

Understanding the Neher-McGrath Calculation and the Ampacity of Conductors

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*For a better background read the article
"Where did Table 310-16 come from"
by clicking [here](#).*

Heat Transfer

The key to understanding ampacity is to learn about heat transfer. The definition of ampacity is given in the National Electrical Code (NEC) as "the current in amperes a conductor can carry continuously under the conditions of use without exceeding its temperature rating." To better understand ampacity we need to examine how heat is transferred and thermal circuits in respect to a current carrying conductor.

When current is carried by a conductor it must pass through the electrical resistance of the conductor. When this happens heat is generated. One unit of heat, watts, can be calculated by I squared times R, where R equals the electrical resistance of the conductor in ohms and I equals the current in amperes. The heat generated in the conductor passes through several thermal barriers by convection, conduction, and radiation and dissipates into the air. Possible thermal barriers are the conductor insulation, the air inside a duct, the duct wall, the soil surrounding an underground duct, and any additional thermal insulation applied such as polyurethane.

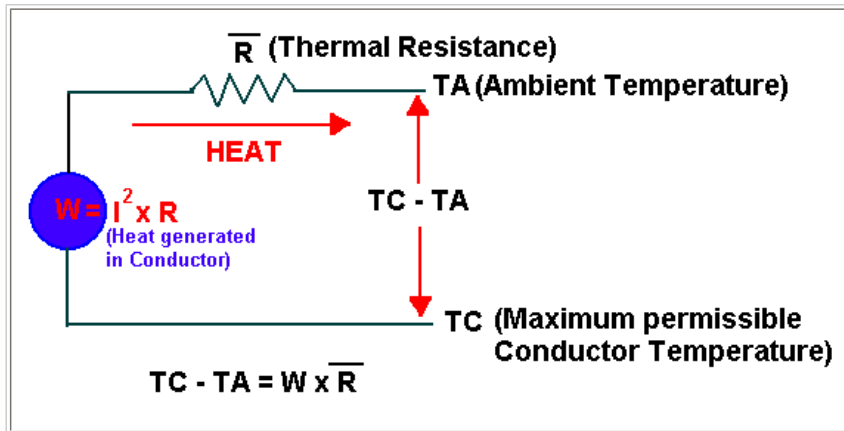
The transfer of heat follows a fundamental law in physics, and heat always flows from the warmer object to the colder object, much like heat flowing from the inside of a house through the walls to the outside on a cold day. The rate of heat transfer is dependent on several variables and can be described by a thermal equation that closely resembles ohms law ($E=I \times R$), substituting heat for current and thermal resistance for electrical resistance. In a heat transfer equation the rate of heat transfer is directly dependent on the difference in temperature between the conductor called TC and the ambient temperature called TA. In a heat transfer equation $TC - TA = (I \times R) \times RCA$, where I is current in amperes, R is electrical resistance in ohms, and RCA is thermal resistance in degrees Centigrade-cm/watt usually called thermal-ohm-feet. TC is the maximum permissible operating temperature in degrees Centigrade of the conductor. TA is the ambient temperature of the air or soil for underground installations. Solving for I:

$$I = \sqrt{\frac{TC - TA}{R \times RCA}}$$

Equation No. 1

Letting heat, $I \times R$ in this case, be represented by W and thermal resistance, RCA, by R with a line over it, we can draw a

thermal circuit that is similar to an electrical circuit.



Neher-McGrath equation

Founded by a man named Fourier in the 1850's, Equation No. 1 is sometimes called the Fourier heat transfer equation. The equation in section 310-15(c) of the NEC, called the Neher-McGrath equation, is a more complex version of the Fourier heat transfer equation. The Neher-McGrath equation was discovered by two cable engineers in 1957. In the Neher-McGrath (NM) equation, Delta TD, is a term added to the ambient temperature, TA, to compensate for heat generated in the jacket and insulation for higher voltages. Delta TD is called the dielectric loss temperature rise and is insignificant for voltages below 2000. Another term in the NM equation, (1+YC), is a multiplier used to convert direct current resistance (RDC) to alternating current resistance or impedance. For wire sizes smaller than No. 2 this term becomes insignificant. Of course, we must remember that the NM equation was developed using the standard power frequency of 60 hertz and sinusoidal wave forms for current and voltage.

