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NEHER-MCGRATH EQUATION

The Neher-McGrath Calculations is a method for calculating underground cable temperatures and cable ampacity ratings. The Calculations method derived from: J. H. Neher and M. H. McGrath,"The

Calculation of the Temperature Rise and Load Capability of Cable Systems", AIEE Transactions, Part III, Volume 76, pp 752-772, October, 1957. This paper considers the heat transfer issues associated with underground system ampacities. The paper cites the following basic equation for calculation of a cable ampacity:

Neher-McGrath Equation

$$I = \sqrt{\frac{Tc - (Ta + Delta\ TD)}{Rdc\ (1 + Yc)\ Rca'}}$$

Where:

I = Ampacity, (kiloamps)
Tc = Conductor temperature, (Deg C)
Ta = Ambient Temperature in degrees C.
Delta TD = Conductor temperature rise due to dielectric loss, (Deg C)
Rdc = Conductor dc resistance,(microhms/foot)
Yc = Loss increment due to conductor skin & proximity effects
Rca' = Thermal resistance between conductor & ambient, (thermal ohm feet)

However, this single equation masks the great complexity involved in these procedures (see calculation example). There are scores of complicated equations involved in developing the terms in this equation and those required for temperature calculations. (The paper defines over 80 variables and contains in excess of 70 formulas excluding appendices.) To solve for unique ampacities or temperatures at each cable position, a multiple set of equations must be developed to take into account interference heating from every position in the system, and a matrix solution technique for simultaneous equations utilized. Many of ampacity calculations we use today are based on a 1957 paper by J.H. Neher and M.H. McGrath. Later work by CIGRE (INTERNATIONAL COUNCIL ON LARGE ELECTRIC SYSTEMS) documented an ampacity procedure into an international standard (IEC-287 and IEC-853) that provides a step-wise approach to calculating ampacity based upon cable construction. The two calculation approaches give similar results, although their treatment of daily load cycles is different. The paper by Neher and McGrath assumes a sinusoidal load shape and uses a 24-hour (daily) loss factor to account for an overall "averaging" effect of heat output from the cable beyond a certain diameter (called DX). Within this diameter, the temperature rise across the thermal resistances in the cable and nearby soil is proportional to the peak heat output from the cable. At distances greater than this diameter away from the cable center, the temperature rise is proportional to the average daily heat output. Many system planners are familiar with a "load factor" which relates the peak load to the average daily load. In cable systems, we are interested in heat output – a function of I2R – so we use the daily "loss factor", which is essential the load factor of the losses as defined by the following equation:

$$\text{Loss Factor} = \frac{\sum_{i=1}^{24} I_i^2}{24 \cdot I_{max}^2}$$

Concept of Ampacity An underground cable circuit rating, or “ampacity”, is the solution to a basic heat transfer problem. Heat generated in the cable is removed by thermal conduction to ambient earth and, ultimately, air. Engineers familiar with Ohm’s Law know that electrical current flowing through an resistance will produce a voltage drop according to the following relationship: Neher-McGrath ampacity equation

$$\Delta \text{Voltage} = \text{Current} \cdot R_{AC}$$

An analogous relationship may be used to describe thermal conduction where heat flowing through a thermal resistance produces a temperature drop (or rise) according to the following:

$$\Delta \text{Temperature} = \text{Heat} \cdot R_{\text{Thermal}}$$

This basic concept is extended to model heat out of a buried cable through the various cable layers, trench backfill and native earth.

Dielectric Heating

Dielectric heating comes from charging and discharging the insulating dielectric at 50 or 60 times per second. The dielectric heat loss, WDielectric, can be found from the following equation:

$$W_{\text{Dielectric}} = 2\pi f C V_{1-g}^2 = \frac{2\pi f \varepsilon V_{1-g}^2 \tan\delta \cdot 10^{-9}}{18 \ln\left(\frac{D_{\text{insulation}}}{D_{\text{Conductor}}}\right)} \text{[W/meter]}$$

where,

C	=	Capacitance, Farads/meter
f	=	power frequency, Hz
ε	=	specific inductive capacitance (dielectric constant)
$\tan\delta$	=	insulation dissipation factor
V_{1_g}	=	line to ground voltage applied across the insulation, volts

