit on a 14 AWG conductor will exceed a 3% voltage drop (3.6 volts) if the circuit is longer than 49 feet from source to load. If the conductor is upsized to 12 AWG the allowable distance increases significantly to 78 feet each way (an increase of 59%). If the load is increased to an allowable maximum of 15 amps for 14 AWG conductor, the allowable length is only 39 feet, and moving to a 12 AWG conductor would increase this to 62 feet (also an increase in length of 59%).

The 1.5% data values are given for situations when it is necessary to comply with NEC 647.4(D). Verify the equipment's actual requirements whenever possible. The much tighter 1.5% voltage drop allowance on the right side of Table 5.3.5 cuts the allowable lengths to only 1/2 of their values at 3% voltage drop. Conductor upsizing is often mandated for the protection of sensitive electronic equipment. Voltage drop can be minimized if the panel or subpanel can be located as close as possible to the point of use.

Another measure is to install sufficient circuits to avoid high current levels on any one circuit. Where loads can be split onto separate circuits, the reduced load per circuit will enhance quality and reliability.

Perusal of Table 5.3.5 inevitably leads to the conclusion that voltage drop is too often ignored. For example, the lengths of many branch circuits in 14 AWG wire exceed even the 3% voltage drop of 39 feet, not to mention the tighter 1.5% drop of 20 feet. When this happens, the integrity of both the wiring and of many loads is put in jeopardy.

Table 5.3.5. Maximum Recommended Lengths [1] of Single-Phase Branch Circuits, as a Function of Load Current, Supply Voltage, and Conductor Size, for Both 3% and 1.5% Voltage Drops. [2,3]

Load Current	Supply Voltage	Maximum One-Way Circuit Length for **3%** Voltage Drop for Copper Conductors				Maximum One-Way Circuit Length for **1.5%** Voltage Drop for Copper Conductors			
amperes	volts	feet [1]				feet [1]			
		14 AWG	12 AWG	10 AWG	8 AWG	14 AWG	12 AWG	10 AWG	8 AWG
		solid	solid	solid	stranded	solid	solid	solid	stranded
8	120	73	117	186	289	37	58	93	145
	208	127	202	322	501	64	101	161	251
	240	147	233	372	578	73	117	186	289
	277	169	269	429	668	85	135	215	334
	480	293	466	744	1,157	147	233	372	578
12	120	49	78	124	193	24	39	62	96
	208	85	135	215	334	42	67	107	167
	240	98	155	248	386	49	78	124	193
	277	113	179	286	445	56	90	143	223
	480	195	311	496	771	98	155	248	386
15	120	39	62	99	154	20	31	50	77
	208	68	108	172	267	34	54	86	134
	240	78	124	198	308	39	62	99	154
	277	90	144	229	356	45	72	114	178
	480	156	249	397	617	78	124	198	308
20	120	—	47	74	116	—	23	37	58
	208	—	81	129	201	—	40	64	100
	240	—	93	149	231	—	47	74	116
	277	—	108	172	267	—	54	86	134
	480	—	187	298	463	—	93	149	231
30	120	—	—	50	77	—	—	25	39
	208	—	—	86	134	—	—	43	67
	240	—	—	99	154	—	—	50	77
	277	—	—	114	178	—	—	57	89
	480	—	—	198	308	—	—	99	154

- Branch circuit lengths shown in the table are *half* the calculated distance from the V = IR Ohm's Law formula, rounded to the nearest 1-foot increment. For example, the calculated value for 14 AWG at a load current of 15 amps and a supplied voltage of 120 volts using the value of 3.07 Ω/1,000 feet for a 3% drop (or 3.6 volts) is 78 feet. Since the conductors must carry the current over and back, the allowable one-way distance from source to load is 39 feet.
- For convenient use of the NEC tables, loads are assumed to be purely resistive, direct-current loads. Alternating current values differ only slightly. Harmonics or inductive loads may accentuate voltage drop, and decrease recommended circuit lengths.
- Calculations are based on resistance values found in NEC Chapter 9, Table 8 for solid, uncoated copper conductors. For 14 AWG, the resistance is 3.07 Ω/1,000 feet, for 12 AWG it is 1.93 Ω/1,000 feet, for 10 AWG it is 1.21 Ω/1,000 feet, and for 8 AWG (stranded) it is 0.778 Ω/1,000 feet. Conductor temperatures higher than 75°C (167°F) will increase these resistances, and vice versa.

6. Conductors for Grounding

The grounding (connecting to earth) and bonding of conductive, but normally non-current-carrying, components of a building's electrical distribution system, and the user equipment that attaches to it, is of vital importance. NEC Article 250 gives the subject major attention.

Lightning protection is beyond the scope of this publication. Details can be found in NFPA 780: *Standard for the Installation of Lightning Protection Systems*.

Conductors used in the grounding system may be divided into three parts:

- Equipment grounding conductors,
- Grounding electrode conductors, and
- Grounding electrodes.

6.1 Equipment Grounding Conductors

Equipment grounding conductors can consist of the wire type or one or more of the wiring methods shown in NEC 250.118.

As stated in the Informational Note 1 to the definition of equipment grounding conductor in NEC Article 100, the equipment grounding conductor also connects equipment together and thus performs a bonding function. This bonding function reduces shock hazard when sized and connected properly.

Equipment grounding conductors must be adequately sized to carry fault currents from the frame or other energized metallic component of an item of user equipment back to the grounding terminal of the service equipment, typically a main panel. This will allow an overcurrent device to operate, clearing the fault and cutting off power to that circuit. The fault may also arise in the wiring system itself, such as an insulation failure allowing an ungrounded conductor to touch the equipment grounding conductor.

Many small appliances utilize a double-insulation system to help prevent shock hazard, in which case the equipment grounding conductor is not used. Most heavy-duty appliances, tools, and equipment, whether cord-connected or hard-wired, require an equipment grounding provision. These devices should be connected to an equipment grounding conductor or to a grounded, three-prong receptacle.

Rules for sizing copper equipment grounding conductors are shown as Table 6.1, taken from NEC Table 250.122. The table shows that, for smaller ampere ratings, 15, 20, and 30 ampere circuits, the equipment grounding conductor must be the same size as the circuit conductors (14 AWG, 12 AWG, and 10 AWG, respectively). For circuits with protection above 30 amps, equipment grounding conductors may be downsized according to the provisions in Table 6.1. Keep in mind, however, that the Table assumes that the overcurrent device operates as designed so as to limit the current (thus heating) imposed on the grounding conductor. Consider installing a full-size grounding conductor at least equal in size to the phase conductor.

In some cases, such as when voltage drop considerations require larger circuit conductors, the size of the equipment grounding conductors must be increased as well. This increase cannot be read directly from the table, but must be calculated on the basis of percentage increase in cross-sectional area of the ungrounded conductors.

Table 6.1. NEC Table 250.122 (part). Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment (copper only).

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size (AWG or kcmil)
15	14
20	12
60	10
100	8
200	6
300	4
400	3
500	2
600	1
800	1/0
1000	2/0
1200	3/0
1600	4/0
2000	250
2500	350
3000	400
4000	500
5000	700
6000	800

Note: Where necessary to comply with 250.4(A)(5) or (B)(4), the equipment grounding conductor shall be sized larger than given in this table.

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6.2 Grounding Electrode Conductors

Typically, the equipment grounding conductors and the system grounded conductors are connected together and end at the main service panel. The grounding electrode conductor(s) carry the connection from that point to one or more grounding electrodes. Bonding conductors or jumpers are used to connect grounding electrodes together to create a grounding electrode system. They may connect the building frame to a ground rod, a panelboard cabinet to a ground ring, a metal water pipe to a concrete-encased electrode, a down conductor of a lightning-protection system to a plate electrode, etc.

The most important aspect is that all the components of the grounding system must be tied together with low-impedance grounding electrode conductors so that "ground" is at one single potential. Not only is this a safety consideration to reduce the risk of shock, but has become increasingly important, for instance, as manufacturing, medical, and myriad other pieces of equipment are computer-controlled and must "talk" to one another. Without a common reference ground for the building or cluster of buildings, many problems can result. It is suggested, for lightning protection equipment, that building steel, down conductors, and grounding connections occur at the lowest point in the building, typically a basement.

Table 6.2, derived from NEC Table 250.66, shows the relationship between the size (or equivalent size) of the ungrounded service-entrance conductors and the required size of grounding electrode conductors. In certain situations some components of the grounding electrode conductor system, such as certain bonding jumpers, may not be required to be sized according to Table 6.2 (see NEC 250.66 Exceptions).

6.3 Grounding Electrodes

Grounding electrodes provide the connection point from the grounding system or equipment to the earth. Several types of grounding electrodes are recognized in NEC 250.52:

- Metal underground water pipes;
- Metal frame of the building or structure;
- Concrete-encased electrodes;
- Ground ring;
- Rod and pipe electrodes;
- Other listed electrodes;
- Plate electrodes; and
- Other local underground systems or structures.

Not permitted are metal underground gas piping systems and aluminum grounding electrodes.

Table 6.2. NEC Table 250.66 (part). Grounding Electrode Conductor for Alternating-Current Systems (copper only).