There are many equations used to calculate the various thermal resistances for the conductor insulation, the air space between a conductor and the inside of a conduit, the conduit or duct wall, and the thermal resistance outside the conduit. Like electrical resistors, thermal resistances in series are added and the total equals RCA.

Ambient temperature, TA, varies but usually 30 or 40 degrees Centigrade is used for above ground installations. For underground installations TA is universally 20 degrees Centigrade. Civil engineers working for the State of Alaska Department of Transportation state that the actual measured temperature 30 inches beneath the surface is 19.3 degrees Centigrade near Fairbanks, Alaska. This of course, is during the summer months. The conductor temperature, TC, for most 600 volt building wire is 60, 75, or 90 degrees Centigrade. The maximum insulation temperature for conductors is determined by conducting aging and elongation tests in environmental chambers.

In the NM calculation there are many variables in the 30 to 40 equations used to account for the number of conductors, number and size of adjacent conduits, number and size of adjacent duct banks, coefficient of surface emissivity, number of cables, axial spacing between cables, extraneous heat sources, and wind velocity. All these factors and more effect the calculation of ampacity. An analysis of the NM calculation reveals many details about ampacity: for instance, the ampacity of conductors in a bright and shiny conduit in free air is higher then the ampacity in a dull and dark conduit because of the coefficient of surface emissivity and its effect on the radiation of heat. Also, one of the most criticized faults of the NM calculation is revealed: The calculation is based on one single linear foot of a conductor that may be several hundred feet long where the conditions vary dramatically along the entire length.

There are ampacity tables in the National Electrical Code that are sufficient for most installations. However, the tables in the NEC are very crude approximations and therefore include a substantial safety margin. There are instances where the application of the ampacity tables including the safety margins are insufficient requiring engineers, installers, and inspectors to perform actual NM calculations using one of the several software packages available. For instance, there are no requirements in the NEC to address the problem of excessive thermal insulation around cables and conduits. What happens if there are several inches of polyurethane foam around a conduit? There are no derating tables in the NEC for this kind of

situation. Yet, the addition of excessive thermal insulation will effect the ampacity of a conductor, especially polyurethane foam that has twice the insulation value of fiberglass. To address this problem we must remember that the NM equation is a radial heat transfer equation and that the NM calculation is performed on one typical foot of an installation that may be several hundred feet long. Radial heat transfer means that heat flows outward at ninety degrees to the length of the conductor as opposed to axial heat transfer where heat flows along the length of the conductor. In the real world there is axial and radial heat transfer. But the NM equation and the NEC assume that a conductor and surrounding thermal barriers are infinitely long and uniform where no axial heat transfer takes place. There are, however, some allowances in the NEC for axial heat transfer. For instance, there are no derating for over three current carrying conductors in a nipple if the nipple is not over 24 inches long. Also, bundled cables are not required to be derated if the bundles are not longer than 24 inches. There is also the ten per cent rule given in section 310-15(c). These are situations where there is enough axial heat transfer to prevent the conductors from overheating. It would also be prudent to assume that where there is excessive thermal insulation not over 24 inches long, the ampacity of the applicable conductors would not be effected because of axial heat transfer.

Derating for 600 volt 3-phase, 60 Hz for Excessive Thermal Insulation using the R-value - Three Single Conductors in a Raceway in free air.

