Determining the CW Power Rating of Coaxial Components

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When evaluating the power handling of coaxial lines, a common analysis has been based upon the peak power capacity of the line as a function of dielectric resistance. However, continuous wave (CW) power cannot be accurately evaluated based upon a peak power rating. CW power handling is a function of the energy transfer capacity of the coaxial line and ambient environment rather than its dielectric resistance. The evaluation of a coaxial line using a combination of thermodynamic and microwave principles will provide the base of knowledge necessary to accurately calculate its CW power capacity.

The Laws of Thermodynamics

The first two laws of thermodynamics form the framework of this coaxial line model. The thermodynamic model is based upon that of an adiabatic system, with the adiabatic wall placed in the ambient environment surrounding the coaxial line. The overall energy within an adiabatic system during steady state heat transfer must be equal to zero. This follows the First Law of Thermodynamics: the conservation of energy. Since the total energy for an adiabatic system must equal zero, the total thermal energy transferred through the layers of the coaxial line must be of an equal and opposite magnitude to that of the energy source, the dissipated input RF power.

The Second Law of Thermodynamics is an expression of entropy. In terms of thermal energy, entropy is a measure of the progress of the irreversible heat migration from a hot region to a cold region until thermal equilibrium is achieved. Taking the First and Second Laws of Thermodynamics in conjunction, the heat transfer model for a coaxial line in thermal equilibrium is bounded by the following two laws: Heat will always move toward the coolest element of the system, and the maximum dissipated RF energy must equal the energy transfer capacity of the system.

The Energy Source in a Coaxial Line

The input RF power in either actual or effective continuous wave form transmitted along the center conductor of the coaxial line will have a percentage of its magnitude decreased by conductor and dielectric losses as well as any wave reflections. The lower the transmission efficiency of the coaxial line, the greater the magnitude of dissipated energy present. This energy raises the temperature of the material layers within the coaxial line as it is conducted away from the source.

The transmission efficiency of the coaxial line is primarily a function of its attenuation. The three components that contribute to the total attenuation of a coaxial line are inner and outer conductor losses and the dielectric loss [3]. The distribution of dissipated energy in the coaxial line from attenuation is shown in Figure 1. The highest concentration of energy is along the center conductor skin and surrounding dielectric. The remaining dissipated energy is along the skin of the outer conductor.

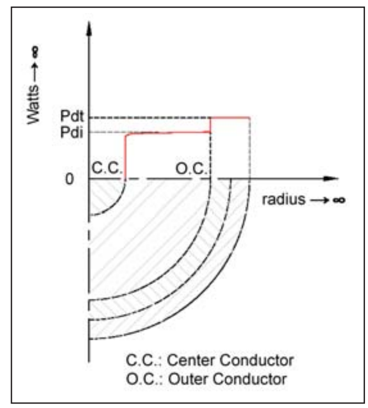

Figure 1 · Distribution of energy in a coaxial line.

The dissipated energy at the center conductor (P_{di}) is not of the same magnitude as the total energy dissipated by line (P_{dt}). This requires that the model account for a two-level magnitude of dissipated energy. The dielectric core is only transferring the dissipated energy due to the center conductor and dielectric losses. The attenuation of the line due to center conductor and dielectric loss (A_i) is dependent on the frequency F (MHz), characteristic impedance Z_0 (ohm) of the line, diameter D_i (m) of the conductor, the loss tangent τ and dielectric constant ε_r of the dielectric, and the length L (m) of the line. The combined loss in dB is expressed as:

$$A_i = L\left(\frac{3.624\times10^{-4}\sqrt{F}}{Z_0 D_i} + .09118F\tau\sqrt{\varepsilon_r}\right) \tag{1}$$

The dissipated energy present at the outer conductor (P_{dt}) is due to the total attenuation A_t of the line. The total attenuation is calculated through the addition of the outer conductor loss with the new variable being the diameter D_o (meters) of the outer conductor. The total attenuation in dB is expressed as:

$$A_i = L\left(3.624\times10^{-4}\sqrt{F}\left(\frac{1}{Z_0 D_i} + \frac{1}{Z_0 D_0}\right) + .09118F\tau\sqrt{\varepsilon_r}\right) \tag{2}$$

Either level of dissipated RF power (P_{dx}), in watts, can be found by inputing the corresponding attenuation from Equation 1 or 2 into the following equation:

$$P_{dx} = P_i - P_i \cdot 10^{(-A_x/10)} \tag{3}$$

Energy dissipation due to reflection of the incident power can also be present. However, the model being presented here is of a coaxial line independent of the effects of reflection and mismatch created by adjacent components within a system. The assumptions of an exact impedance match and a VSWR of unity are taken, thereby removing these variables from the model [3]. If necessary, the magnitude of the additional heat due to system mismatch losses can be calculated using the methods shown in [4] and [16] and added into this model.