Size of Largest Ungrounded Service-Entrance Conductor or Equivalent Area for Parallel Conductors [a] (AWG/kcmil)		Size of Grounding Electrode Conductor (AWG/kcmil)
Copper	Aluminum or Copper-Clad Aluminum	Copper
2 or smaller	1/0 or smaller	8
1 or 1/0	2/0 or 3/0	6
2/0 or 3/0	4/0 or 250	4
Over 3/0 through 350	Over 250 through 500	2
Over 350 through 600	Over 500 through 900	1/0
Over 600 through 1100	Over 900 through 1750	2/0
Over 1100	Over 1750	3/0

Notes:

- Where multiple sets of service-entrance conductors are used as permitted in 230.40, Exception No. 2, the equivalent size of the largest service-entrance conductor shall be determined by the largest sum of the areas of the corresponding conductors of each set.
- Where there are no service-entrance conductors, the grounding electrode conductor size shall be determined by the equivalent size of the largest service-entrance conductor required for the load to be served.

[a] This table also applies to the derived conductors of separately derived ac systems.

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As a Code minimum, a single rod, pipe, or plate electrode is considered sufficient if it has a resistance to ground less than or equal to 25 ohms; otherwise, a supplemental electrode must be provided at a distance of at least six feet and must be bonded to the first electrode. This minimum requirement is not considered good practice. The Code, for example, does not require that a particular resistance be achieved. Many electronic applications stipulate a resistance to ground of 2 ohms or less. Per the IEEE Green Book, 5 ohms or less is considered adequate for most industrial applications.

Additionally, vertical or single element grounding electrodes should be placed a minimum of two times the length of each electrode apart, to minimize overlapping “spheres of influence.” For example, two 8-foot ground rods should be placed a minimum of 16 feet apart, if real estate permits.

Grounding electrode conductors are connected to electrodes using either exothermic welding, listed lugs, listed pressure connectors, listed clamps, or other listed means, as discussed in NEC 250.70. If the connection is to be buried or encased in concrete, the listing must cover this condition. Copper conductors are the best choice to be used in concrete or in direct contact with earth, or where exposed to the elements. This does not apply to Copper-clad or Aluminum conductors. Per 2011 NEC

250.64 Grounding Electrode Conductor Installation.
Grounding electrode conductors shall be installed as specified in 250.64(A) through (F).
(A) Aluminum or Copper-Clad Aluminum Conductors.
Bare aluminum or copper-clad aluminum grounding conductors shall not be used where in **direct contact with masonry or the earth** or where subject to corrosive conditions. Where used outside, aluminum or copper-clad aluminum grounding conductors shall not be terminated within 450 mm (18 in.) of the earth.

7. Power Quality Basics

Power quality concerns have traditionally focused on harmonics, which are generated by nonlinear loads, although there are many other concerns regarding isolating sensitive loads from transient disturbances, uneven ground potentials, or phase imbalances. Poor power quality affects the reliable operation of computers and computer-based equipment, which are now ubiquitous, plus standard equipment such as motors. Sometimes poor power quality can be a safety issue. The power quality issues found here, and others, are discussed in more detail in the articles and case histories found on www.copper.org.

Nonlinear loads are those wherein the current waveform is not in proportion to the operating voltage waveform, with or without a shift in phase angle. Nonlinear loads are typically created by electronic switching power supplies, such as those found in computers, copiers, printers, electronic lighting ballasts, uninterruptible power supplies, adjustable speed drives, medical equipment, telecommunications equipment, entertainment equipment, etc. Many times, the equipment that causes poor power quality is also susceptible to malfunction from poor power quality.

Nonlinear loads can cause elevated operating temperatures in phase and neutral conductors. Overloaded conductors overheat which degrades their insulation and shortens their life expectancy. Shared or downsized neutral conductors are particularly susceptible to overheating from triplen harmonics. Triplen harmonics are harmonics that are odd integer multiples of the third harmonic of the 60 Hz fundamental frequency, including the third harmonic itself (180 Hz), the ninth harmonic (540 Hz), the fifteenth harmonic (900 Hz), etc. In Wye-connected three-phase systems, triplen harmonic waveforms are in phase, do not cancel in the neutral conductor, and are arithmetically additive.

In cases where the effects of poor power quality are encountered in an existing facility, a careful study is recommended to determine the best course of action. Implementing the recommended building wiring practices of this publication at the time of installation can minimize the effect of poor power quality on equipment operation.

7.1 Recommended Practices for Power Quality

7.1.1 Dedicated Branch Circuits. Install individual branch circuits for sensitive electronic loads, such as laser printers, photocopiers, facsimile machines, individual computer workstations, etc. Individual branch circuits help shield sensitive equipment from harmonics, noise, and transients generated in other circuits, and prevent the malfunction of other equipment on the same branch circuit.

7.1.2 Dedicated Panelboards. In addition to individual branch circuits, supply sensitive electronic equipment from dedicated panelboards separate from other loads such as motors and lighting. Install separate, dedicated panelboards and feeders from the service entrance to supply the segregated loads. Segregating loads shields equipment from voltage disturbances such as those resulting from starting large electric motors. By segregating sensitive electronic loads, harmonics can be trapped at or near the dedicated panel by use of appropriate filtering transformers or harmonic filters.

7.1.3 Feeder and Branch Circuit Conductors. In locations where power quality is or could be critical, install larger phase conductors than would otherwise be necessary in order to safely handle harmonic loads, to minimize voltage drop, to minimize heating from the skin effect when supplying higher frequency nonlinear loads, and to improve efficiency. Do not reduce the size of the neutral conductors even when permitted by the NEC. For Wye-connected three-phase, four-wire feeder circuits, install larger neutral conductors than Code-minimum, preferably with 200% of the ampacity of the phase conductors.

Do not install multi-wire branch circuits with a common neutral conductor. Install a separate, full-sized neutral conductor for each phase conductor.

7.1.4 Number of Receptacles per Circuit. Although the NEC allows up to 13 general-purpose receptacles supplying non-continuous loads on a 20-ampere branch circuit in nonresidential construction, and an unlimited number of general-purpose receptacles on a branch circuit in residential construction, this is not a prudent practice.

Installation of not more than three to six receptacles per branch circuit and in some cases fewer, depending upon the types of loads served, is recommended. Limiting the number of receptacles installed on a single circuit will restrict the number and variety of sensitive electronic equipment sharing circuit conductors, reduce the possibility that harmonics will accumulate to damaging levels, minimize voltage drop, minimize the chance of interaction, and provide for future load growth.

7.1.5 Electromagnetic Interference. Properly grounded metal-clad cables, shielded cables, or metal conduits provide electromagnetic shielding and minimize interference for circuits that serve sensitive electronic equipment. Many design techniques can be employed but are beyond the scope of this publication.

7.1.6 Non-Linear Panelboards. Install panelboards that are suitable for non-linear loads to supply sensitive electronic loads. Such panelboards typically have double-capacity neutral buses to allow for individual neutral conductors for each phase conductor and double-capacity neutral lugs for the panelboard feeder.

8. Grounding and Bonding

Grounding and bonding are the basis upon which safety and power quality are built. The grounding system provides a low-impedance path for fault current and limits the voltage rise on the normally non-current-carrying metallic components of the electrical distribution system. During fault conditions, low impedance results in high fault current flow, causing overcurrent protective devices to operate, clearing the fault quickly and safely. The grounding system also allows transients such as lightning to be safely diverted to earth.

Bonding is the intentional joining of normally non-current-carrying metallic components to form an electrically conductive path. This helps ensure that these metallic components are at the same potential, limiting potentially dangerous voltage differences. See the IEEE Emerald Book, page 5, for definitions. Careful consideration should be given to installing a grounding system that exceeds the minimum NEC requirements for improved safety and power quality.

8.1 Recommended Practices for Grounding

8.1.1 Equipment Grounding Conductors. The IEEE Emerald Book recommends the use of equipment-grounding conductors in all circuits, not relying on a raceway system alone for equipment grounding. Use equipment grounding conductors sized equal to the phase conductors to decrease circuit impedance and improve the clearing time of overcurrent protective devices.

Bond all metal enclosures, raceways, boxes, and equipment grounding conductors into one electrically continuous system. Consider the installation of an equipment grounding conductor of the wire type as a supplement to a conduit-only equipment grounding conductor for especially sensitive equipment. The minimum size the equipment grounding conductor for safety is provided in NEC 250.122, but a full-size grounding conductor is recommended for power quality considerations.

8.1.2 Isolated Grounding System. As permitted by NEC 250.146(D) and NEC 408.40 Exception, consider installing an isolated grounding system to provide a clean signal reference for the proper operation of sensitive electronic equipment.

Isolated grounding is a technique that attempts to reduce the chances of “noise” entering the sensitive equipment through the equipment grounding conductor. The grounding pin is not electrically connected to the device yoke, and, so, not connected to the metallic outlet box. It is therefore “isolated” from the green wire ground. A separate conductor, green with a yellow stripe, is run to the panelboard with the rest of the circuit conductors, but it is usually not connected to the metallic enclosure. Instead it is insulated from the enclosure, and run all the way through to the ground bus of the service equipment or the ground connection of a separately derived system. Isolated grounding systems sometimes eliminate ground loop circulating currents.

Note that the NEC prefers the term *isolated ground*, while the IEEE prefers the term *insulated ground*.

8.1.3 Branch–Circuit Grounding. Replace branch circuits that do not contain an equipment ground with branch circuits with an equipment ground. Sensitive electronic equipment, such as computers and computer-controlled equipment, require the reference to ground provided by an equipment grounding conductor for proper operation and for protection from static electricity and power surges. Failure to utilize an equipment grounding conductor may cause current flow through low-voltage control or communication circuits, which are susceptible to malfunction and damage, or the earth.

Surge Protection Devices (SPDs) *must* have connection to an equipment grounding conductor.