Derating is required for excessive thermal insulation. This derating can be done using the R Value for one inch of the insulation. R Values are typically about 3.2 per inch for fiberglass and 6.0 per inch for sprayed on polyurethane foam. Multiply the R Value for one inch of insulation (that is in BTUth-in / hr-ft*ft-F) by 694 to convert to C-cm / Watt, the units used in the Neher McGrath Equation for finding thermal ohm feet. The equation using the R value is $R_i = (.012)*694*R\text{-Value}*LOG10(\text{Outside Diameter of thermal insulation in inches}/\text{Outside Diameter of Raceway in inches})$
 For a quick approximation of the derated ampacity add this calculated thermal ohm feet value to the RCA value used in the NM original calculation and recalculate the ampacity. Finding the original RCA value is easier than it looks. Use the ampacity from Table in 310-16 in the 75 degree column. Use $T_A = 30$, $T_C = 75$, degrees C. Next find the 75 degree C. DC resistance from Table 8 in Chapter 9. Multiply this resistance by 1000 to convert to microhms per foot of conductor, the value and units used in the NM equation. Use this for RDC in the NM equation. Now solve the NM Equation 1, above, to find RCA. Next recalculate ampacity using the NM equation, but this time add the new R_i value for the thermal insulation to RCA found using the original data. The new ampacity is your derated ampacity. This method can be used for other temperature ampacities if the resistance from Table 8 Chapter 9 is recalculated for the same temperature as the conductor ampacity temperature. This procedure is a quick approximation and assumes no axial heat transfer and uses DC resistance for impedance that may vary for wire sizes above No. 2 depending on power factor. Remember the NM equation gives ampacity in kiloamperes so you have to multiply by 1000 to get amperes. Also, the thermal insulation is assumed to be evenly spaced around the raceway or cable.
 This method does not apply if there are different types of thermal insulations along the length of the raceway or cable such as where the raceway or cable may pass through wooden members. In these cases boundary limits can be found by assuming that the intervening thermal medium with the lower R-value is the primary thermal insulation. Wood has an R-value of .89 for hardwoods to 1.48 for cedar. These lower R-values can set a limit on the maximum ampacity while the higher R-values can establish the minimum ampacity. A more advanced method using the calculus of finite differences can be used if more accurate results are required. This is a subject covered in heat transfer physics taught in mechanical engineering. R-values and thermal conductivity values can be found in the 1985 ASHRAE Handbook.

Derating for 600 volt 3-phase, 60 Hz for Excessive Thermal Insulation using the N-M Equation - Three Single Conductors in a Raceway in free air.

The chart below was made using the values found with an Excel 7.0 spread sheet calculator. In this calculation the R values were not used although the calculator has two methods, one using the thermal conductivity and one using the R-Values. The thermal conductivity values in BTU-in/hr-ft*ft-F were used to calculate the chart. These values were multiplied by .00144131 to convert them to W/cm C and then the inverse of W/cm C was taken to get the correct units, C-cm/Watt, of Thermal resistance for the Neher McGrath calculation. These values were confirmed by using a United Kingdom internet web page calculator at <http://www.omnis.demon.co.uk/indexfrm.htm> to verify that no errors had been made. The normal ampacity was calculated using the N-M equation following the format given in IEEE paper "Neher McGrath Calculations for Power Cables" by Peter Pollack written in 1984. This method, shown below in the example, gives good results for under 2,000 volts and for building wire applications leaving out some of the more complicated equations in the N-M paper. For Thermal Conductivity of materials try <http://www.mayahtt.com/tmwiz/default.htm>.