Typical Thermal Conductivity at 25°C (W/mK)	
Teflon® PTFE	0.23
Teflon FEP®	0.195
Fluoroloy H®	1.21
Kapton®	0.14
Aluminum	209.4
Copper (SPC)	384
77% PTFE	0.18
Air	0.026
SS 304	16
82% PTFE	0.17
BeCu	105

Table 1 · Thermal conductivities for various common materials.

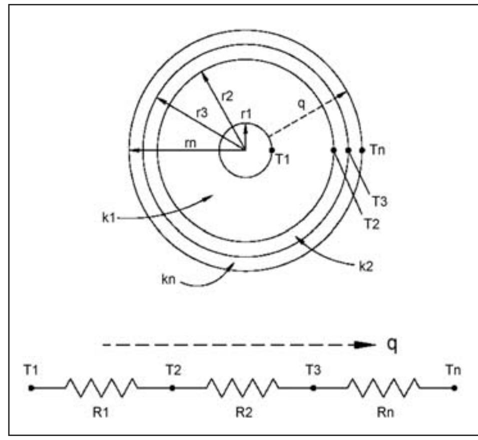

Figure 2 · Heat flow path diagram for a coaxial structure.

Conductive Heat Transfer

Thermal energy moves through any material using a combination of the three modes of heat transfer: conduction, convection, and radiation. Within the coaxial line, the energy is transferred using conduction between the different materials. Analysis of the conductive heat transfer process within the coaxial line is based upon the following conditions:

1. Heat transfer is radial and one-dimensional within a coaxial line that is symmetrical and uniform in dimensions along the axis of the conductors.
2. There is internal heat generation at the surfaces of the center and outer conductors as well as throughout the dielectric.
3. There is uniform temperature at each face.
4. The materials have constant thermal conductivity.
5. There is perfect thermal contact between each layer within the coaxial line.
6. The coaxial line has reached a point of thermal stability and heat transfer is steady state under CW RF power [7].

With these conditions in place, the mathematical analysis of the one-dimensional distribution and flow of energy at any radial point within a coaxial line is expressed by the Poisson equation [6]:

$$\nabla^2 T(\bar{r}) + \frac{q(\bar{r})}{k} = 0 \qquad (4)$$

This equation follows the first two laws of thermodynamics and confirms both the conservation of and entropic distribution of energy within an adiabatic system. The resultant sum of the thermal energy flux (q) and the Laplacian of the temperature ($\nabla^2 T$) vectors indicates that their magnitudes are directly opposite to each other [6]. The thermal conductivity (k) of the material is the only modifier of this relationship. Table 1 gives typical values for the thermal conductivity of materials common to coaxial line construction.

The solution to Poisson's Equation (Eq. 4) for a coaxial line in terms of conductive energy transfer (Q) is:

$$Q = \frac{2\pi L (T_1 - T_n)}{\sum_{k_1, r_1}^{k_n, r_n} \left[\frac{\ln (r_n / r_{n-1})}{k_{n-1}} \right]} \qquad (5)$$

The conductive heat flow within a composite cylinder is a function of the total temperature delta and material thermal resistance. The logarithm of the inner and outer diameter of each layer is an important factor in the cylindrical model as the heat flux is being conducted radially away from the center through a continually increasing surface area [14]. The individual diameter relationship and thermal conductivity of each layer is added together to derive the total series resistance along the coaxial line radius. Figure 2 illustrates the application of this equation within a coaxial line with n layers [2].

Convective Heat Transfer

In non-vacuum environments the outer surface of the coaxial line is cooled by the transfer of heat into a fluid medium, liquid or gas, through the processes of conduction and convection. Conductive heat transfer into a fluid is less efficient than it is through a solid material because of the larger distance between the molecules. Heat transfer into a gas is the least effective of all conductive paths. However, convective heat transfer, unique to fluids, increases the energy transfer rate at the outer surface of the coaxial line.

There are two types of convective heat transfer: free convection and forced convection. Forced convection is used throughout the electronics industry to cool components with the use of fans or heat pipes that are forcibly moving a gas or liquid past the heated element. Forced convection is more effective than free convection, which depends upon the natural motion of the fluid caused by differences in density as portions of its volume experience a rise in temperature [1]. The fluid movement in free convection is of a much lower velocity than that present in forced convection. Forced convection can occur naturally in the form of turbulent flow, but this is not present at coaxial line surface temperatures less than 200°C [15]. Therefore, free convection accurately models the environment that most coaxial lines operate within and is a conservative baseline.