Some typical insulation parameters are listed in the following table

Typical Cable Insulation Material Parameters

Insulation Material	Dielectric Constant		Dissipation Factor	
	Range	Typical	Range	Typical
Impregnated Paper	3.3-3.7	3.5	0.002-0.0025	0.0023
Laminated Paper-Polypropylene	2.7-2.9	2.7	0.0007-0.0008	0.0007
Cross-linked Polyethylene	2.1-2.3	2.3	0.0001-0.0003	0.0001
Ethylene-Propylene-Rubber	2.5-4.0	3.0	0.002-0.08	0.0035

The AC resistance increment for conductor skin effect, YCS, can be found from the following equation, where kS is the skin effect factor based on the conductor construction.

$$X_S = \frac{8\pi f k_S \cdot 10^{-7}}{R_{dcT}} \qquad Y_{CS} = \frac{X_S^2}{192 + 0.8 \cdot X_S^2}$$

The AC resistance increment for conductor proximity effect, YCP, can be found from the following equation, where kP is the proximity effect factor based on the conductor construction.

$$X_P = \frac{8\pi f k_P \cdot 10^{-7}}{R_{dcT}}$$

$$Y_{CP} = \left(\frac{X_P^2}{192 + 0.8 \cdot X_P^2}\right) \cdot \left(\frac{D_{\text{Conductor}}}{d_{\text{phase}}}\right)^2 \cdot \left[0.312 \cdot \left(\frac{D_{\text{Conductor}}}{d_{\text{phase}}}\right)^2 + \frac{1.18}{\frac{X_P^2}{192 + 0.8 \cdot X_P^2} + 0.27}\right]$$

Shield Loss Increments for Eddy Currents

Eddy current losses occur when a continuous concentric metallic layer exists around the cable core (e.g., a corrugated or extruded metal sheath or longitudinally taped metallic shield, but not to stranded shields). Also, eddy currents are negligible for pipe-type cables.

The mechanics for calculating the eddy current losses is somewhat onerous but not particularly complicated. The equations to perform these calculations were derived empirically and are listed below. For a more detailed explanation, please see IEC-287.

$$m = \frac{2\pi f \cdot 10^{-7}}{R_{S'}}$$

$$Y_{Se0} = 6\cdot\left(\frac{m^2}{1+m^2}\right)\cdot\left(\frac{D_S}{2\cdot S}\right)^2 \quad Y_{Sel} = 0.86\cdot m^{3.08}\cdot\left(\frac{D_S}{2\cdot S}\right)^{1.4\cdot m+0.7} \quad \text{for flat formation}$$

$$Y_{Se0} = 3\cdot\left(\frac{m^2}{1+m^2}\right)\cdot\left(\frac{D_S}{2\cdot S}\right)^2 \quad Y_{Sel} = \left(1.14\cdot m^{2.45}+0.33\right)\cdot\left(\frac{D_S}{2\cdot S}\right)^{0.92\cdot m+1.66} \quad \text{for trefoil formation}$$

$$\beta 1 = \sqrt{\frac{8\pi^2 f}{\rho_{Shield}\cdot 10^7}} \quad g_s = 1+\left(\frac{t_{Shield}}{D_S}\right)^{1.74}\cdot\left(\beta 1\cdot D_S\cdot 10^{-3}-1.6\right)$$

$$Y_{EC} = \left(\frac{R_S}{R_{acc}}\right)\cdot\left(g_s\cdot Y_{Se0}\cdot\left(1+Y_{Sel}\right)+\frac{\left(\beta 1\cdot t_{Shield}\right)^4}{12\cdot 10^{12}}\right)$$

Terms

Density, ρ The amount of mass per unit volume. In heat transfer problems, the density works with the specific heat to determine how much energy a body can store per unit increase in temperature. Its units are kg/m³.

Emissive power The heat per unit time (and per unit area) emitted by an object. For a blackbody, this is given by the Stefan-Boltzmann relation $\sigma * T^4$

Graybody A body that emits only a fraction of the thermal energy emitted by an equivalent blackbody. By definition, a graybody has a surface emissitivy less than 1, and a surface reflectivity greater than zero.

Heat flux, *q* The rate of heat flowing past a reference datum. Its units are W/m².

Internal energy, *e* A measure of the internal energy stored within a material per unit volume. For most heat transfer problems, this energy consists just of thermal energy. The amount of thermal energy stored in a body is manifested by its temperature.

Radiation view factor, F_{12} The fraction of thermal energy leaving the surface of object 1 and reaching the surface of object 2, determined entirely from geometrical considerations. Stated in other words, F_{12} is the fraction of object 2 visible from the surface of object 1, and ranges from zero to 1. This quantity is also known as the Radiation Shape Factor. Its units are dimensionless.