8.1.4 Ground Resistance. Measure the resistance of the grounding electrode system to ground. Take reasonable measures to ensure that the resistance to ground is 25 ohms or less for typical loads. In many industrial cases, particularly where electronic loads are present, there are requirements which need values as low as 5 ohms or less many times as low as 1 ohm. For these special cases, establish a maintenance program for sensitive electronic loads to measure ground resistance semi-annually, initially, using a ground resistance meter. Ground resistance should be measured at least annually thereafter. When conducting these measurements, appropriate safety precautions should be taken to reduce the risk of electrical shock. Record the results for future reference. Investigate significant changes in ground resistance measurements compared with historical data, and correct deficiencies with the grounding system. Consult an electrical design professional for recommendations to reduce ground resistance where required.

8.1.5 Ground Rods. The NEC permits ground rods to be spaced as little as 6 feet apart, but spheres-of-influence of the rods overlap. Recommended practice is to space multiple ground rods a minimum of twice the length of the rod apart. Install deep-driven or chemically-enhanced ground rods in mountainous or rocky terrain, and where soil conditions are poor. Detailed design of grounding systems are beyond the scope of this document.

8.1.6 Ground Ring. In some cases, it may be advisable to install a copper ground ring, supplemented by driven ground rods, for new commercial and industrial construction in addition to metal water piping, structural building steel, and concrete-encased electrodes, as required by Code. Grounding rings provide a convenient place to bond multiple electrodes of a grounding system, such as multiple Ufer grounds, lightning down-conductors, multiple vertical electrodes, etc. Install ground rings completely around buildings and structures and below the frost line in a trench offset a few feet from the footprint of the building or structure. Where low, ground impedance is essential, supplement the ground ring with driven ground rods in a triplex configuration at each corner of the building or structure, and at the mid-point of each side. The NEC-minimum conductor size for a ground ring is 2 AWG, but sizes as large as 500 kcmil are more frequently used. The larger the conductor and the longer the conductor, the more surface area is in contact with the earth, and the lower the resistance to earth.

8.1.7 Grounding Electrode System. Bond all grounding electrodes that are present, including metal underground water piping, structural building steel, concrete-encased electrodes, pipe and rod electrodes, plate electrodes, and the ground ring and all underground metal piping systems that cross the ground ring, to the grounding electrode system. Bond the grounding electrodes of separate buildings in a campus environment together to create one grounding electrode system. Bond all electrical systems, such as power, cable television, satellite television, and telephone systems, to the grounding electrode system. Bond outdoor metallic structures, such as antennas, radio towers, etc. to the grounding electrode system. Bond lightning protection down-conductors to the grounding electrode system.

8.1.8 Lightning Protection System. Copper lightning protection systems may be superior to other metals in both corrosion and maintenance factors. NFPA 780 (Standard for the Installation of Lightning Protection Systems) should be considered as a minimum design standard. A lightning protection system should only be connected to a high quality, low impedance, and robust grounding electrode system.

8.1.9 Surge Protection Devices (SPD) (formerly called *TVSS*). The use of surge protection devices is highly recommended. Consult IEEE Standard 1100 (The Emerald Book) for design considerations. A surge protection system should only be connected to a high quality, low impedance, and robust grounding electrode system.

Generally, a surge protection device should not be installed downstream from an uninterruptible power supply (UPS). Consult manufacturers' guidelines.

A good source of further information on these and additional techniques is the CD-ROM "Power Quality". See the website *www.copper.org/pq* for ordering information.

9. Future Electrical Capacity

Electrical wiring is often installed without consideration for how the use of the space may change over time, particularly in residential construction. This publication recommends wiring practices that meet the NEC and provide for future flexibility and load growth in residential and nonresidential construction.

9.1 Circuit Conductors

Several measures will improve the performance of circuit conductors:

- Install oversized phase conductors to improve efficiency when conductors will see long-term, near-capacity use, and to minimize heating from the skin effect when supplying nonlinear loads.
- Install oversized or, preferably, double-sized neutral conductors with 200% of the ampacity of the phase conductors for three-phase, four-wire feeder circuits when it is anticipated that significant nonlinear loads will be served, now or in the future.
- Install a separate, full-sized neutral conductor for each phase conductor for 120-volt and 277-volt single-phase branch circuits when they supply or probably will supply significant nonlinear loads.

For general-purpose residential circuits, install a minimum of 12 AWG conductors, protected by 20-amp circuit breakers, but designed with 15 ampere load standards to accommodate future load growth.

Most service-entrance and feeder conductors for residential use are adequately sized due to the diversity of the loads served.

9.2 Number of Receptacles

The general requirement of the Code is that no point on a residential wall should be more than six horizontal feet from a receptacle to accommodate the average length of extension cords and lamp cords. In areas such as kitchen countertops, no point may be more than two horizontal feet from a receptacle. This means that receptacle outlets are usually located twelve feet or four feet apart.

This spacing of receptacles may be inconvenient or inadequate in many situations, since it is difficult to anticipate how furniture will be arranged when the building is built, and certainly in the future as room usage changes. In addition, the number of available outlets at those locations may be inadequate as evidenced by the number of outlet power strips that are often used today for final connections of equipment. Quadplex receptacles should be used in locations with a known high concentration of loads, such as offices, computer workstations, and home theater and entertainment centers.

Limiting the number of receptacles installed on a single circuit will restrict the number and variety of sensitive electronic equipment sharing circuit conductors, reduce the possibility that harmonics will accumulate to damaging levels, minimize voltage drop, minimize the chance of interaction, and provide for future load growth.

It is recommended that connections be made with binding screws or pressure plates contained in high-quality wiring devices, such as those of specification grade. Push-in connections are not recommended.

9.3 Number of Circuits

For nonresidential construction, limiting the number of receptacles installed per circuit helps protect the integrity of sensitive electronic equipment and provides additional capacity per receptacle for future load growth.

For residential construction, the number of receptacles per circuit is unrestricted per Code. However, it is good practice to install a limited number of duplex receptacles on a general-purpose branch circuit, depending on the location. Homes with large kitchens and multiple bathrooms need additional circuits beyond Code minimums for the high-capacity appliances routinely used in these rooms.

Consider limiting the number of general use receptacles on each circuit. A fifteen amp circuit is capable of 1800 Volt Amps at 100 % use, but NEC allows the use of the circuit at 80% for continuous use, or 1440 Volt Amps. Even a small electric space heater uses between 900 and 1500 Volt Amps. Any additional loads connected to a receptacle on the same circuit would be likely to cause an overload condition.

Reducing the number of receptacles on individual branch circuits to four to six helps to reduce the risk of sustained overload resulting in overheating of conductor terminations.

Install lighting outlets on separate circuits from receptacle outlets. When lighting and receptacle outlets are connected on the same circuit, an overloaded receptacle would cause the lighting to go out when the circuit breaker trips.

9.4 Individual Branch Circuits

Whether in a residential or nonresidential setting, a significant number of circuits are dedicated to one use for many reasons, and some are required by the NEC. It is recommended that high-capacity loads, sensitive electronic equipment, and equipment that causes poor power quality be supplied by individual circuits to prevent interference with other equipment on the same circuit.

Install individual branch circuits for sensitive electronic loads, when the location is known, for items such as individual computer workstations, laser printers, photocopiers, facsimile machines, etc. Individual branch circuits help shield sensitive equipment from harmonics generated in other circuits, prevent the incorrect operation of other equipment on the same branch circuit by isolating high neutral currents generated by sensitive electronic equipment to those circuits, and minimize voltage drop.

9.5 Raceways

Raceway systems provide the ability to upgrade conductors easily, providing the pathway for pulling conductors throughout a building. Size raceways that serve general-purpose circuits for future expansion. Install spare raceways during construction for future use and ease of conductor installation later.

9.6 Lighting and Switching

Lighting and switching provide several opportunities to plan for the future in residential and nonresidential construction. Provide several levels of switching for lighting. Separately switch luminaires, lamps, or ballasts to provide different levels of lighting. Provide switching at both ends of halls, stairways, large rooms, and of garages with multiple doors.

Provide switched receptacle outlets or split receptacles with switching in addition to switched lighting outlets in the same room. As an example, it would be convenient to provide separate switching for ceiling fans and plug-in lamps.

Provide for outdoor lighting, including installing switch-controlled holiday lighting receptacles in the eaves; receptacles on each side of the home; multiple receptacles in patios, decks and other areas where people congregate; and additional circuit extensions for future outdoor lighting for landscaping and other purposes.

Electronic lighting-control devices, such as motion detectors, are increasingly common. Most require a small standby current to maintain the steady state. *Effective with the 2011 Code, NEC 404.2(C) requires that, in most cases, a neutral conductor must be provided to lighting switchboxes to accommodate a return current, even when the original installation does not use electronic switching.*

10. Electrical System Cost and Efficiency

Electrical system efficiency is primarily related to the equipment connected to the electrical distribution system, particularly the efficiency of motors and transformers, which are beyond the scope of this standard. However, all the components of the distribution system, including the electrical conductors are important and must be considered.

Many of the recommendations elsewhere in this publication, such as in the voltage drop section, result in heavier-gage wiring and equipment based on operation and safety of circuits and equipment; It must be noted that these increases are usually more energy efficient and less costly overall.

The National Electrical Code®, is designed only to provide minimum levels of safety. Cost and energy efficiency are not a consideration.

When Conductors are increased in size electrical resistance and the resulting I^2R heat losses are lower. As the cross-section of the copper conductor increases, R decreases and so do heat losses, assuming a constant current. Energy efficiency can often be added to the benefits of these measures at no extra cost, but its value should be taken into account in justifying these extra measures.