The convective heat transfer (Q) equation (in watts) based upon the Poisson Equation (Eq. 4) is:

$$Q = a_c \cdot A_n (T_n - T_a) \quad (6)$$

The convective heat transfer is a function of the heat transfer coefficient (a_c), surface area (A_n), and temperature delta ($T_{n,a}$). Convective heat transfer is primarily focused within the boundary layer around the surface of the coaxial line, not at the surface itself [5] (see Fig. 3). The thickness and density of this boundary layer are included within the calculation of the convective heat transfer coefficient.

As a model of the fluid flow about the surface of the coaxial line, the heat transfer coefficient is unique to the profile and orientation of the component. If the major axis of the coaxial line is in the horizontal axis, the coefficient (in W/m^{2}K) is determined by the following equation [8]:

$$a_c = \frac{Nu_h k}{D} \quad (7\text{-}1)$$

However, if the major axis of the coaxial line is in the vertical axis, the coefficient is determined by the equation [8] (in W/m^{2}K):

$$a_c = \frac{Nu_v k}{H} \quad (7\text{-}2)$$

The variables for thermal conductivity of the fluid (k) and outside diameter of the coaxial line (D) or its height (H) are intuitive. The dimensionless parameter added is the Nusselt Number ($Nu_{h,v}$). The Nusselt Number is directly related to the boundary film layer thickness enveloping the surface of the coaxial line and is also dependent upon the coaxial line orientation. As the value of the Nusselt Number grows, it indicates that the heat transfer rate is being increased by convection [13] within the thermal boundary layer. A coaxial line with its major axis in the vertical position will have a larger Nusselt Number than if it is oriented in the horizontal position. Therefore, a coaxial line that is running vertically has a larger energy transfer capacity. The variances in convective flow are modeled by these equations for any non-vacuum ambient environment.

[Editor's note—Appendix A, Nusselt Number Calculation, will be included in the version of this article archived online at: www.highfrequencyelectronics.com]

Radiant Heat Transfer

Energy transfer in the form of electromagnetic radiation occurs between the exterior surfaces of all solids [1]. Radiant heat flow moves through any medium separating the two solids including vacuum. Radiant heat transfer also occurs within composite solids but only becomes a factor if there is an air-spaced core present [9]. The rate of radiant heat transfer is typically very small and may be omitted from the coaxial line model unless one of the surfaces is at least 150°C. However, other than conduction, radiant heat transfer is the only process that will heat or cool the coaxial line in a vacuum environment making it a vital process to model for these applications.

Surface Material Emissivity Coefficient at 300K	
Aluminum, Polished	0.048
Aluminum, Comm.	0.09
Teflon FEP®	0.85
Polyethylene, Black	0.92
Beryllium Copper	0.03
Brass, Dull	0.22
Brass, Polished	0.03
Copper, Polished	0.038
Gold, Polished	0.026
Dry Air [11, 12]	0.833
Nickel, Polished	0.072
Silver, Polished	0.025
SS 304	0.11
SS, Polished	0.075

Table 2 · Emissivities for materials used in coaxial lines.

The heat transfer equation for radiant energy (in watts) is similar to the solution for convective heat transfer:

$$Q = a_r \cdot A_n (T_n - T_a) \quad (8)$$

The radiant heat transfer coefficient (a_r) is calculated very differently than that for convection. It takes into account the essential constants and variables that apply to radiant heat flow. These are the Stefan-Boltzmann Constant (σ) of 5.67×10^{-8} W/m^{2}K^4, the Geometric Form Factor (F) of the solids as well as the specific emissivities (ε) and surface areas (A) of the solids. The radiant heat transfer coefficient (in W/m^{2}K) for the coaxial line is calculated from the equation [8]:

$$a_r = \frac{F\left(T_n^4 - T_a^4\right)}{\left[\dfrac{1}{\sigma\varepsilon_n} + \dfrac{A_n}{A_a}\left(\dfrac{1}{\sigma\varepsilon_a} - \dfrac{1}{\sigma\varepsilon_s}\right)\right]\left(T_n - T_a\right)} \quad (9)$$

For enveloping cylinders in the model being considered here, the Geometric Form Factor (F) is equal to 1. However, for other geometric configurations and solid profiles, the Geometric Form Factors and charts can be found in [5] and [10]. The surface area A_n is that of the coaxial line and A_a that of the enveloping surface. The radiation constant $\sigma\varepsilon_s$ is that of a black body. The radiation constant $\sigma\varepsilon_x$ for the other surfaces, considered gray bodies, is dependent on the relative emissivity (ε_x) of the surface materials, with a black body having a reference emissivity of 1. Table 2 shows the relative emissivities of common surface materials for coaxial lines as well as dry air.

