History of Ampacity

Since 1889, many individuals and organizations have attempted to find the correct ampacity for conductors so they would not overheat and ruin the insulations. In 1889, one of the first tables listed 46 amperes as the ampacity of a #10 conductor.

In 1890, it was listed 19.1 amperes, and in 1894, the insurance industry listed 20 amperes as the ampacity for the same conductor. But that was not the end of it.

By 1937 there were 16 ampacities discovered for the same size conductor. In 1938, Anaconda Wire and Cable Company, conducted a thorough investigation to find the correct ampacities for all the standard size conductors used at that time.

To establish the maximum prolonged operating temperature for insulations, they performed aging and elongation tests in environmental ovens. A structure was built, and wired, embedded thermocouples in the conductors, and applied voltages and measured the ampacities and temperatures. The findings were published in a paper titled, "The Current-Carrying Capacity of Rubber-Insulated Conductors" delineating the results of the experiments.

The work resulted in a table XI that became Table 310-16 of the National Electrical Code. The original table was based on an ambient temperature of 30 degrees centigrade and a conductor temperature of 50 degrees centigrade for code grade rubber, the type of insulation used in those days. If we convert the ampacities in table XI to 60 degrees centigrade using the formula given in note 1 to tables 310-69 through 310-84, setting delta TD equal to 0 (delta TD is for high voltages: we are only concerned with 600 volts and under), and rounding off to the nearest 5 amperes, we can calculate the ampacities for 60 degree insulations as found in the first column of table 310-16.

Likewise, the same calculation can determine the the ampacities for the 75 degree and 90 degree columns in table 310-16.

Faults with Table 310-16

There are three very important deficiencies in the paper. First, it did not investigate the effects of proximal heating from adjacent conduits, ducts, and duct banks. Secondly, his experiments were only for **above ground** installations. Thirdly, **the heat produced by high voltages was not investigated.** But for most applications when load calculations are performed according to Article 220, there is enough safety margin built in to preclude any problems. To explain this, a fine print note was added to section 310-15(a) in the 1990 NEC stating that Tables 310-16 through 310-19 are application tables that are for use in determining conductor sizes on loads calculated in accordance with Article 220.

When calculating loads per Article 220, a substantial safety margin is included as opposed to some engineering calculations that calculate the "actual" load.

The deficiencies to Table 310-16 became a problem in the 1950's when Americans began installing very large air conditioning systems in the larger buildings, using underground service laterals run in massive underground duct banks. In cases where engineers performed load calculations using **engineering methods** in place of Article 220, and used Table 310-16 to determine the size of conductors, conductors overheated and burned open, especially the conductors located near the center of the duct banks. They used a basic heat transfer equation with the addition of a term "n" for the number of conductors in the same cable or raceway. But there were no terms in his equation to adjust the ampacity for heat that came from adjacent ducts and duct banks, or for the differences for heat dissipation in an underground installation. Later calculations using the Neher-McGrath equation found in 310-15(b) of the NEC would determine that the center conductors in a 3 by 3 duct banks must be derated to almost 60 percent because of the proximal heating effect from adjacent ducts and duct banks.

To develop a more accurate method of finding the ampacity of conductors in underground installations, two cable engineers, in 1957, developed the Neher-McGrath equation found in 310-15(c) of the 1999 NEC.

AMPACITY TABLES

Tables 300.5 through 310.17 and 310.21

When selecting a table always read the heading.

LOOK FOR
KEY WORDS

Table 300.5 Minimum Cover Requirements, 0 to 1000 Volts,
Nominal, Burial in Inches

Table 300.50 Minimum Cover Requirement Over 1000 volts

Table 310.4 (A) Conductor Applications and Insulations
Rated 600 Volts

Table 310.4 (B) Thickness of Insulation for Nonshielded Types
RHH and RHW
Solid Dielectric Insulated Conductors rated 2000 volts

Table 310.15(B)(1) CORRECTION FACTORS
For ambient temperatures other than 30°C (86°F), multiply the
allowable ampacities from
the ampacity tables by the appropriate factor shown below.