Rate of heat generation, q_{gen} A function of position that describes the rate of heat generation within a body. Typically, this new heat must be conducted to the body boundaries and removed via convection and/or radiation heat transfer. Its units are W/m³.

specific heat, *c* A material property that indicates the amount of energy a body stores for each degree increase in temperature, on a per unit mass basis. Its units are J/kg-K.

Stefan-Boltzmann constant, σ Constant of proportionality used in radiation heat transfer, whose value is 5.669 x 10^{-8} W/m²-K⁴. For a blackbody, the heat flux emitted is given by the product of σ and the absolute temperature to the fourth power.

Surface emissitivy, ε The relative emissive power of a body compared to that of an ideal blackbody. In other words, the fraction of thermal radiation emitted compared to the amount emitted if the body were a blackbody. By definition, a blackbody has a surface emissivity of 1. The emissivity is also equal to the absorption coefficient, or the fraction of any thermal energy incident on a body that is absorbed.

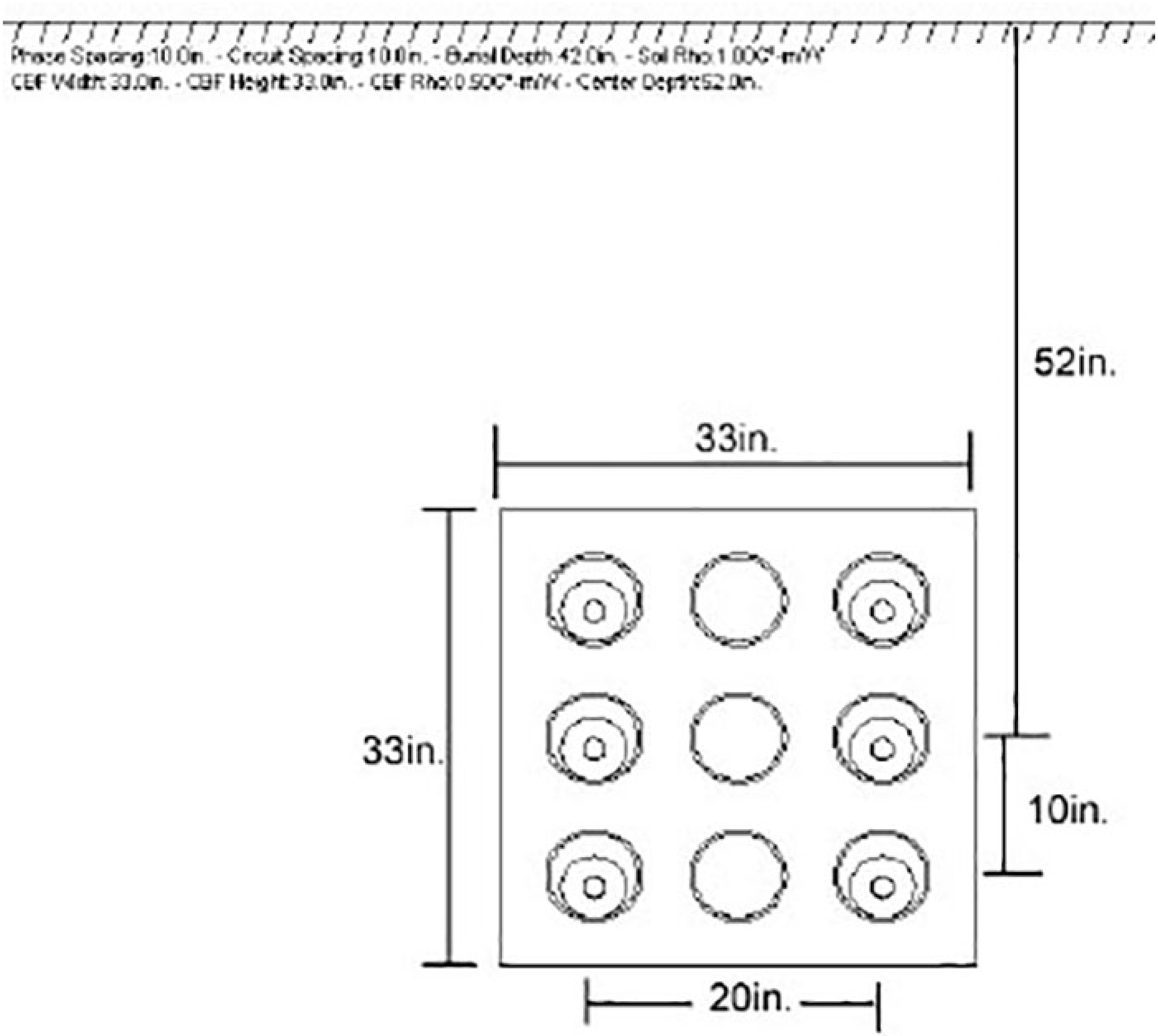
Thermal conductivity, *k* A material property that describes the rate at which heat flows within a body for a given temperature difference. Its units are W/m-k.