Designing for overall cost and energy efficiency is always a balance between the extra initial cost of heavier gage copper and the lifetime energy savings that will result. Generally, applications that offer the most favorable results are those that require heavy loads for a significant percentage of the day, and in which there is a significant length of conductor supplying the load.

When calculations are completed, the additional cost of such increases may well show a shorter payback period due to reductions in I^2R losses.

Energy losses may be referred to as “voltage drop (VD),” “voltage loss,” “impedance,” “electrical conductor heating losses,” “I^2R loss,” “line loss” or simply as electrical energy loss. By any name, inefficiency is waste. The financial impact can be startlingly enormous.
All types of electrical wiring systems have these losses, and losses exist in all portions of power generation, transmission, distribution and load-side wiring.

Voltage drop represents most of the waste in our entire electrical infrastructure.

Simple upsizing of electrical conductors is one solution while limiting circuit length is also possible. In retrofit situations copper conductors sized relative to aluminum can be retrofitted into conduits which were originally large to house aluminum conductors to reduce the voltage drop.

There are increased initial costs associated with sizing conductors to reduce energy losses, but these costs can often be justified financially. A five-year return, or less, on investment is generally desirable for any energy saving scenario. The typical return for upsizing is usually less.

Unfortunately, it's not easy to retrofit or rewire a building after it's constructed, so prospective purchasers or lessees should have a reasonable understanding of the building's electrical design. Efficiency decisions will affect the lifetime operating cost of the building.

Higher efficiency means less heat is generated by the conductors, which results in reduced spending for fans and air conditioning systems.

As calculations will show, increasing a given conductor by one incremental size, not only increases energy efficiency by reducing I^2R heat losses, but reduces the lifetime cost of the installation.

Key elements that affect the economic incentive to install larger wire gauges, are the duty cycle, load factor and electricity price. When using the same size conduit, the increased cost of wire is minimal.

Examples A**, B, C,** and **D**) demonstrate the payback for upsizing, which can be quite short (often, less than two years), even in single-phase lighting circuits, or in one for two-shift commercial settings.

A simple way to understand the impact of wire size on energy efficiency and costs is to examine the numbers in these examples where just one wire size above Code minimum is installed.

10.1 Examples:

Voltage Drop

$$\frac{2 \cdot K \cdot I \cdot L}{CM} = VD$$

Where:

K = Resistance per foot of wire x CM area at a given temperature
(Values may be found in Table 8, NEC®)
I = Amperes
L = Length of run to load
CM = Circular mils
VD = Voltage drop for single-phase circuits

Source: National Electrical Code, 2011

Using the above formula from the NEC®, let's look at a couple of examples of voltage drop situations and what dramatic effect a simple upsizing of a circuit's conductors can have. Remember, voltage can never fall below the minimum requirements of the manufacturer. What we do here is further assurance against coming too close to that threshold.

10.1.1 Example A. The voltage drop from a 120 V room air-conditioner circuit 70 ft from the supply with a 9 A load, would be 3.86 V or 3.2%. Increasing to a 12 AWG conductor would reduce the voltage drop to 2.4 V or 2.0%.

The retail cost of 14-2 NMB cable is $0.165 per ft x 70 ft = $11.55; a 12-2 NMB cable is $0.253 per ft x 70 ft = $17.71.* To determine the cost increase, we subtract the cost of the 14 gauge from the 12 gauge and get $6.16.

The 2.40 V in **Example A** is subtracted from 3.86 V, leaving 1.46 V; 1.46 V x 9 A = 13.14 W. Assuming the circuit is on 10 hours per day, 120 days per year, this would result in 15.77 kWh of lost energy per year.

Using the U.S. average residential power rate, $0.1314, the payback is $0.1314 x 15.77 kWh = $2.07 per year; and for the South Atlantic area, $0.1083 x 15.77 = $1.70. In the worst case, the additional $6.16 investment would be returned in around 3.6 years.

10.1.2 Example B. A retail center parking lot circuit consists of 8-400 W metal halide lamps (460 W ballasts) on 30 ft. tall poles. The circuit length is 200 ft. to the farthest pole. The circuit load is 15.3 A (8 x 460 W/240 V). At 240 V using 10 AWG solid copper, the voltage drop is 8.5 V or 3.5%. If we use 8 AWG wire, the voltage drop is 5.34 V at 2.3%.

Power Cost, $/kWh (2013)

	Pacific Contiguous	Mid-Atlantic	South Atlantic	East N. Central	New England	U.S. Average
Residential	0.14.94	0.16.48	0.11.81	0.12.05	0.1740	0.12.52
Commercial	0.14.05	0.13.86	0.09.48	0.0949	0.14.31	0.10.59

Source: Energy Information Administration, U.S. DoE, Sep. 2013.

In **Example B**, the cost difference between 10 AWG and 8 AWG is $0.10 per ft. Assuming the conduit size remains the same: 230 ft. (200 ft. run plus 30 ft. pole height) x 2 x $0.10 = a $46.00 increase in cost.

The 5.34 V in **Example B** is subtracted from 8.5 V leaving 3.16 V. 3.16 V x 15.3 Amps = 48.34 W. Assuming the lighting is on 8 hours per day, 365 days per year, 48.34 W x 8 hrs. x 365 days = 141.15 kWh lost per year. The one-year recovery using the U.S. average commercial rate of $0.1059/kWh would be $14.97; while in New England, the one-year recovery would be $20.20. The national average payoff, for increasing one wire size, is less than three years, and the New England payoff is just over two years.

What's more, after the initial investment is recaptured, the savings paybacks continue year after year for the life of the circuit.

Note: We are assuming a unity power factor and, therefore, using watts (W) instead of volt-amps (VA) in the above examples.

11.1.4 Example C. The same I^2R savings and short paybacks apply to single-phase systems also. Take the case of a single-phase, 15 A lighting load operating 5,000 hours per year (roughly 14 hours a day). To simplify, assume the load is concentrated 100 ft from the panel.

	#12 AWG	**#10 AWG**
Conduit Size	1/2 in	1/2 in
Estimated Loss (15 A load, 75°C conductor temp.)	89 W	54 W
Wire Cost (ground wire size not increased)	$27.00	$39.00
Conduit Cost (EMT)	$32.35	$32.35
Incremental Cost		$12.00
Energy Savings		175 kWh/year
Dollar Savings at $0.18 per kWh, Payback period		$31.50/year, 3.2 months
Dollar Savings at $0.11 per kWh, Payback period		$19.25/year, 7 months

11.1.5 Example D. Even when larger conduit is required, there may be a reasonable payback for wire upsizing. Consider the case of a wye-connected, three-phase 40 A lighting load operating only 4,000 hours per year. To simplify, assume the load is concentrated 200 ft. from the load center. In this example, a total of 5 conductors are used in a rigid metal conduit: three phase conductors, and full-size neutral and ground conductors.

	#8 AWG	**#6 AWG**
Conduit Size	3/4 in	1 in
Estimated Loss (100% load, 75°C conductor temp.)	423 W	272 W
Wire Cost	$193	$286
Conduit Cost (IMC)	$235	$297
Incremental Cost		$155
Energy Savings		604 kWh/year
Dollar Savings at $0.18 per kWh, Payback period		$108.7/year, 1.4 years
Dollar Savings at $0.11 per kWh, Payback period		$66.44/year, 2.3 years

(*) *Wire and conduit costs in the above examples are based on those found at a large Nevada retailer in Nov 2013.*

11. Installing Copper Building Wire

Install cables and conductors in accordance with manufacturer recommendations and instructions, and in accordance with the NEC.

The long-term functional success of wiring requires proper installation techniques, preparation, connectors, tools, and long-term inspection, with rare maintenance.

Unlike other materials promoted for use as building wire, copper building wire does not require special preparation (joint compounds, wire brushing or tightening procedures), installation techniques, connectors, tools or special long-term maintenance programs.

Although copper is heavier than other wiring materials it reacts to heat better and is more compact allowing installation in smaller spaces. Often, smaller raceway can be used.

Copper is also more “forgiving” if installation isn’t done exactly right. Maintenance can be much less costly. Periodic retightening is generally not necessary.

11.1 Environmental Considerations

Wiring methods, raceways, fittings, boxes, supports, support hardware, accessories, etc., must be suitable and approved for the environment in which they are installed. Install conductors and cables listed for the installed environment, such as ducts, plenums, wet locations or sunlight resistant, and approved for the application.

11.2 Raceways

Install raceways to protect conductors and cables where they are exposed to physical damage or conditions that are destructive and corrosive. Prior to installing conductors and cables:

- Verify that raceway installation is complete and ready to receive conductors and cables before installing them.

- Verify that raceways are properly sized in accordance with the NEC. Keep in mind that raceways sized larger than the Code-required minimum can make pulling conductors and cables easier, and can allow space for expansion in the future.

- Visually inspect exposed raceways to ensure that the raceways are not flattened around the bends. Replace flattened sections of raceways to ensure adequate cross-sectional area to install conductors in accordance with the NEC fill requirements.

- Verify that raceways do not exceed the maximum number of bends between pull-points.

11.2.1 Bending Radii. Handle conductors and cables carefully. Make bends in cables and conductors such that cables, conductors, sheaths, armor, etc., are not damaged. Do not bend conductors and cables to less than the NEC and manufacturer recommended minimum bending radii. Inspect raceway bends to ensure that the bending radius is not less than the minimum required for conductors and cables. Inspect raceways, cables, conductors, jacketing, sheathing, and protective coverings, etc., for damage from excessive bending.