Table 310.15(B)(2) CORRECTION FACTORS
For ambient temperatures other than 40°C (104°F), multiply the
allowable ampacities from
the ampacity tables by the appropriate factor shown below.

Table 310.15(C)(1) Adjustment Factors for More Than Three
Current-Carrying Conductors

Table 310.16. Allowable Ampacities of Insulated Conductors
Rated 0-2000 Volts, 60°to 90°C (140°to 194°F)
Not More Than Three Conductors in Raceway or Cable or Earth
(Directly Buried), Based on Ambient Temperature of 30°C (86°F)*

Table 310.17 Ampacities of Single-Insulated
Conductors in Free Air

Table 310.18 Ampacities of Insulated Conductors with Not More Than
Three Current-Carrying Conductors in a Raceway or Cable
Temperature Rating of Conductor [See Table 310.4(A)]
150°C (302°F) 200°C (392°F) 250°C (482°F) 150°C (302°F)

Table 310.19 Ampacities of Single Insulated Conductors in Free Air
Temperature Rating of Conductor [See Table 310.4(A)]
150°C (302°F) 200°C (392°F) 250°C (482°F) 150°C (302°F)

Table 310.20 Ampacities of Conductors on a Messenger
Temperature Rating of Conductor [See Table 310.4(A)]
75°C (167°F) 90°C (194°F)

Chapter Two

Ampacity

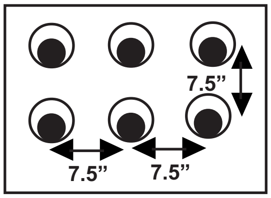
The Neher - McGraph formula

Manual method of calculation

Learn about "equations"

Thermal resistance

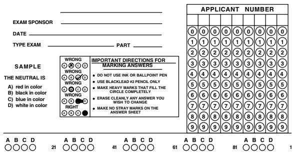
The duct bank



I have written three books on calculations, and now in the 2020 NEC much has changed with the word ***ampacity***. From Articles 300, 310, the new 311, to Annex B in the back pages of the NEC. Today we need to learn about "**equations**" and explain the Neher-McGraph formulas.

NEC section 310.15(B). Ampacities for ambient temperatures other than those shown in the ampacity tables shall be corrected in accordance with Table 310.15(B)(1) or Table 310.15(B)(2), or shall be permitted to be calculated using Equation 310.15(B).

You can select the ampacity from a table or solve the ampacity by the **equation**. The latter method can be complex and time consuming and requires engineering supervision. However, it can result in lower installation costs in some cases, and if the equation is done properly, it provides a mathematically **exact ampacity**. Where more than one ampacity applies for a given circuit length, the **lowest value shall be used**.



EXAM SPONSOR
DATE
TYPE EXAM PART

SAMPLE
THE NEUTRAL IS
A) red in color
B) black in color
C) blue in color
D) white in color

WRONG
WRONG
WRONG
WRONG
RIGHT

IMPORTANT DIRECTIONS FOR MARKING ANSWERS
- DO NOT USE INK OR BALLPOINT PEN
- USE BLACKLEAD #2 PENCIL ONLY
- MAKE HEAVY MARKS THAT FILL THE CIRCLE COMPLETELY
- ERASE CLEANLY ANY ANSWER YOU WISH TO CHANGE
- MAKE NO STRAY MARKS ON THE ANSWER SHEET

APPLICANT NUMBER

A B C D ○○○○ 21 A B C D ○○○○ 41 A B C D ○○○○ 61 A B C D ○○○○ 81 A B C D ○○○○ 1

Exam Questions

It would be my guess most electricians would refer to Table 310.15(B)(1) rather than solve the **"equation"** of 310.15(B) shown below.

But, I feel with the new Article 311, **exam questions** will start asking about your knowlege of **equation**. One must first understand how the **equation** is applied.