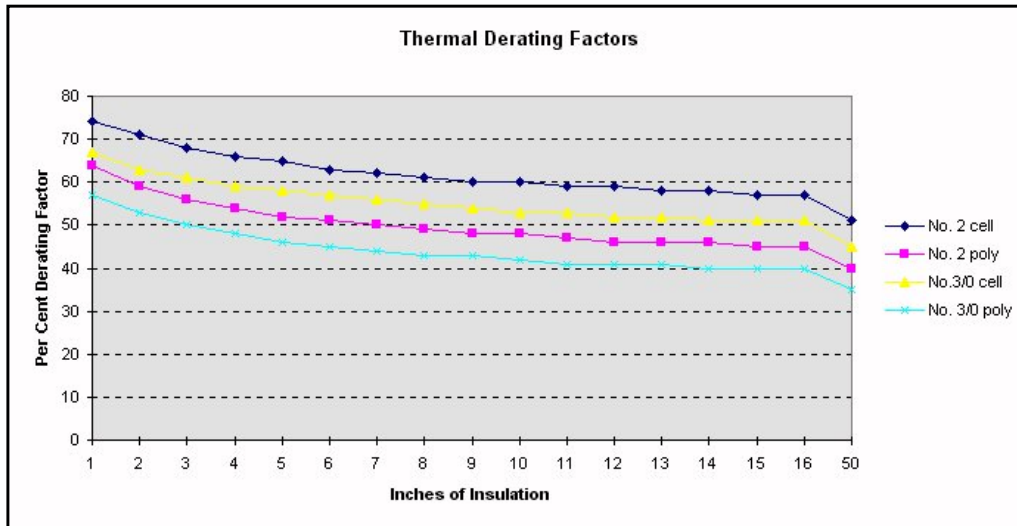
The second part of the spread sheet calculation found the thermal resistance of the insulation for sprayed on polyurethane foam and loose cellulose and fiberglass using the same equation that was used to calculate R_i . The R_e value is subtracted

from the first RCA value then the thermal resistance, R_i''' of the thermal insulation is added to the initial R_i and R_{sd} values. A new R_e is calculated for the thermal insulation using an emissivity of .3 since the insulation is assumed to not be bright and shiny. This new R_e''' value is added to the R_i , R_{sd} and R_i''' to find the new RCA value. This value of RCA is then used to perform a new N-M calculation to find the ampacity. The new ampacity is divided by the previously calculated ampacity and multiplied by 100 to give per cent derating. The per cent derating then when multiplied times the first ampacity calculated gives the reduced ampacity found in the second calculation. The advantage of the spread sheet is that the many variables can be changed and the new values are instantaneously calculated. Cells with formulas in the spread sheet have been locked so the spread sheet must be unprotected to change them. The accuracy of this calculator can be checked by comparing calculated values to the values in Table 310-16 and by comparing the calculated ambient derating factors to the ambient derating factors at the bottom of Table 310-16.

The AC resistance of a single foot of conductor effects the N-M Calculation significantly. For wire sizes above No. 2 Table 9 in Chapter 9 of the NEC should be used to find the AC impedance instead of using the DC resistance, either calculated or taken from table 8 in Chapter 9. The spreadsheet calculator calculates AC resistance in the same manner as the Pollack paper. First the DC resistance is calculated using the N-M paper formula for the temperature T_c , using 12.9 ohms, the circular mil ohms per foot at 75 degrees C. for copper. The DC resistance is multiplied by the AC/DC ratio. The AC/DC ratio is taken from the Standard Handbook for Electrical Engineers Tenth Edition Page 17-20.

[To use the spreadsheet Calculator for Excel 7.0 click here.](#)

The below graph is from the spreadsheet. The 3/0 are 3 each THWN copper in 1 1/2 inch EMT and the No. 2 copper are 3 XHHW each in a 1 inch rigid in free air . Poly is for sprayed on polyurethane foam and the cell is for fiberglass or cellulose. An ambient of 30 degrees C is used. T_c is 90 degrees C for the No. 2 and 75 degrees C for the 3/0. A thermal conductivity of .17 BTU-in/hr-ft²-F is used for polyurethane and .30 BTU-in/hr-ft²-F is used for fiberglass or cellulose.