Ensure that tools and accessories used to install conductors and cables, such as rollers, sheaves, trolley assemblies, tube guides, and/or raceways, are properly sized and utilized to be greater than the minimum bending radii of conductors and cables.

Control the bending of conductors and cables during handling and installation. Minimize bending where conductors and cables enter or exit raceways. Do not install cables that have been bent or kinked to a radius less than the recommended dimension.

11.3 Pulling Conductors in Raceways

Pull cables in accordance with cable manufacturer and pulling equipment manufacturer recommendations. Use installation equipment, tools, and materials as necessary, such as sheaves, pulling eyes, basket grips, winches, cable reels and/or cable reel jacks, duct entrance funnels, and pulling tension gauges, and approved pulling lubricants where required to facilitate cable pulling. Ensure that the manufacturer's maximum recommended pulling tension and sidewall pressures are not exceeded while installing conductors and cables in raceways.

Avoid abrasion and other damage to cables during installation. Provide physical protection of cables, such as using flexible cable guides or feed-in tubes, at the entrance of manholes, underground ducts, and conduits. Use guides adequately sized for the cable being pulled and for the duct, along with properly sized bell and duct adapters. Always ensure that the conduit interior is clean. If necessary, clean inside of conduit prior to pulling cable to remove foreign material.

Use cable-pulling lubricants that are suitable for use with cable, conductors, and raceways. Do not use lubricants that deteriorate conductor insulations and coverings. Use caution with lubricants that harden or become adhesive with age. Apply lubricant where cables enter ducts and conduits and at all intermediate access points on long or difficult pulls.

11.4 Installing Conductors in Trays and Racks

As with raceways, ensure that the installation of cable trays is completed prior to installing conductors and cables. *NOTE: Install cable tray systems in accordance with NECA/NEMA 105-2002, Recommended Practice for Installing Metal Cable Trays (ANSI).*

Use large-radius sheaves around bends and smaller sheaves on the straight sections of cable support trays to reduce the required pulling tensions and to prevent damage to the wires or cables.

11.5 Direct Burial Installations

For direct-burial applications use only conductors and cables that are listed for direct burial. Ensure that direct-buried cables are installed to meet the minimum cover requirements in accordance with NEC 300.5. Protect direct-buried conductors and cables emerging from the ground using enclosures or raceways extending from the minimum cover distance, or a minimum of 18 inches below finished grade, to the building entrance or a minimum of 8 feet above finished grade.

11.6 Cable Installation and Supports

Support and secure cables and conductors by approved means and methods using approved materials. Support wires that do not provide secure support shall not be permitted as the sole means. Do not support cables and raceways by ceiling grids. See NEC 300.11.

Support and protect cables installed without raceways in accordance with manufacturers' recommendations and the National Electrical Code. See NEC 300.4.

Install and support cables installed without raceways parallel to framing members in both exposed and concealed locations, such as joists, rafters, or studs, such that the nearest outside surface of the cable or raceway is not less than 32 mm (1-1/4 in.) from the nearest edge of the framing member where nails or screws are likely to penetrate, or protect cables by steel plates, sleeves, or the equivalent that are a minimum of 1.6 mm (1/16 in.) thick.

Cables or raceways (except RMC and IMC) under metal-corrugated sheet roof decking should be installed so the nearest outside surface of the cable or raceway is not less than 38 mm (1-1/2 in.) from the nearest surface of the roof decking.

Protect cables installed without raceways in shallow grooves in framing members to be covered by wallboard, siding, paneling, carpeting, or similar finish, by a minimum of 1.6 mm (1/16 in.) thick steel plate, sleeve, or the equivalent or by not less than 32 mm (1-1/4 in.) of free space for the full length of the groove in which the cable is installed.

Support conductors in vertical raceways in accordance with manufacturer recommendations using approved materials and methods and in accordance with NEC 300.19. Install one cable support at the top of the vertical raceway or as close to the top as practical. Intermediate supports shall be provided as necessary to limit supported conductor lengths to not greater than those values specified in NEC Table 300.19(A).

TABLE 300-19(A). Spacing for Conductor Supports					
		Conductors			
		Aluminum or Copper-Clad Aluminum		Copper	
Size of Wire	Support of Conductors in Vertical Raceways	m	ft	m	ft
18 AWG through 8 AWG	Not greater than	30	100	30	100
6 AWG through 1/0 AWG	Not greater than	60	200	30	100
2/0 AWG through 4/0 AWG	Not greater than	55	180	25	80
over 4/0 AWG - 350 kcmil	Not greater than	41	135	18	60
over 350 kcmil - 500 kcmil	Not greater than	36	120	15	50
over 500 kcmil - 750 kcmil	Not greater than	28	95	12	40
over 750 kcmil	Not greater than	26	85	11	35

Application	Recommended O-Z/Gedney Cable Support	Catalog Page #
TWO or more wires - Indoors - at voltages to 600V	Type S	QA3
ONE or more wires - Indoors - at all voltages	Type R	QA5
Retrofit - TWO or more wires - Indoors - at voltages to 600V	Type D	QA4
Retrofit - ONE or more wires - Indoors - at all voltages	Type DR	QA6
Ventilating - ONE or more wires - Outdoors - at all voltages	Type CMT	QA7
Ventilating - Bakelite - ONE or more wires - Outdoors - at all voltages	Type V	QA8
Non-ventilating - ONE or more wires - Outdoors - at all voltages	Type C	QA9
Locking - Horizontal/Vertical - ONE or more wires - Indoors - at all voltages	Type K	QA10
Space Maker - ONE or more wires - Indoors - at all voltages	Type M	QA11
Pull Box - ONE or more wires - Outdoors at all voltages	Type W	QA12
Wire Armored Cable - In conduit or supported by structure	Type F/FS/FT	QA15

11.7 Splices, Taps, Connections, and Terminations

Copper building wire is easily stripped, spliced, and terminated. Manufacturers' instructions should be followed.

11.7.1 Stripping Insulation. Conductors and cables should be prepared in accordance with the conductor, cable, splice and termination component manufacturers' recommendations and instructions. Follow the manufacturer's recommendations for measuring and stripping the cable sheathing, jacket, shield, insulation, and conductor for splices and terminations. Train or work the conductors and cables into final position and mark for cutting, allowing for the connector or terminal to be used. Remove armor, cable jacket, metallic shield, insulation, etc., in accordance with the manufacturers' instructions for the cable and the termination or splice. Cut conductors and cables using tools and methods which ensure a square cut. Preferably, use one of several types of insulation strippers that are commonly available. Do not nick or damage conductors. *NOTE: Install Armored and Metal Clad cables in accordance with NECA/NACMA 120-2012, Standard for Installing Armored Cable (AC) and Metal-Clad Cable (MC) (ANSI).*

Strip the insulation from the end of each conductor back far enough so that the conductor inserts fully into the connector or termination with the insulation fitting closely to the connector or termination. Insert the conductor fully into the connector or termination. Tighten the connector or termination using the manufacturer's recommended tools, materials, and methods. Ensure that crimping tools, when used, are designed for the type of connector or termination used. Select the correct crimping tool die for the size of the connector or termination and the conductor. Insulate connections and terminations using tape, heat or cold-shrinkable tubing or other approved insulating material, if required.

11.7.2 Splices and Taps. Make and insulate conductor splices and taps by approved methods using materials listed for the application. Make splices and taps in accessible locations such as junction boxes, cabinets, enclosures, etc. Locate splices and taps as required by NEC 300.15. Do not pull splices into raceways.

Make all terminations between the conductors or cables and equipment using an approved method for that type of conductor or cable. Make splices and taps in junction boxes or other enclosures. Use approved cabinets, boxes, fittings, etc., for the wiring method. Ensure that cable armor and sheathing is continuous between cabinets, boxes, fittings, etc., or outlets.

Compression-type connectors and terminals are typically made inside a splice box. Ensure that boxes are properly sized for the number of conductors and connectors. Screw-type connections are typically made inside junction boxes or equipment with built-in terminal strips or lugs such as those supplied as an integral part of equipment such as motors and transformers.

Provide a minimum of 6 inches of free conductor from the point where the conductors emerge from raceways or cable sheaths at all accessible locations where splices, taps, or terminations are made in outlet and junction boxes, and at each switchpoint. Where the opening to an outlet, junction, or switch point is less than 8 inches in any dimension, each conductor should be long enough to extend at least 3 inches outside the opening.

Where conductors are only pulled through the enclosure, consider leaving a loop which would allow future splicing or tapping. Changes in use can make this essentially cost-free option very valuable.

Cable splices made and insulated by approved methods may be located within a cable tray. Splices should be accessible and should not project above the side rails. Splice or tap direct-buried conductors or cables using devices listed for direct burial.

11.7.3 Connections and Terminations. With copper, joint compounds are not normally needed or used in making connections or terminations. Always follow manufacturers' instructions when making connections or terminations.

Ensure that conductor temperature and ampacity ratings are compatible with connectors, terminals, and equipment to which they are to be connected. Refer to equipment markings, installation instructions, or shop drawings for this information.

Install pigtails on wiring devices to ensure that the continuity of a circuit conductor is not dependent upon device connections (such that the removal of the device would interrupt continuity). This is especially critical for neutrals of multiwire circuits. It is recommended that conductors be terminated on screw-terminals or pressure plates only; do not use backstab or spring-wire terminations.