Thermal diffusivity, α A material property that describes the rate at which heat diffuses through a body. It is a function of the body's thermal conductivity and its specific heat. A high thermal conductivity will increase the body's thermal diffusivity, as heat will be able to conduct across the body quickly. Conversely, a high specific heat will lower the body's thermal diffusivity, since heat is preferentially stored as internal energy within the body instead of being conducted through it. Its units are m²/s.

Linear Heat Equations

- **Heat Equation** $\frac{\partial w}{\partial t} = a\frac{\partial^2 w}{\partial x^2}$
- **Nonhomogeneous Heat Equation** $\frac{\partial w}{\partial t} = a\frac{\partial^2 w}{\partial x^2} + \Phi(x,t)$
- **Convective Heat Equation with a Source** $\frac{\partial w}{\partial t} = a\frac{\partial^2 w}{\partial x^2} + b\frac{\partial w}{\partial x} + cw + \Phi(x,t)$
- **Heat Equation with Axial Symmetry** $\frac{\partial w}{\partial t} = a\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right)$
- **Heat Equation of the Form** $\frac{\partial w}{\partial t} = a\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right) + \Phi(r,t)$
- **Heat Equation with Central Symmetry** $\frac{\partial w}{\partial t} = a\left(\frac{\partial^2 w}{\partial r^2} + \frac{2}{r}\frac{\partial w}{\partial r}\right)$
- **Heat Equation of the Form** $\frac{\partial w}{\partial t} = a\left(\frac{\partial^2 w}{\partial r^2} + \frac{2}{r}\frac{\partial w}{\partial r}\right) + \Phi(r,t)$

Neher-McGrath Calculation Example


Phase Spacing:10.0in. - Circuit Spacing:10.0in. - Burial Depth:42.0in. - Soil Rho:1.00C°-m/W
CBF Width:33.0in. - CBF Height:33.0in. - CBF Rho:0.50C°-m/W - Center Depth:52.0in.
52in.
33in.
33in.
10in.
20in.

Extruded Dielectric Cable (XLPE) Ampacity Worked Example

The ampacity calculation is for a 230kV 1750 kcmil segmented copper conductor circuit, with 866mils XLPE insulation, and lead metallic sheath, 2 circuits installed in a vertical duct bank and 0.60 loss factor. The sheath is cross bonded to minize circulating current.

Cable Data:

$A := 1750$	Conductor area, Cl $\rho_{conductor} := 0.017241$ ohm-meters
$ks := 0.435$	Conductor skin effect factor, dry segmental
$kp := 0.6$	Conductor proximitty effect factor, dry segmental
$Dc := 1.416$	Diameter of the segmental conductor, inches
$Tc := 90$	Maximum allowable normal conductor operating temperature, C
$tcs := 0.0787$	Thickness of conductor semiconducting shield, inches
$ti := 0.866$	Insulation wall thickness, inches
$tis := 0.0984$	Thickness of insulation semiconducting shield, inches
$tms := 0.125$	Thickness of lead moisture barrier / metallic sheath
$tj := 0.125$	Jacket thickness, inches
$SIC := 2.3$	Dielectric constant of the insulation
$\tan\delta := 0.001$	Dissipation factor of the insulation, numeric

Duct Data:

$OD_{duct} := 6.625$	PVC Duct outside diameter, inches
$ID_{duct} := OD_{duct} - 2 \cdot 0.28$ $ID_{duct} = 6.065$	Duct inside diameter, inches

Installation Data:

$Burial := 42$	Depth to center of top conduit, inches
$d_{phases} := 10$	Distance between adjacent phases, inches
$d_{circuits} := 20$	Distance between adjacent circuits, inches
$Ta := 20$	Earth ambient temperature summer, °C
$f := 60$	Power frequency, Hz
$LF := 0.60$	24 hour loss factor
$E := 230000$	System line to line voltage, volts
$n := 1$	Number of conductors per duct
$N := 6$	Number of occupied ducts