Neher McGrath Table VII Constants used for finding R_{sd}

Condition	A	B	C	A'	B'
In metallic conduit	17	3.6	0.029	3.2	0.19
In fiber duct in air	17	2.1	0.016	5.6	0.33
In fiber duct in concrete	17	2.3	0.024	4.6	0.27
In transite duct in air	17	3.0	0.014	4.4	0.26
In transite duct in coincrete	17	2.9	0.029	3.7	0.22
Gas-filled pipe at 200 psi	3.1	1.16	0.0053	2.1	0.68

Oil filled pipe or duct	0.84	0	0.0065	2.1	2.45
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Ds' = multiplier for converting circumscribed conductors to equivalent circle.

1.00 x diameter for one cable
1.65 x diameter for two cables
2.15 x diameter for three cables
2.50 x diameter for four cables

Decimal Equivalents

1/16	.0625
1/8	.125
3/16	.187
1/4	.250
5/16	.312
3/8	.375
7/16	.437
1/2	.500
9/16	.562
5/8	.625

Dimensions of EMT

Electrical Metallic Tubing

Trade Size in Inches	Outside Dia. in Inches	Inside Dia. in Inches	Wall Thickness in Inches
1/2	.706	.622	.042
3/4	.922	.824	.049
1	1.163	1.049	.057
1 1/4	1.510	1.380	.065
1 1/2	1.740	1.610	.065
2	2.197	2.067	.065
2 1/2	2.875	2.731	.072
3	3.500	3.356	.072
3 1/2	4.00	3.834	.083
4	4.500	4.334	.083
5	--	--	--
6			

Dimensions of Rigid Conduit

Steel or Aluminum

Trade Size in inches	Outside Dia. in Inches	Inside Dia in Inches	Wall thickness in Inches
1/2	.840	.632	.104
3/4	1.050	.836	.107
1	1.315	1.060	.126
1 1/4	1.660	1.394	.133
1 1/2	1.900	1.624	.138
2	2.375	2.083	.146
2 1/2	2.875	2.489	.193
3	3.500	3.090	.205
3 1/2	4.00	3.570	.215
4	4.500	4.050	.225
5	5.563	5.073	.245
6			

Dimensions of IMC

Intermediate Metal Conduit

Trade Size in Inches	Outside Dia. in Inches	Inside Dia. in Inches	Wall Thickness in Inches
1/2	.815	.675	.070
3/4	1.029	.879	.075
1	1.290	1.120	.085
1 1/4	1.638	1.468	.085
1 1/2	1.883	1.703	.090
2	2.360	2.170	.095
2 1/2	2.857	2.597	.130
3	3.476	3.216	.130
3 1/2	3.971	3.711	.130
4	4.466	4.206	.130
5	--	--	--
6			

RIGID ALUMINUM

Trade Size	O.D.	I.D.	Wall	Weight Per 100'	Ft. Per Bundle
1/2	0.840	0.622	.109	30	100
3/4	1.050	0.824	.113	37	100
1	1.315	1.049	.133	60	100
1-1/4	1.660	1.380	.140	78	100
1-1/2	1.900	1.610	.145	100	50
2	2.375	2.067	.154	125	30
2-1/2	2.875	2.469	.203	200	10
3	3.500	3.068	.216	260	10
3-1/2	4.000	3.548	.226	330	10
4	4.500	4.026	.237	370	10
5	5.563	5.047	.258	530	10
6	6.625	6.065	.280	660	10

P.V.C. TYPE A

Trade Size	O.D.	I.D.	Wall	Weight Per 100'	Ft. Per Bundle
1/2	0.840	0.720	.060	11	100
3/4	1.050	0.930	.060	13	100
1	1.315	1.195	.060	17	100
1-1/4	1.660	1.520	.070	25	50
1-1/2	1.900	1.740	.080	32	50
2	2.375	2.175	.100	50	10
2-1/2	2.875	2.655	.110	67	10
3	3.500	3.250	.125	90	10
4	4.500	4.200	.150	146	10

P.V.C. TYPE 40 (SCHEDULE 40)