Torque connections to manufacturer recommendations. Ensure that Belleville washers, where installed, are properly compressed.

11.7.4 Conductors Installed in Parallel. Conductors installed in parallel in each phase, polarity, neutral, or grounded circuit conductor must be the same size, material, and length, and must have the same insulation material, termination manner, and wiring method. Install the same number of conductors in parallel raceways. Compliance with conduit fill requirements will dissipate heat and will promote installation or withdrawal of the conductors without damage to the conductors or to their insulation.

12. Fire - Resistive Cable Systems

Fire resistive cable systems have become an important means for accomplishing the goal of fire protection for conductors when needed for buildings and systems. Improvements such as new products, installation techniques and code requirements are being introduced rapidly as technology evolves.

12.1 Fire Resistive Cable System Requirements

A new article 728 has been added to the 2014 edition of the NEC. This article specifically addresses the installation requirements of fire-resistive cable systems as required by other articles of the NEC. Proper installation of fire resistive cables is essential to insure their continued operation under fire conditions and for the specified period of time. The installations of these cables are critical to their ability to perform during a fire. These systems must be installed in accordance with very specific materials, supports, and requirements and are critical for their survival under fire conditions. There are many specific details outlined in article 728 for installing fire-rated cables that differ from other types of cable installations. These differences include the types of conduit, types of conduit supports, types of couplings, vertical and horizontal supports, boxes, and splices used in the installation.

12.2 Applications and Ratings

Fire resistive cables are used for emergency circuits in many applications, including high-rise buildings and places of assembly. Emergency circuits include feeders for fire pumps, elevators, smoke control equipment, fire alarm systems and other life safety circuits. These circuits are required by the National Electrical Code and the Canadian National Building Code to have a 2-hour fire rating. This added level of survivability is intended to allow sufficient time for building occupants to exit a building during an emergency and to provide uninterrupted power for first responders, firefighting equipment performance and emergency communication systems.

12.3 Certifications

Fire resistive cable systems must be tested and listed as a complete system. In this case the cable along with the types of conduit, types of conduit supports, types of couplings, vertical and horizontal supports, boxes, and splices used in the installation must all be tested as a system in order to gain a listing. Underwriters Laboratory maintains inspections and conducts testing of cable systems in accordance with UL 2196, standard for tests of fire resistive cable. The testing is rigorous but is necessary to insure circuit performance for 2 hours under fire conditions.

12.4 Standards and Installation Practice

Installers and AHJs now have NEC article 728 to resource for specific methods of mounting, supporting, splicing, and guidance on listings of raceways, couplings and even pulling lubricants that can be used in fire resistive cables systems. In addition, installers and AHJs should avail themselves of the information in the specific UL 2196 system listing as well as the instructions provided by the cable manufacturers. Listings requirements include the following in article 728, mounting, supports, raceways, couplings, cable trays, boxes, pulling lubricants, vertical supports, splices, grounding and markings. Please see UL and ULC specific system listings at www.ul.com in the Online Certifications Directory.

Annex A: Sample Calculations to Determine Conductor Sizing and Overcurrent Protective Device (OCPD) Rating

Perhaps the most useful way to learn the NEC rules applicable to sizing of conductors and determination of ratings for overcurrent devices is by considering a number of examples. These examples will reference the NEC Articles summarized in Table 4.7 in the main text. In all cases it will be assumed that the calculated loads were determined through proper application of NEC Article 220.

A.1 High Ambient Temperatures

A.1.1 What conductor size and OCPD are required for a 30 ampere, noncontinuous load, at a 42°C (108°F) ambient temperature, using THHN/THWN-2 conductors?

OCPD:
A 30 ampere OCPD will protect the load.

Conductor: THHN/THWN-2 is a 90°C (194°F) insulated conductor. The size needed from the 90°C (194°F) column of Table 310.15(B)(16) is 12 AWG, rated at 30 A. However, the conductor is subject to a 42°C (108°F) ambient temperature, so the derating factors of Table 310.15(B)(2)(a) apply, in this case 0.87.

A method to determine the required conductor ampacity is to divide the load of 30 A by the temperature correction factor of 0.87.

30 A ÷ 0.87 = 34.5 A

Therefore, a 10 AWG conductor is required, with a 90°C (194°F) ampacity of 40 A, more than enough for the application.

NEC 110.14(C)(1)(a) applies to the conductor terminations. The requirement is that termination provisions for circuits rated 100 amps or less, or marked for 14 AWG through 1 AWG conductors, is one of the following:
(1) 60°C (140°F)
(2) conductors with higher insulation temperature ratings are permitted to be used, provided the ampacity of such conductors is determined based on the 60°C (140°F) ampacity of the conductor size used. In that column of Table 310.15(B)(16), 10 AWG has a rated ampacity of 30 A.

The application requires a 10 AWG conductor.

A.1.2 Same example as A.1.1, but an ambient of 61°C (142°F).

OCPD: **No change; the 30 ampere OCPD is still adequate.**

Conductor: In this case, the derating factor for the ambient temperature in the 90°C (194°F) column of Table 310.15(B)(2)(a) is 0.65.

30 A ÷ 0.65 = 46.2 A minimum conductor ampacity.

By reference to Table 310.15(B)(16) this requires an 8 AWG conductor with a 90°C rating of 55 A. The 10 AWG conductor selected in example A.1.1 continues to be adequate for the load and would prevent overheating the terminals of the overcurrent device . However, the 10 AWG conductor with an ampacity of 40 amperes in the 90°C column of Table 310.15(B)(16) is too small.

The application requires an 8 AWG conductor.

A.1.3 What conductor size and OCPD are required for a 34 ampere, noncontinuous load, which does not include multiple receptacles for cord- and plug-connected devices, at a 61°C (142°F) ambient temperature, using THHN/THWN-2 conductors?

OCPD: The 30 A breaker is no longer adequate. There is no standard 34 A breaker. The next larger size is selected which, according to NEC 240.6(A), is 35 A.
The application requires a 35 A OCPD.

Conductor: Apply the 0.65 derating factor from Table 310.15(B)(2)(a) to the 90°C (194°F) column of Table 310.15(B)(16) to determine the minimum ampacity of conductor,

34 A ÷ 0.65 = 52.3 A minimum conductor ampacity.

An 8 AWG with an ampacity of 55 A is selected.

55 A X 0.65 = 35.75 A, which exceeds the 34 A load.

From the 60°C (140°F) column of Table 310.15(B)(16), the 8 AWG conductor has an ampacity of 40 A, and is protected by the 35 A OCPD. The 8 AWG conductor will prevent overheating the terminals of the overcurrent device.

The application requires an 8 AWG conductor.

A.1.4 Same example as in A.1.3, the circuit to be served is still noncontinuous, but now includes multiple receptacle outlets serving cord- and plug-connected loads. To summarize, the load is 34 A and the ambient is 61°C (142°F).

OCPD: NEC 210.20(A) requires an OCPD not less than the noncontinuous load. The next larger size according to NEC 240.6(A) is 35 A. However, NEC 210.3 requires the rating for other than individual branch circuits to be 15, 20, 30, 40, or 50 A – 40 A in this case.
The application requires a 40 A OCPD.

Conductor: Since the circuit supplies multiple receptacles serving cord- and plug-connected loads, the rule in NEC 240.4(B)(1) permitting rounding up of overcurrent protection does not apply. The conductors must have an ampacity in the 60°C column not less than 40 A to match the breaker rating. An 8 AWG conductor would satisfy this requirement. Assume a 60°C circuit breaker terminal temperature rating unless it is marked for 75°C. But we're not through, because we still have to do the ambient temperature correction.

Again, using 0.65 for ambient temperature correction from the 90°C (194°F) column of Table 310.15(B)(16) the minimum conductor allowable ampacity must be not less than:

40 A ÷ 0.65 = 61.5 A

The 90°C column of Table 310.15(B)(16) shows a 6 AWG conductor provides an ampacity of 75 A. As a check,

75 A x 0.65 = 48.75 A , which satisfies the requirement for 40 A ampacity.

The application requires a 6 AWG conductor.

A.2 More Than Three Conductors in a Raceway

A.2.1 What conductor and OCPD are required for a 20 ampere, noncontinuous load, consisting of four (4) current-carrying conductors in a raceway, using THWN conductors?

OCPD:
A 20 A OCPD is required.

Conductor: From Table 310.15(B)(3)(a) the adjustment factor is 0.8, since there are 4 to 6 current-carrying conductors in the raceway.

20 A ÷ 0.8 = 25 A minimum conductor ampacity.

THWN is a 75°C (167°F) conductor. From Table 310.15(B)(16), in the 75°C (167°F) column, a 12 AWG conductor has the necessary ampacity rating of 25 A, and is being protected by a 20 A OCPD in accordance with NEC 240.4(D).

The terminals of the overcurrent device will not be overheated as the 12 AWG conductor is rated for 20 amperes in the 60°C (140°F) column of Table 310.15(B)(16).

The application requires a 12 AWG conductor.

A.2.2 Same as A.2.1, except twelve (12) current-carrying conductors in the raceway.

OCPD:
A 20 A OCPD is required.

Conductor: From Table 310.15(B)(3)(a) the adjustment factor for 12 conductors in the raceway is now 0.5.

20 A ÷ 0.5 = 40 A

From Table 310.15(B)(16), in the 75°C (167°F) column, an 8 AWG conductor is the smallest size satisfying the requirement of 40 A, with an ampacity of 50 A.

The terminals of the overcurrent device will not be overheated as the 8 AWG conductor is rated greater than 20 amperes in the 60°C (140°F) column of Table 310.15(B)(16).