310.15(B) Equation

$$I' = I\sqrt{\frac{T_c - T_a'}{T_c - T_a}}$$

Ampacity is defined as "the current in amperes a conductor can carry **continuously** under the conditions of use (conditions surrounding medium in which the cables are installed) without exceeding its temperature rating."

•Always remember ***heat*** is the great enemy of electrical systems.

Current passing through a conductor produces I^2R losses in the form of **heat**, which results from conductor losses and appears as a **temperature rise** in the conductor. This heat must pass through the cable insulation, the air in the raceway, and the raceway itself to the surrounding medium, usually earth or concrete, where it is dissipated into the air by radiation and convection. **Unless the heat is dissipated,** the temperature in the conductor will exceed the rating of the conductor insulation.

All of the **heat** created by an **underground** electrical cable must be dissipated through the adjacent soil to the ambient.

The ampacity calculation is a relatively simple matter; the only difficulty experienced is that of determining the proper thermal constants for the components of the thermal circuit.

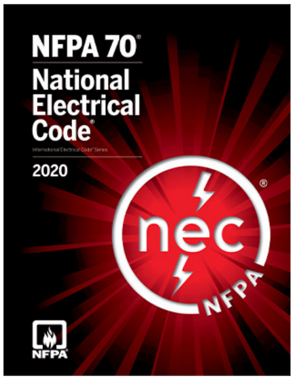
Temperature Limitation of Conductors. No conductor shall be used in such a manner that its operating temperature exceeds that designated for the type of insulated conductor involved.

The most common use for the Neher-McGrath formula is to calculate the ampacity of conductors in **underground electrical ducts** (raceways), although the formula is applicable to all conductor installations.

The formula was developed by Neher and McGrath to determine conductor ampacity. It is actually a composite of a number of separate formulas.

The Neher-McGrath formula is a heat transfer formula, composed of a series of heat transfer calculations, that takes into account all heat sources and the thermal resistances between the heat source and free air.

It is because of these many variables, and the complexities of the many formulas involved, that the Code requires that the calculation be made under **engineering supervision**.



The Code tables cannot always be used to determine cable ampacity. The number of ducts, their proximity, and **site-specific conditions** combine to make ampacity calculations a complex undertaking.

The computer software program takes into account each adjustment factor which together account for the more significant effects indicated in **underground installations.** Thousands of computer runs were made to determine the adjustment factor tables.

In the Neher-McGraph calculation, there are many variables in the **30-40 equations** used to account for the number of conductors, number and size of adjacent conduits, number of adjacent duct banks, coefficient of **surface emissivity**, number of cables, axial spacing between cables, unrelated heat sources, and wind velocity.

Although it is not necessary to understand these concepts of heat transfer in order to use cable ampacity computer programs, such knowledge may be helpful for understanding how physical parameters affect ampacity.

A simple **manual method** of determining cable ampacities is presented in this book to have a direct effect on the operating temperatures of the conductors.

A **manual method** was developed that uses adjustment factors to simplify cable derating for some very specific conditions of use and produce close approximations to actual ampacities. The results from the **manual method** can then be entered as the initial ampacities for input into a cable ampacity computer program.

The ampacity of a conductor depends on a number of factors are the following:
(1) Ambient temperature
(2) Thermal characteristics
(3) Heat generated by the conductor due to its own losses
(4) Heat generated by adjacent conductors

Once the size and location of electrical loads are determined, an adequate distribution system must be designed. The total number of required circuits, their sizes, and method of routing are significant elements in the design problem. In addition, accurate cable sizing becomes especially critical that the cables are adequate to carry the required load without being subjected to temperatures that exceed their temperature ratings.