Thermal Resistivities:

$\rho_{insulation} := 3.50$	Thermal resistivity of the insulation, C°-m/w
$\rho_{jacket} := 3.50$	Thermal resistivity of the jacket, C°-m/w
$\rho_{duct} := 6.00$	Thermal resistivity of the duct, C°-m/w
$\rho_{native} := 1.00$	Thermal resistivity of the native earth, C°-m/w
$\rho_{backfill} := 0.50$	Thermal resistivity of the duct concrete, C°-m/w
$Width_{cbf} := 33$ $Height_{cbf} := 33$	Width and height of backfill, inches

Calculate Cable Geometry:

$D_{cs} := Dc + 2\cdot tcs$	Diameter over the conductor shield, inches	$D_{cs} = 1.573$
$D_{insulation} := D_{cs} + 2\cdot ti$	Diameter over the insulation, inches	$D_{insulation} = 3.305$
$D_{is} := D_{insulation} + 2\cdot tis$	Diameter over the insulation shield, inches	$D_{is} = 3.502$
$D_{ms} := D_{is} + 2\cdot tms$	Diameter over the metallic shield/moisture barrier, inches	$D_{ms} = 3.752$
$D_{mms} := \frac{D_{is} + D_{ms}}{2}$	Mean metallic shield diameter, inches	$D_{mms} = 3.627$
$D_{jacket} := D_{ms} + 2\cdot tj$	Diameter over jacket, inches	$D_{jacket} = 4.002$
$Clearance := ID_{duct} - D_{jacket}$	Clearance in conduit, inches	$Clearance = 2.063$

Metric Conversion of Variables

$Area_{conductor} := \frac{A}{1.9735}$	$Area_{conductor} = 886.749$	mm^2
$D_{conductor} := Dc\cdot 25.4$	$D_{conductor} = 35.966$	mm
$D_{cond\_shield} := D_{cs}\cdot 25.4$	$D_{cond\_shield} = 39.964$	mm
$D_{insulation} := D_{insulation}\cdot 25.4$	$D_{insulation} = 83.957$	mm
$D_{insl\_shield} := D_{is}\cdot 25.4$	$D_{insl\_shield} = 88.956$	mm
$D_{mean\_shield} := D_{mms}\cdot 25.4$	$D_{mean\_shield} = 92.131$	mm
$D_{met\_shield} := D_{ms}\cdot 25.4$	$D_{met\_shield} = 95.306$	mm
$tms := tms\cdot 25.4$	$tms = 3.175$	mm
$D_{jacket} := D_{jacket}\cdot 25.4$	$D_{jacket} = 101.656$	mm
$OD_{duct} := OD_{duct}\cdot 25.4$	$OD_{duct} = 168.275$	mm
$ID_{duct} := ID_{duct}\cdot 25.4$	$ID_{duct} = 154.051$	mm
$Burial := Burial\cdot 25.4$	$Burial = 1.067\times 10^3$	mm
$d_{phases} := d_{phases}\cdot 25.4$	$d_{phases} = 254.000$	mm
$d_{circuits} := d_{circuits}\cdot 25.4$	$d_{circuits} = 508.000$	mm

Calculate the dielectric losses:

$$W_d := \frac{2\cdot\pi\cdot f\cdot SIC\cdot\left(\frac{E}{\sqrt{3}}\right)^2\cdot\tan\delta\cdot 10^{-9}}{18\cdot\ln\left(\frac{D_{insulation}}{D_{cond\_shield}}\right)} \qquad W_d = 1.144 \quad \text{W/m}$$

Calculate Conductor Resistance:

$R_{dc20} := \frac{\rho_{conductor}}{Area_{conductor}}$ $R_{dc20} = 1.944\times 10^{-5}$ ohms/meter

$R_{dc90} := R_{dc20}\cdot\left(\frac{234.5+Tc}{234.5+20}\right)$ $R_{dc90} = 2.479\times 10^{-5}$ ohms/meter