The application requires an 8 AWG conductor. Since 240.4(D) does not apply to sizes larger than 10 AWG, the selection of a 20 A OCPD is confirmed.

A.2.3 Same as A.2.2, except the load is only 17 amperes.

OCPD: NEC 210.20(A) requires an OCPD not less than the noncontinuous load. The next larger size according to NEC 240.6(A) is 20 A.

A 20 A OCPD is required.

Conductor: From Table 310.15(B)(3)(a) the derating factor is still 0.5.

17 A ÷ 0.5 = 34 A

From Table 310.15(B)(16), in the 75°C (167°F) column, a 10 AWG conductor has an ampacity of 35 A. 35 A x 0.5 =17.5 A. NEC 240.4(B) permits protecting the circuit with the next higher OCPD.

The terminals of the overcurrent device will not be overheated as the 10 AWG conductor is rated greater than 20 amperes in the 60°C (140°F) column of Table 310.15(B)(16).

The application requires a 10 AWG conductor.

A.3 Bundled Cables

A.3.1 What conductor size and OCPD are required for a 20 ampere, noncontinuous load, consisting of three Type NM-B cables, each with two current-carrying conductors, bundled together without maintaining spacing for a distance of 40 inches?

OCPD:
A 20 A breaker or fuse is required.

Conductor: Since these are multiconductor cables installed without maintaining spacing for a distance greater than 24 inches, NEC 310.15(B)(3)(a) applies. There are six current-carrying conductors, since the equipment-grounding conductors in Type NM cable are not counted. From Table 310.15(B)(3)(a) the derating factor is 0.8.

20 A ÷ 0.8 = 25 A minimum conductor ampacity

Type NM cable contains 90°C (194°F) conductors. From Table 310.15(B)(16), in the 90°C (194°F) column, a 14 AWG conductor has the necessary ampacity rating of 25 A.

NEC 110.14(C)(1)(a) requires that the 60°C (140°F) column of Table 310.15(B)(16) be used for circuits through 100 A. In that column a 14 AWG conductor has an allowable ampacity of 15 A and is too small. A 12 AWG conductor with an allowable ampacity of 20 A in the 60°C (140°F) column of Table 310.15(B)(16) will prevent overheating the terminals of the overcurrent device.

The application requires a 12 AWG conductor.

A.3.2 Same as C.3.1, except twelve (12) current-carrying conductors in the cables.

OCPD:
A 20 A breaker or fuse is required.

Conductor: From Table 310.15(B)(3)(a) the derating factor is now 0.5.

20 A ÷ 0.5 = 40 A minimum conductor ampacity

From Table 310.15(B)(16), in the 90°C (194°F) column, a 10 AWG conductor has an ampacity rating of 40 A.

A check of the 60°C (140°F) column yields the same result as the previous example: only a 12 AWG conductor would be required for the overcurrent device. However, the 12 AWG conductor does not have the required 40 A rating in the 90°C (194°F) column and is too small. Therefore the more severe result must be applied. Again, however, NEC 240.4(D) must be consulted. That shows that a 10 AWG conductor does not allow for overcurrent protection over 30 A.

The application requires a 10 AWG conductor.

A.3.3 What conductor size and OCPD are required for a 20 ampere, noncontinuous load, consisting of three Type NM cables, each with two current-carrying conductors, bundled together without maintaining spacing for a distance of 6 inches, but in contact with thermal insulation?

OCPD:
A 20 A breaker or fuse is required.

Conductor: This is the same as A.3.1 above, except the distance is less than 24 inches and the cables are enclosed in insulation. Therefore, NEC 310.15(B)(3)(a) does not apply because of the shorter length, but NEC 334.80 does, due to contact with the insulation. The result is exactly the same: Table 310.15(B)(3)(a) must be used, and all other details of A.3.1 above are the same.

The application requires a 12 AWG conductor.

A.3.4 What conductor size and OCPD are required for a 40 ampere, noncontinuous load, consisting of five Type NM cables, each with two current-carrying conductors, bundled together without maintaining spacing and passing through a hole in a top plate above a wall for a distance of 4 inches, where the hole is fire-stopped?

OCPD:
A 40 A breaker or fuse is required.

Conductor: Similar to the case with bundled cables in insulation, NEC 334.80 applies to this situation. The derating factor for 10 current-carrying conductors from Table 310.15(B)(3)(a) is 0.50.

40 A ÷ 0.5 = 80 A minimum conductor ampacity

The 90°C (194°F) column of Table 310.15(B)(16) shows that a 4 AWG conductor has an ampacity of 95 A.

To prevent overheating the terminals of the overcurrent device, NEC 110.14(C)(1)(a) requires that the 60°C (140°F) column be used, which would permit an 8 AWG, with an ampacity of 40 A, to be used.

The conductor must be large enough after derating for the 40 A load and overcurrent device.

The application requires a 4 AWG conductor.

A.4 Conductors in Circular Raceways Above Rooftops

A.4.1 What conductor size and OCPD are required for three THWN conductors in a raceway in full sunlight on a rooftop in Minneapolis? The load is 75 amperes, noncontinuous, and the raceway is mounted with its bottom 5 inches from the rooftop.

OCPD: From NEC 240.4(B) and NEC 240.6(A), the next higher OCPD can be used.
An 80 A OCPD is required.

Conductor: Since only three conductors are in the raceway, NEC 310.15(B)(3)(a) does not apply. However, NEC 310.15(B)(3)(c) does. From Annex B of this publication, the design outdoor summer temperature for Minneapolis is 32°C (90°F). A temperature adder must be found in Table 310.15(B)(3)(c) for the specific situation of 5 inches above the roof. In this case 17°C (30°F) is added to the design outdoor temperature to arrive at an ambient temperature of the air inside the raceway in summer of 49°C (120°F). Since THWN is a 75°C (167°F) conductor, the derating factor from Table 310.15(B)(2)(a) is 0.75.

The minimum conductor ampacity is 75 ÷ 0.75 = 100.0 A

This requires a 3 AWG conductor with an ampacity of 100 A.

To prevent overheating the terminals of the overcurrent device, the conductor must have an allowable ampacity of not less than 80 A in the 60°C (140°F) column of Table 310.15(B)(16), since the circuit is not greater than 100 A. The 3 AWG satisfies this requirement with an ampacity of 85 A.

The application requires a 3 AWG conductor.

A.5 Continuous Loads

A.5.1 Determine the circuit breaker rating and conductor size for a continuous hard-wired lighting load determined to be 42 amperes, using THHN copper conductors, with circuit breaker terminals rated at 75°C.

OCPD: First determine the circuit breaker (or fuse) rating. Since the load is continuous, NEC 210.20(A) requires that the load be multiplied by 125%.

42 A x 1.25 = 52.5 A

NEC 240.4(B)(1) permits the next larger standard breaker to be used, provided the circuit does not include multiple receptacles serving cords and plugs (it does not). The next larger size, according to NEC 240.6(A) is 60 A.

A 60 A OCPD is required.

Conductor: NEC 210.19(A)(1) contains the same rule for conductors as for breakers above: multiply the load by 125%.

42 A x 1.25 = 52.5 A.

THHN is a 90°C conductor. From Table 310.15(B)(16), the smallest conductor to carry 52.5 A in the 90°C column is 8 AWG, rated at 55 A.

However, the circuit breaker terminals are rated only at 75°C. NEC 110.14(C) requires that the temperature rating associated with the ampacity of a conductor must be selected and coordinated so as not to exceed the lowest temperature rating of any connected termination. From the 75°C column of Table 310.15(B)(16), we see this would require a 6 AWG conductor rated at 65 A.

The application requires a 6 AWG conductor.

A.6 Multiple Derating

A.6.1 Ambient Temperature and More Than Three Conductors in a Raceway:
What conductor size and OCPD are required for eight THHN conductors in a raceway in an indoor space at 48°C (118°F). The calculated load for each conductor is 195 amperes.

OCPD: The next larger standard breaker is 200 A, according to NEC 240.6(A).
A 200 A OCPD is required.

Conductor: According to Table 310.15(B)(3)(a), eight current-carrying conductors result in a derating factor of 0.70. According to the 90°C (194°F) column of Table 310.15(B)(2)(a), the derating factor for 46-50°C (114-122°F) ambient temperature is 0.82.

Multiply the two derating factors 0.70 x 0.82 = 0.57, which is the final derating factor.

The minimum conductor ampacity is 195 A ÷ 0.57 = 342.1 A

In the 90°C (194°F) column of Table 310.15(B)(16), a 350 kcmil conductor will carry 350 A.

To prevent overheating the overcurrent device terminals, the conductor must have an allowable ampacity in the 75°C (167°F) column of Table 310.15(B)(16) of 195 A. This would only require a 3/0 AWG conductor (200 A rating). This conductor satisfies the requirement in NEC 110.14(C)(1)(b).

The application requires a 350 kcmil conductor.

A.6.2 More Than Three Conductors in a Raceway On or Above a Rooftop Exposed to Sunlight:

What conductor size and OCPD are required for five current-carrying THWN conductors in a raceway lying directly on the roof in full sunlight in Phoenix, Arizona? The calculated load for each conductor is 45 amperes.

OCPD: 45 A is a standard size, according to NEC 240.6(A).

A 45 A breaker is required.

Conductor: The five conductors result in a derating factor of 0.80, according to Table 310.15(B)(3)(a).