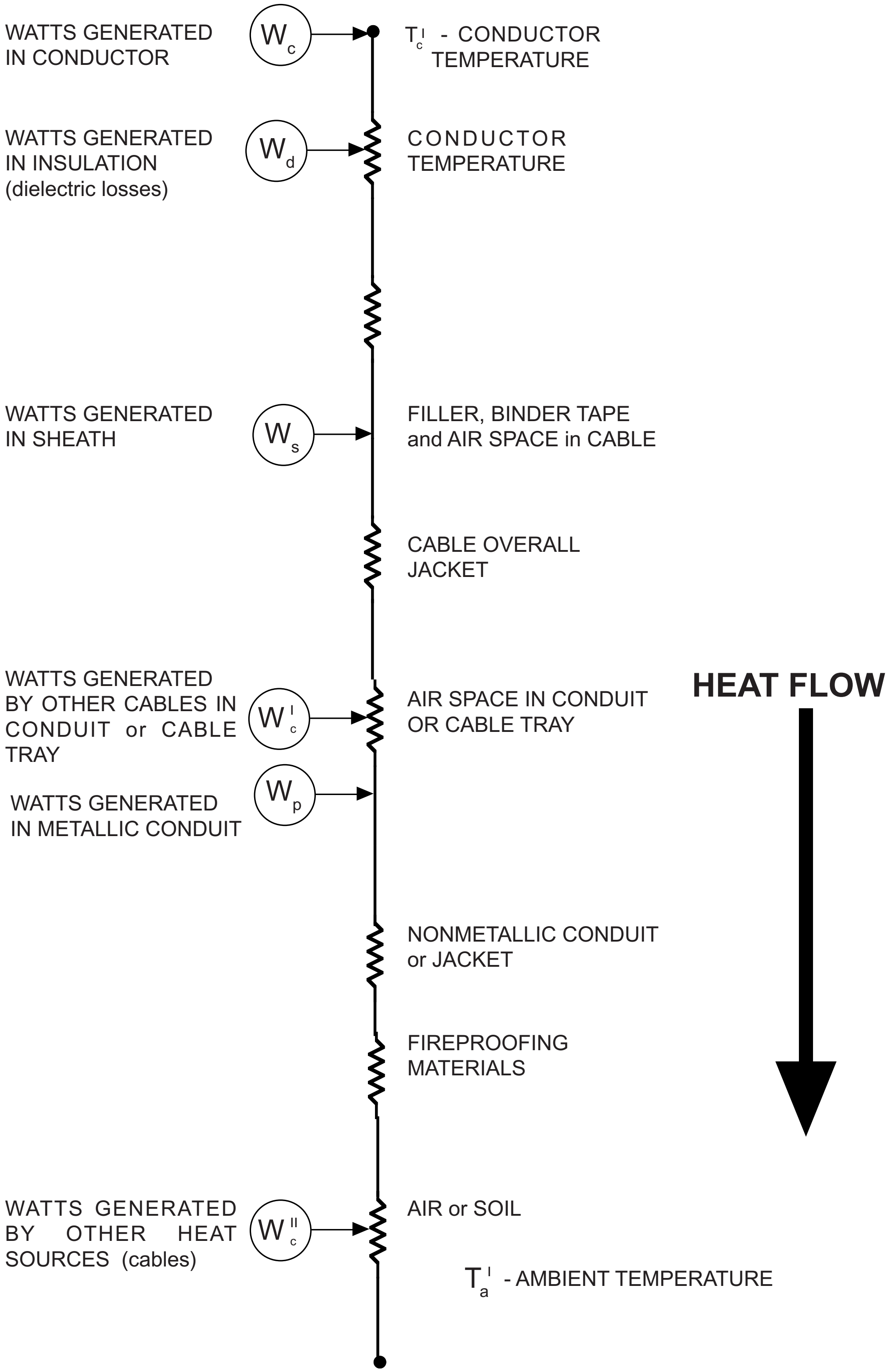
As an electrical current flows through a cable, it generates **heat**. The type of cable and how it is connected and installed determines how many components of heat generation are present, I^2R losses, sheath losses, etc.