The radiant heat transfer formula is applicable for a coaxial line that is engaged in heat transfer with another solid at a relatively similar temperature. The applicability of this formula is dependent upon both surfaces emitting energy within the infrared spectrum. Within the infrared spectrum, emissivity (ε) and absorptivity (α) are mathematically equivalent following Kirchhoff's Law. However, in

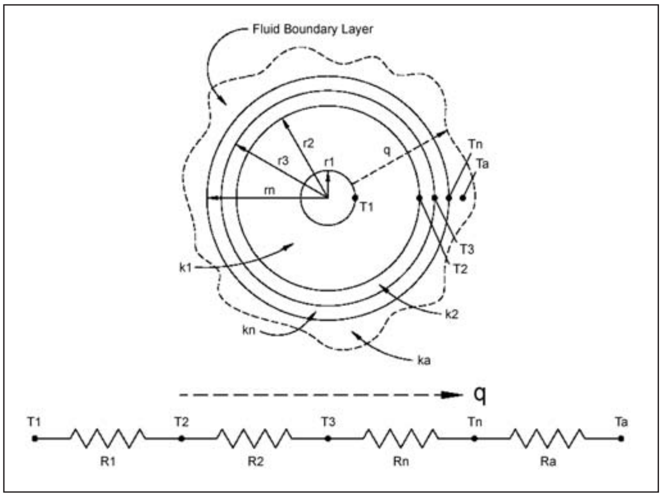

Figure 3 · Composite heat transfer paths, including radiant transfer to surrounding fluid (usually air).

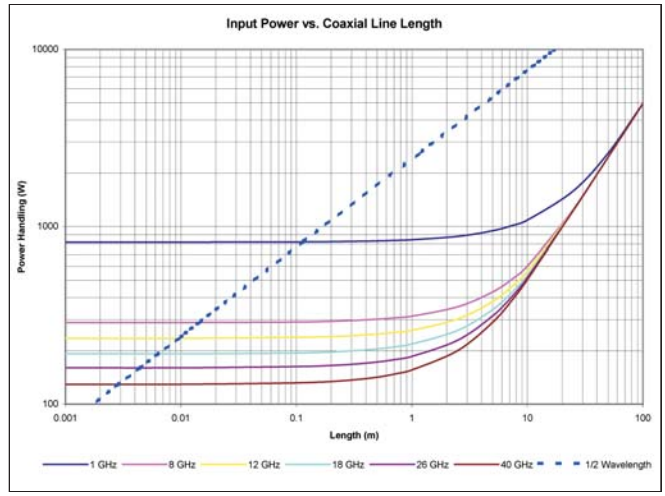

Figure 4 · Power handling vs. line length at various microwave frequencies.

applications in which the coaxial component surface will be exposed to radiant energy in the visible spectrum, emissivity and absorptivity are no longer equivalent. Radiant energy in the visible spectrum is absorbed, but the surface of the coaxial line will only be able to emit energy in the infrared spectrum. In this case, material absorptivity must be included in the model.

The Composite Heat Transfer Model

The composite coaxial line model combines the conductive, convective, and radiant modes of heat transfer to provide a complete analysis of the process. The effects of convective and radiant heat transfer can be merged together as they transfer energy away from the surface of the line in parallel. This heat transfer combination (in watts) is:

$$Q = (a_c + a_r) \cdot A(T_n - T_a) \tag{10}$$

The convective and radiant parallel resistance is added in series to the conductive resistance of Equation 5 to create an equation that accurately models the entire coaxial line heat transfer process:

$$Q = \frac{2\pi L(T_1 - T_a)}{\sum_{k_1, r_1}^{k_n, r_r}\left[\frac{\ln(r_n / r_{n-1})}{k_{n-1}}\right] + \frac{1}{r_n(a_c + a_r)}} \tag{11}$$

Figure 3 illustrates the application of this equation to a coaxial line with n layers and surrounded by fluid a [2].

The Applied Model

The energy transfer capacity of the coaxial line is directly dependent upon the thermal potential, or delta, between the center conductor and the environment. With known ambient temperature, pressure, and radiation constants, the center conductor temperature can be raised and lowered to determine the energy transferred away from the center conductor. The conservation of energy within the model requires the equivalence of the magnitudes of input energy, the maximum dissipated RF power (P_{dx}), and output energy, the heat transfer capacity of the line (Q), under the specified boundary temperatures.