Assume 2.5% Stranding of Conductor

$R_{dc90} := R_{dc90}\cdot 1.025$ $R_{dc90} = 2.541\times 10^{-5}$ ohms/meter

$Xs := \frac{8\cdot\pi\cdot f\cdot(ks)\cdot 10^{-7}}{R_{dc90}}$ $Xs = 2.581$

$Y_{cs} := \frac{Xs^2}{192+0.8\cdot Xs^2}$ $Y_{cs} = 0.034$

$Xp := \frac{8\cdot\pi\cdot f\cdot(kp)\cdot 10^{-7}}{R_{dc90}}$ $Xp = 3.561$

$$Y_{cp} := \left(\frac{Xp^2}{192+0.8\cdot Xp^2}\right)\cdot\left(\frac{D_{conductor}}{d_{phases}}\right)^2\cdot\left[0.312\left(\frac{D_{conductor}}{d_{phases}}\right)^2 \dots + \frac{1.18}{\left(\frac{Xp^2}{192+0.8\cdot Xp^2}\right)+0.27}\right]$$

$Y_{cp} = 4.468\times 10^{-3}$

$R_{acc} := R_{dc90}\cdot\left(1+Y_{cs}+Y_{cp}\right)$ $R_{acc} = 2.638\times 10^{-5}$ ohms/meter

Calculate the shield losses:

Assume that the conductors will lie in a flat (vertical) configuration for purposes of calculating shield losses. The metallic sheath consists of lead, and the bonding scheme is cross-bonded, so there will be no circulating current and only eddy current losses.

Sheath material is lead $\rho_{lead} := 21.4\cdot 10^{-8}$

$Area_{sheath} := \pi\cdot\frac{\left(D_{ms}^2 - D_{is}^2\right)}{4}$ $Area_{sheath} = 1.424$ mm^2

$Area_{sheath} := Area_{sheath}\cdot 10^{-6}$ m^2

$R_{sheath} := \frac{\rho_{lead}}{Area_{sheath}}$ $R_{sheath} = 0.150$

Estimated sheath temperature: $Tm_{shield} = 78.777$

$R_{sheath} := R_{sheath}\cdot\frac{Tm_{shield}-(-236.0)}{20-(-236.0)}$ $R_{sheath} = 0.185$

Eddy current loss increment

$$m := \frac{2 \cdot \pi \cdot f \cdot 10^{-7}}{R_{sheath}} \qquad m = 2.041 \times 10^{-4}$$

$$Y_{Se0} := 6 \cdot \left(\frac{m^2}{1+m^2}\right) \cdot \left[\left[\frac{(D_{mean\_shield})}{2 \cdot d_{phases}}\right]^2\right] \qquad Y_{Se0} = 8.219 \times 10^{-9}$$

$$Y_{Se1} := 0.86 \, (m)^{3.08} \cdot \left(\frac{D_{mean\_shield}}{2 \cdot d_{phases}}\right)^{1.4 \, m + 0.7} \qquad Y_{Se1} = 1.120 \times 10^{-12}$$

$$\beta_1 := \sqrt{\frac{8 \cdot \pi^2 \cdot f}{\rho_{lead} \cdot 10^7}} \qquad \beta_1 = 47.050$$

$$g_s := 1 + \left(\frac{tms}{D_{mean\_shield}}\right)^{1.74} \cdot \left(\beta_1 \cdot D_{mean\_shield} \cdot 10^{-3} - 1.6\right) \qquad g_s = 1.008$$

$$Y_{se} := \left(\frac{R_{sheath}}{R_{acc}}\right) \cdot \left[g_s \cdot Y_{Se0} \cdot (1 + Y_{Se1}) + \frac{(\beta_1 \cdot tms)^4}{12 \cdot 10^{12}}\right] \qquad Y_{se} = 0.291$$

$Y_{sc} := 0$ Single point bonded so no circulating currents

$$R_{acs} := R_{dc90} \cdot (1 + Y_{cs} + Y_{cp} + Y_{sc} + Y_{se}) \qquad R_{acs} = 3.377 \times 10^{-5}$$

Calculate Cable Thermal Resistances

$$R_i := \frac{\rho_{insulation}}{2 \cdot \pi} \cdot \ln\left(\frac{D_{insl\_shield}}{D_{conductor}}\right) \qquad R_i = 0.504$$

$$R_j := \frac{\rho_{jacket}}{2 \cdot \pi} \cdot \ln\left(\frac{D_{jacket}}{D_{met\_shield}}\right) \qquad R_j = 0.036$$

$Tm_{duct} = 73.578$ Estimate of mean temperature in duct

$$R_{cable\_to\_duct} := \frac{5.2}{1 + 0.1 \cdot (0.91 + 0.01 \cdot Tm_{duct}) \cdot (D_{jacket})} \qquad R_{cable\_to\_duct} = 0.293$$

$$R_{duct} := \frac{\rho_{duct}}{2 \cdot \pi} \cdot \ln\left(\frac{OD_{duct}}{ID_{duct}}\right) \qquad R_{duct} = 0.084$$