The terms “conductor” and “cable” are used interchangeably. For clarity, the term “conductor,” as used, indicates the **current-carrying** part of a cable. The term “cable” refers to a complete assembly, for example, conductors, filler, insulation, jacket, armor, servicing, etc.

Conductor

Cable

The operating temperature that the cable ultimately reaches is directly related to the amount of heat generated and the net effective value of the thermal resistance through which it flows.



Conductivity makes **rigid metal conduit** useful for electrical shielding. The higher thermal conductivity of metal removes heat more quickly.

Is PVC a good thermal insulator?

PVC is a polymer with good insulation property, but because of its higher polar nature, the electrical insulating property is **lower** to non-polar polymers such as polyethylene and polypropylene.

Thermally conductivity in a **plastic** provides the ability to meet demanding engineering requirements in many applications more cost effectively than other materials.

PVC softening starts at approximately 250°F. Material having flow at 350°F. Material carbonizes at 425°F.

Does concrete have a high thermal conductivity?

One of the most important parameters that affect the heat transfer through the building envelope is thermal conductivity of **lightweight concrete** is generally lower than that of normal-weight concrete due to the lower thermal conductivity of **air.** You can use concrete blocks, tiles, brick, rammed earth and stone. Three factors determine how good a material is at absorbing and storing heat. The ideal material is a reasonably good heat conductor as **heat has to be able to flow in and out.**

Conductivity of concrete depends on its composition. In case of saturated concrete, conductivity ranges from 1.4 to 3.6 joule/meter square per second.

The thermal conductivity of concrete, a composite widely used as construction material. **Twenty-one different concretes** were made with densities that varied.

What is the K-value in thermal conductivity?

K-value is simply shorthand for thermal conductivity. Thermal conductivity, n: the time rate of steady heat flow through a unit area of the same degree material induced by a unit temperature gradient in a direct perpendicular to that unit area.

Is soil a good conductor of heat?

Gravel, soil and rock do **conductive and radiative fairly well**, **but not convective**. Although it can reach higher temperatures than water. Mud is water+gravel+rock+soil and suffers all the limits of the above. But, mud can do all three of the heat transfer modes better.

Is soil a good insulator?

So, **soil is a good insulator**. The good: average temperature is usually (but in very cold regions and mountains) above freezing point. This blocks radiation of soil, so it keeps warmer [and for summer it blocks also water evaporation]. To have warmer soil during night, also another effect is used: heat storage.

What is thermal resistivity of soil?

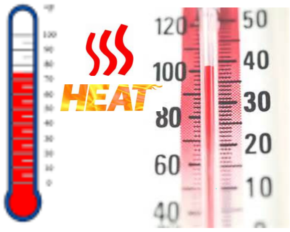
Soil thermal resistivity is defined as “the difference in degrees centigrade between opposite faces of a centimeters cube of soil caused by the transference of one watt of heat and is expressed in thermal ohm/cm or °C cm/watt. ... **Soil resistivity varies over a period of 12 months**.

What is the thermal conductivity of sand?

Thermal Sand is an insulative form of sand widely used throughout the power industry to improve underground electrical performance. Thermal sand is rated and tested to provide proven heat transfer, allowing cables to operate at optimal levels.

Material/Substance	Temperature
Sand, dry	0.15 - 0.25
Sand, moist	0.25 - 2
Sand, saturated	2 - 4

While the solid phase of sand has the highest conductivity, it is the variability of soil moisture that largely determines thermal conductivity.



As the name suggests, thermal resistance is a measurement of a temperature difference of a material’s ability to resist the flow of heat. **Heat is energy that is transferred from one object or substance to another because of a difference in temperature between them**.

The opposition of a body to the flow of heat through it is called thermal resistance of the body. Thermal resistance is similar to electric resistance which opposes flow of electric current in a conductor. **Greater is the thermal conductivity of a material, the smaller is its thermal resistance**.