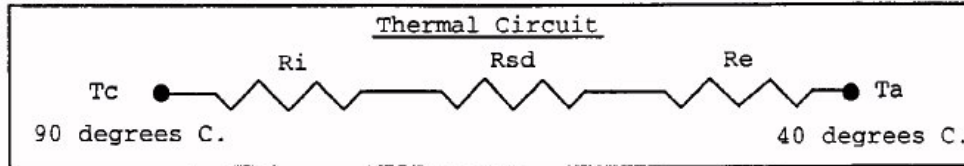
Trade Size	O.D.	I.D.	Wall	Weight Per 100'	Ft. Per Bundle
1/2	0.840	0.622	.109	16	100
3/4	1.050	0.824	.113	22	100
1	1.315	1.049	.133	32	100
1-1/4	1.660	1.380	.140	43	50
1-1/2	1.900	1.610	.145	52	50
2	2.375	2.067	.154	69	10
2-1/2	2.875	2.469	.203	109	10
3	3.500	3.068	.216	142	10
3-1/2	4.000	3.548	.226	170	10
4	4.500	4.026	.237	202	10
5	5.563	5.047	.258	271	10
6	6.625	6.065	.280	350	10

P.V.C. TYPE 80 (SCHEDULE 80)

Trade Size	O.D.	I.D.	Wall	Weight Per 100'	Ft. Per Bundle
1/2	0.840	0.546	.147	21	100
3/4	1.050	0.742	.154	28	100
1	1.315	0.957	.179	41	100
1-1/4	1.660	1.278	.191	57	50
1-1/2	1.900	1.500	.200	68	50
2	2.375	1.939	.218	94	10
2-1/2	2.857	2.323	.276	142	10
3	3.500	2.900	.300	190	10
3-1/2	4.000	3.364	.318	232	10
4	4.500	3.826	.337	278	10
5	5.563	4.813	.375	385	10
6	6.625	5.761	.432	530	10

Example of a Neher-McGrath Calculation

Calculate the ampacity of 3 - No. 2 concentric stranded XHHW insulated copper cables in a 1 inch steel conduit in 40 degree centigrade ambient air.



Cable buildup

t = insulation thickness 2t = 2 x .045 in. = .090 in.
(from NEC table 310-13)
DC = conductor diameter = .292
(from NEC table 8, chapter 9)

$$DI = .090 + .292 = .382 \text{ in.}$$

$$Ri = .012 \text{ Pi log (DI/DC)}$$

$$Ri = .012 (400) \text{ log (.382/.292)}$$

$$Ri = .560$$

$$Rsd = \frac{n' A'}{Ds' + B'}$$

From N-M Table VII
A' = 3.2 B' = 0.19
1 inch Rigid Steel Conduit ID = 1.049 in, OD=1.315 in.
From N-M table VII Ds' = 2.16 x DI
Ds' = 2.16 (.382) = .825

$$Rsd = 3(3.2)/(.825 + 0.19)$$

$$Rsd = 9.458$$

$$Re = 9.5 n' / (1 + 1.7Ds' (e + 0.41))$$

$$Ds' = \text{conduit OD (1.315 in.)}$$

$$e = 0.95 \text{ (emissivity)}$$

$$Re = 9.5(3) / (1 + 1.7(1.315)(.95 + .41))$$

$$Re = 7.05$$

$$Rca = Ri + Rsd + Re$$

$$Rca = 17.1$$

$$Rdc \text{ at } 75 \text{ deg. C} = 194 \text{ microhms}$$

$$Rdc \text{ at } 90 \text{ deg. C} = (194) \left(\frac{234.5 + 90}{234.5 + 75} \right)$$

$$Rdc = 203.4 \text{ microhms}$$

$$I = \sqrt{\frac{90 - 40}{(203.5) (17.1)}}$$

I = .120 kiloamperes
(Table 310-16 lists 130 amperes, Ta=30)
with Ta=30, I=.131 kiloamperes