The Phoenix location has an outdoor design temperature of 43°C (110°F), which can be found in Annex B of this document. Since the raceways are lying directly on the roof, Table 310.15(B)(3)(c) requires an adder of 33°C (60°F). Adding the two results in an ambient temperature inside the raceway of 76°C (170°F), which is off the charts for a 75°C (167°F) conductor. Only a 90°C (194°F) conductor can be used, because of the correction factors in Table 310.15(B)(2)(a), and the rating of the conductor. Therefore the conductor should be switched to THWN-2, resulting in a derating factor of 0.41.

Multiplying the factors together results in 0.80 x 0.41 = 0.33, the final derating factor.

The minimum conductor ampacity is 45 A ÷ 0.33 = 136.4 A

This results in the need for a 1 AWG conductor, which has an ampacity of 145 A in the 90°C (194°F) column of Table 310.15(B)(16). One could easily skip the next step resulting from NEC 110.14(C)(1)(a), knowing it will result in a considerably smaller conductor. It does, where the 60°C (140°F) column of Table 310.15(B)(16) shows that 45 A could be carried by a 6 AWG conductor.

The application requires a 1 AWG conductor *and* a switch to a conductor rated at 90°C (194°F) in the wet location.

A.6.3 Ambient Temperature Correction and Continuous Loads:
What conductor size and OCPD are required for three THWN conductors in a raceway serving a load of 25 amperes that is expected to extend well over three hours? The load consists only of "hard-wired" lighting outlets, and the ambient temperature in the indoor space where the conduit is located is 33ºC (91ºF).

OCPD: According to NEC 210.20(A), since the load is continuous, it must be multiplied by 125% to determine the necessary OCPD rating.

25 A x 1.25 = 31.3 A

NEC 240.4(B)(1) allows the next higher breaker rating which, according to NEC 240.6(A), is 35 A.

A 35 A breaker is required.

Conductor: According to NEC 210.19(A)(1), the branch circuit's conductor size, *before* the application of any adjustment factors, must be multiplied by 125%.

25 A x 1.25 = 31.3 A

By reference to Table 310.15(B)(16), the smallest conductor in the 75°C (167°F) column that has an allowable ampacity larger than 31.3 amperes is a 10 AWG. This is the smallest conductor that will satisfy the requirement for continuous loads in NEC 210.19(A)(1). It may be required to be larger when derating factors are applied but is not permitted to be smaller.

The correction factor for the 33ºC (91ºF) ambient for the 75°C (167°F) column of Table 310.15(B)(2)(a) is 0.94.

The minimum conductor ampacity when correcting for elevated ambient temperature is 25 A ÷ 0.94 = 26.6 A

The 10 AWG conductor selected above with an ampacity of 35 A in the 75°C (167°F) column easily satisfies the conductor size requirement after a correction factor of 0.94 is applied:

35 x 0.94 = 32.9 A

Since the circuit is less than 100 A, NEC 110.14(C)(1)(a) would allow a 10 AWG to be used to prevent overheating the overcurrent device terminal for the 25 A load. The terminals on the overcurrent device are assumed to have a rating not greater than 60°C (140°F) so the conductor must be selected from that column in Table 310.15(B)(16).

But we have one more step. NEC 240.4(D) says in part that overcurrent protection shall not exceed 30 A for 10 AWG *after* any correction factors for ambient temperature and number of conductors have been applied. We require a 35 A breaker, but a 10 AWG conductor cannot be protected by a breaker larger than 30 A. The only way we can resolve this is to move to the next larger conductor, 8 AWG, at which point NEC 240.4(D) no longer applies. In the 75°C (167°F) column of Table 310.15(B)(16), an 8 AWG conductor has an ampacity of 50 A.

An 8 AWG conductor is required for this application.

Annex B: Selected Rooftop Circular Raceway Data

The National Electrical Code, and good design practice, requires ampacity correction of wires and cables installed in ambient temperature conditions that are higher than those upon which the listed ampacities of Table 310.15(B)(16) are based. Ambient temperature is understood to mean the temperature of the air surrounding the conductor. For conductors in circular raceways, the ambient to which the insulated conductor is subjected is the temperature of the air inside the raceway.

To help determine the temperature insulation will be subjected to—under unloaded conditions—CDA has compiled a table of outdoor temperatures for various U.S. and Canadian locations, as well as expected temperatures inside raceways on and at various heights above rooftops, based on ASHRAE data and NEC Table 310.15(B)(3)(c). These data are available in more detail at www.copper.org/rooftop.

For each location, Table B.1 contains:

An average of the 2% ASHRAE design temperatures for each location for June through August.

Likely temperatures inside rooftop raceways (unloaded) exposed to direct sunlight:

- On the roof, and up to ½ inch above roof
- Greater than ½ inch and up to 3½ inches above roof
- Greater than 3½ inches and up to 12 inches above roof
- Greater than 12 inches and up to 36 inches above roof

ASHRAE's reported "extreme annual design condition"—*i.e.*, the maximum dry-bulb temperature reading for the location over the last 50 years.

The research is described in two articles, both of which are available at www.copper.org/rooftop:

Brender, D. and Lindsey, T.L., *Effect of Rooftop Exposure in Direct Sunlight on Conduit Ambient Temperatures*, IEEE Transactions on Industry Applications, Vol. 44, No. 6, Nov/Dec 2008.

Lindsey, T.L., et al, *Effect of Rooftop Exposure on Ambient Temperatures inside Conduits,* IAEI News, January-February, 2006, and reprinted in the March-April 2009 issue.

Table B.1. Outdoor Temperatures and Temperatures Inside Raceways on Rooftops Exposed to Direct Sunlight for Selected U.S. and Canadian Metropolitan Statistical Areas (MSAs).

MSA By Decreasing Population	Metropolitan Statistical Area	State/Province	2% Design Outdoor Temp, °F	Design Temperature Inside Raceway, °F up to _______ above roof				Maximum Outdoor Temp, °F
				½"	3-1/2"	12"	36"	
1.	New York	New York	91	151	131	121	116	104
2.	Los Angeles	California	78	138	118	108	103	106
3.	Chicago	Illinois	91	151	131	121	116	106
4.	Dallas	Texas	99	159	139	129	124	113
5.	Philadelphia	Pennsylvania	92	152	132	122	117	105
6.	Houston	Texas	96	156	136	126	121	108
7.	Toronto	Ontario	74	134	114	104	99	93
8.	Washington	Dist. Columbia	93	153	133	123	118	106
9.	Miami	Florida	91	151	131	121	116	99
10.	Atlanta	Georgia	93	153	133	123	118	105
11.	Boston	Massachusetts	90	150	130	120	115	103
12.	San Francisco	California	78	138	118	108	103	105
13.	Detroit	Michigan	89	149	129	119	114	103
14.	Riverside	California	98	158	138	128	123	115
15.	Phoenix	Arizona	110	170	150	140	135	122
16.	Montreal	Quebec	84	144	124	114	109	89
17.	Seattle	Washington	83	143	123	113	108	102
18.	Minneapolis	Minnesota	90	150	130	120	115	106
19.	San Diego	California	79	139	119	109	104	107
20.	St. Louis	Missouri	95	155	135	125	120	107
21.	Tampa	Florida	92	152	132	122	117	99
22.	Baltimore	Maryland	93	153	133	123	118	106
23.	Denver	Colorado	93	153	133	123	118	105
24.	Vancouver	Brit. Columbia	76	136	116	106	101	83
25.	Pittsburgh	Pennsylvania	89	149	129	119	114	102
26.	Portland	Oregon	89	149	129	119	114	107
27.	Sacramento	California	99	159	139	129	124	114
28.	San Antonio	Texas	98	158	138	128	123	109
29.	Orlando	Florida	93	153	133	123	118	101
30.	Cincinnati	Ohio	92	152	132	122	117	105
31.	Cleveland	Ohio	89	149	129	119	114	102
32.	Kansas City	Missouri	94	154	134	124	119	110
33.	Las Vegas	Nevada	108	168	148	138	133	118
34.	San Jose	California	90	150	130	120	115	108
35.	Columbus	Ohio	90	150	130	120	115	102
36.	Charlotte	North Carolina	93	153	133	123	118	105
37.	Indianapolis	Indiana	90	150	130	120	115	102
38.	Austin	Texas	98	158	138	128	123	111
39.	Virginia Beach	Virginia	93	153	133	123	118	104
40.	Providence	Rhode Island	87	147	127	117	112	NA
41.	Nashville	Tennessee	93	153	133	123	118	105
42.	Milwaukee	Wisconsin	89	149	129	119	114	105
43.	Jacksonville	Florida	94	154	134	124	119	104
44.	Memphis	Tennessee	95	155	135	125	120	106
45.	Louisville	Kentucky	93	153	133	123	118	105
46.	Richmond	Virginia	94	154	134	124	119	106
47.	Oklahoma City	Oklahoma	98	158	138	128	123	112
48.	Edmonton	Alberta	80	140	120	110	105	88
49.	Hartford	Connecticut	90	150	130	120	115	103
50.	New Orleans	Louisiana	93	153	133	123	118	102

Annex C: Reference Standards

NFPA 70, National Electrical Code, 2011 Edition, NFPA.

NEC 2011 Handbook, 12^{th} Edition, NFPA.

IEEE Gray Book, IEEE Std 241-1990-Recommended Practice for Electric Power Systems in Commercial Buildings.

IEEE Emerald Book, IEEE Std 1100-2005-Recommended Practice for Powering and Grounding Electronic Equipment.

NFPA 780: Standard for the Installation of Lightning Protection Systems, 2008 Edition.

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