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$$Y_{cp} := \left(\frac{Xp^2}{192 + 0.8 \cdot Xp^2} \right) \cdot \left(\frac{D_{conductor}}{d_{phases}} \right)^2 \cdot \left[0.312 \left(\frac{D_{conductor}}{d_{phases}} \right)^2 \ldots + \frac{1.18}{\left(\frac{Xp^2}{192 + 0.8 \cdot Xp^2} \right) + 0.27} \right]$$

$Y_{cp} = 4.468 \times 10^{-3}$

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$$\beta_1 := \sqrt{\frac{8\cdot\pi^2\cdot f}{\rho_{lead}\cdot 10^7}} \qquad \beta_1 = 47.050$$

$$g_s := 1 + \left(\frac{tms}{D_{mean\_shield}}\right)^{1.74}\cdot\left(\beta_1\cdot D_{mean\_shield}\cdot 10^{-3} - 1.6\right) \qquad g_s = 1.008$$

$$Y_{se} := \left(\frac{R_{sheath}}{R_{acc}}\right)\cdot\left[g_s\cdot Y_{Se0}\left(1+Y_{Se1}\right) + \frac{(\beta_1\cdot tms)^4}{12\cdot 10^{12}}\right] \qquad Y_{se} = 0.291$$

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$$R_{duct} := \frac{\rho_{duct}}{2\cdot\pi}\cdot\ln\left(\frac{OD_{duct}}{ID_{duct}}\right) \qquad R_{duct} = 0.084$$

Calculate External Thermal Resistances

Calculate geometric correction factor for backfill envelope:

$x := \mathrm{Width}_{cbf}$ $x := x \cdot 25.4$ $x = 838.200$ $y := \mathrm{Height}_{cbf}$ $y := y \cdot 25.4$ $y = 838.200$

$$D_b := e^{\left[\left(\frac{1}{2}\right)\cdot\left(\frac{x}{y}\right)\cdot\left(\frac{4}{\pi}-\frac{x}{y}\right)\cdot\ln\left(1+\frac{y^2}{x^2}\right)+\ln(x)\right]} \qquad D_b = 921.455$$

$$L_b := \mathrm{Burial} + d_{phases} \qquad L_b = 1.321\times 10^3$$

$$G_b := \ln\left(\frac{2\cdot L_b + \sqrt{4\cdot L_b{}^2 - D_b{}^2}}{D_b}\right) \qquad G_b = 1.714$$

Calculate diameter Dx

$$\alpha_n := \frac{6.71\cdot 10^4}{\left(\rho_{native}\cdot 100\right)^{0.8}}$$ Thermal diffusivity of native soil $\frac{mm^2}{hour}$ $\alpha_n = 1.685\times 10^3$

$D_x := 1.02\sqrt{\alpha_n \cdot 24}$ Diameter beyond which 24 hour average losses apply, mm $D_x = 205.148$

The self and mutual earth thermal resistances each consist of two terms. The first term assumes that the concrete resistivity applies everywhere, the second term corrects for the excess of the native earth resistivity over the concrete resistivity.

$L := \mathrm{Burial} + d_{phases}$ $L = 1.321\times 10^3$ mm

Middle phase has highest total thermal resistance

$$R_{earth} := \frac{\rho_{backfill}}{2\cdot\pi}\cdot\left(\ln\left(\frac{D_x}{OD_{duct}}\right) + LF\cdot\ln\left(\frac{2\cdot L + \sqrt{4\cdot L^2 - OD_{duct}{}^2}}{D_x}\right)\right) \qquad R_{earth} = 0.171$$

Earth thermal resistance for AC losses

$$R_{earth'} := \frac{\rho_{backfill}}{2\cdot\pi}\cdot\left(\ln\left(\frac{D_x}{OD_{duct}}\right) + \ln\left(\frac{2\cdot L + \sqrt{4\cdot L^2 - OD_{duct}{}^2}}{D_x}\right)\right) \qquad R_{earth'} = 0.274$$

Earth thermal resistance for dielectric losses

$$R_{correction} := LF\cdot\frac{\left(\rho_{native} - \rho_{backfill}\right)}{2\cdot\pi}\cdot n\cdot N\cdot G_b \qquad R_{correction} = 0.491$$