A measure of a body's ability to **prevent heat from flowing through it**, equal to the difference between the temperatures of opposite faces of the body divided by the rate of heat flow. Also known as **heat resistance**.

Soil Thermal Conductivity Testing.

The standard probe has proven its suitability for soils, thermal backfill measurement of the thermal conductivity (or thermal resistivity) of the medium.

The thermal resistivity and conductivity of the soils is critical in the design of underground power transmission systems. The purpose of the thermal resistivity testing is to provide the thermal conductivity (in W/m oK) or thermal resistivity (in oK cm/W) of **soils at a selected depth**.

The needle sensor is fully inserted into an isothermal sample and a measurement is made with the push of a button. After 180 seconds, results are displayed for thermal conductivity and thermal resistivity.

Soil resistivity testing is the process of measuring a volume of soil to determine the conductivity of the soil. The resulting soil resistivity is expressed in ohm-meter or ohm-centimeter. Good soil models are the basis of all grounding designs and they are developed from accurate soil resistivity testing.

A value often assumed for thermal resistivity of soil in buried cable.

Heat transfer in a porous medium like soil can be a complex process.

A heat source, is buried at a depth in uniform soil (constant ambient temperature, constant thermal resistivity, etc.) Heat will migrate from the source to all points of lower temperature conduction (and by convection and radiation if enclosed in a pipe or conduit containing air). If the heat sink is treated as a single point, represented by the reflected image of the source, the temperature rise can be found from the difference in the two heat flows.

The deeper the duct is buried, the greater the thermal resistance.

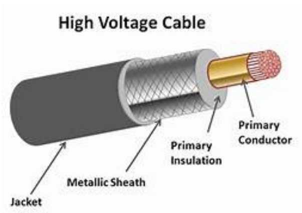
The air space within the conduit is the only area within a duct bank that does **not** conduct heat. In the air space convection occurs in lieu of conduction. The main method of heat transfer within a duct bank is conduction; therefore the air within the conduit will have less of an effect of heating.

The calculations used in cable ampacity programs are normally based on the Neher-McGraph method. In computing cable ampacities in duct banks, only power cables need to be considered since control cables, carry very little current, **contribute very little to the over all temperature rise**.

- The first step in designing an underground cable installation is to establish which circuits are to be routed through the duct bank.

Consideration should be given to present circuits as well as to circuits that may be added in the future.

Only power cables need to be included as current carrying conductors, but space allowances must be made for spare ducts or for control and instrumentation circuits.



Conductor size, conductor material (copper or aluminum), operating voltage, type of shield or sheath, temperature rating, insulation type, and jacket type are especially important.

An initial cable placement layout should be designed, based on anticipated loads and load factors. Circuits with high currents and load factors (ratio of average to peak load over a given load cycle) should be placed in outside ducts near the top of the bank to eliminate the need for larger conductors due to unnecessarily reduced ampacity.

If the load factor cannot be evaluated readily, a conservative of 1.0 may be entered, which implies that the circuit always operates at **peak load**.

The following is a list of factors:

(1) Conduit type
(2) Conduit wall thickness
(3) Conduit inside diameter
(4) Asymmetrical spacing of cables or conduits
(5) Conductor load currents and load cycles
(6) Height, width, and depth of duct bank
(7) Thermal resistivity of backfill and/or duct bank
(8) Thermal resistance of cable insulation
(9) Dielectric losses of cable insulation
(10) AC/DC ratio of conductor resistance

Once the initial design is established and all necessary data have been collected, the user should enter the program data interactively or prepare an input data file for a batch program.

After a program is run, the user should carefully analyze the results to varify that the design currents are less than ampacities or that actual temperatures are less than rated temperatures.

If the initial design is shown to be inadequate, various corrective measures should be considered. These include increasing conductor sizes, modifying cable locations, and changing the physical design of the bank.

The results of such an analysis should be documented and permanently archived for use in properly controlling and/or analyzing future changes in duct bank usage.