Correction for native backfill thermal resistance for AC losses

$$R_{correction'} := \frac{\left(\rho_{native} - \rho_{backfill}\right)}{2\cdot\pi}\cdot n\cdot N\cdot G_b \qquad R_{correction'} = 0.819$$

Correction for native backfill thermal resistance for dielectric losses

Mutual Heating

$$F1 := \left(\frac{2\cdot \text{Burial} + d_{phases}}{d_{phases}}\right)\cdot\left(\frac{2\cdot \text{Burial} + 3\cdot d_{phases}}{d_{phases}}\right) \qquad F2_1 := \left[\frac{\left[\left[2\cdot(\text{Burial} + d_{phases})\right]^2 + {d_{circuits}}^2\right]^{.5}}{d_{circuits}}\right]$$

$$F2_2 := \left[\frac{\left[(2\cdot \text{Burial} + d_{phases})^2 + {d_{circuits}}^2\right]^{.5}}{\left({d_{circuits}}^2 + {d_{phases}}^2\right)^{.5}}\right]\cdot\left[\frac{\left[(2\cdot \text{Burial} + 3\cdot d_{phases})^2 + {d_{circuits}}^2\right]^{.5}}{\left({d_{circuits}}^2 + {d_{phases}}^2\right)^{.5}}\right]$$

$F := F1\cdot F2_1\cdot F2_2$ $\qquad F = 1.262\times 10^4$

Mutual thermal resistance for AC losses:

$$R_{mutual} := \frac{\rho_{backfill}}{2\cdot\pi}\cdot LF\cdot\ln(F) + (N-1)\cdot n\cdot LF\cdot\frac{(\rho_{native} - \rho_{backfill})}{2\cdot\pi}\cdot G_b \qquad R_{mutual} = 0.860$$

Mutual thermal resistance for dielectric losses:

$$R_{mutual'} := \frac{\rho_{backfill}}{2\cdot\pi}\cdot\ln(F) + (N-1)\cdot n\cdot\frac{(\rho_{native} - \rho_{backfill})}{2\cdot\pi}\cdot G_b \qquad R_{mutual'} = 1.434$$

Calculate temperature rise from dielectric heating

$$\Delta T_d := W_d\cdot\left(\frac{1}{2}\cdot R_i + R_j + R_{cable\_to\_duct} + R_{duct} + R_{earth'} + R_{mutual'} + R_{correction'}\right) \qquad \Delta T_d = 3.653$$

Calculate the Ampacity

$$\begin{aligned}\Sigma RacRthermal := {} & R_{acc}\cdot R_i \ldots \\ & + R_{acs}\cdot R_j \ldots \\ & + R_{acs}\cdot R_{cable\_to\_duct} \ldots \\ & + R_{acs}\cdot R_{duct} \ldots \\ & + R_{acs}\cdot R_{earth} \ldots \\ & + R_{acs}\cdot R_{correction} \ldots \\ & + R_{acs}\cdot R_{mutual}\end{aligned} \qquad \Sigma RacRthermal = 7.867\times 10^{-5}$$

C° / A^2

$\Delta T_{cond} := Tc - \Delta T_d - Ta$ $\qquad \Delta T_{cond} = 66.347$

$I_{rated} := \sqrt{\dfrac{\Delta T_{cond}}{\Sigma RacRthermal}}$ — Ampacity per phase group, amperes: $\qquad I_{rated} = 918.3$

$I_{total} := 2\cdot I_{rated}$ — Total ampacity, amperes $\qquad I_{total} = 1836.7$

Check and adjust the estimated shield and duct air temperatures:

$Wc := {I_{rated}}^2\cdot R_{acc}$ — Loss at the conductor, w/m $\qquad Wc = 22.249$

$T's := Tc - Wc\cdot R_i$ — Check temperature of shield which was estimated at $\qquad T's = 78.777$

$Tm_{shield} = 78.777$

$Ws := {I_{rated}}^2\cdot R_{acs}$ $\qquad Ws = 28.478$

$T'm := T's - Ws\cdot\left(R_j + \dfrac{R_{cable\_to\_duct}}{2}\right)$ — Check mean temperature between cable surface and inside of duct which was estimated at: $\qquad T'm = 73.578$

$Tm_{duct} = 73.578$

Wikipedia

Basic information about the Neher McGrath method, Calculations, Complexities, heating and

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Other News

NFPA-70E 5-Year Refresh Requirement

Friday, 6th April 2020

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New Code Requirements

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