However, the distribution of dissipated energy shown in Figure 1 indicates that the energy transfer capacity of the coaxial line is equivalent to the two quantities of dissipated energy, applied in series over separate geometries. An expanded derivation of Eq. (11) is created to evaluate this, where the dissipated power levels (P_{di}, P_{dt}) are substituted for the energy transfer capacity (Q). This final equation is expressed in terms of the center conductor temperature as:

$$T_1 = T_a + \frac{P_i \ln(r_2 / r_1) \cdot 10^{-A_i/10}\left(10^{A_i/10} - 1\right)}{2\pi k_1 L} + \frac{P_i\left(\sum_{k_1, r_1}^{k_n, r_r}\left[\frac{\ln(r_n / r_{n-1})}{k_{n-1}}\right] + \frac{1}{r_n(a_c + a_r)}\right) \cdot 10^{-A_t/10}\left(10^{A_t/10} - 1\right)}{2\pi L} \tag{12}$$

This equation accurately calculates the temperature at the center conductor, or any intermediate layer within a coaxial line, under any combination of ambient conditions. Equation 12 is the applied form of the general heat transfer relationship that defines the temperature rise as a function of energy magnitude and thermal resistance:

$$\Delta T = P_{di} R_1 + P_{dt} \sum_{2}^{n} R_n \tag{13}$$

Coaxial Line Length

The length of the coaxial line (L) in Equation 12 has a linear relationship with the magnitude of its energy transfer capacity. The natural conclusion is to input the physical length of the coaxial line into the equation. This is not the case. At the input side of the coaxial line the power is of the greatest magnitude. As the RF current flows along the

Coaxial Line Features		Test Condition Variables				Coaxial Line Surface Temperature Accuracy		
Cable Construction	Cable Diameter	Input RF Power	Frequency	Ambient Environment	Distance from Input (m)	Model Temp. (C)	Measured Temp. (C)	Error
Flex: 3-shield	.142 in.	97 W	7.19 GHz	25°C Sea Level	0.5	76.3	71.5	6.29%
Flex: 3-shield	.215 in.	96 W	7.19 GHz	25°C Sea Level	0.5	53.4	52.6	1.50%
Flex: 3-shield	.300 in.	160 W	2.45 GHz	60°C Vacuum	0.1	115.5	115.1	0.34%
Flex: 3-shield	.300 in.	160 W	2.45 GHz	60°C Vacuum	0.35	113.4	107.6	5.11%
Flex: 3-shield	.300 in.	160 W	2.45 GHz	60°C Vacuum	0.6	111.1	107.2	3.51%
Semi-Rigid	.250 in.	250 W	1.70 GHz	100°C Vacuum	0.5	239.2	230.0	3.85%
Semi-Rigid	.141 in.	97 W	7.19 GHz	25°C Sea Level	0.5	85.1	86.3	1.41%

Table 3 · Comparison of modeled and measured data for some of the tested cable types.

Coaxial Line Features		Test Condition Variables				Coaxial Line Layer Temperature Accuracy		
Cable Layer (O.D.)	Cable Diameter	Input RF Power	Frequency	Ambient Environment	Distance from Input (m)	Model Temp. (C)	Measured Temp. (C)	Error
Dielectric	.156 in.	96 W	7.19 GHz	25°C Sea Level	0.5	58.6	58.2	0.68%
Outer Cond.	.168 in.	96 W	7.19 GHz	25°C Sea Level	0.5	58.3	58.0	0.52%
Binder	.175 in.	96 W	7.19 GHz	25°C Sea Level	0.5	57.8	57.1	1.21%
Shield Braid	.194 in.	96 W	7.19 GHz	25°C Sea Level	0.5	57.7	56.9	1.39%
Jacket	.215 in.	96 W	7.19 GHz	25°C Sea Level	0.5	53.4	52.6	1.50%

Table 4 · Comparison of modeled and measured data for internal layers of a coaxial cable.

length of the coaxial line, the dissipated power follows a nonlinear regression in magnitude. Conversely, as the length of the coaxial line increases so does its energy transfer capacity. This creates an increasing divergence between the magnitudes of dissipated energy and energy transfer capacity along the coaxial line. With this divergence present, the requirement of energy conservation falsely indicates that the coaxial line can handle more dissipated power due to its increased transfer capacity.

To avoid this incorrect result, the coaxial line must be analyzed using a length at which this divergence is not present. The location at which the magnitudes of dissipated energy and energy transfer capacity approach equivalence is at a line length approaching zero. As the length approaches zero, the attenuation dissipates an increasing magnitude of energy per unit length. This input region in the coaxial line is a primary limiting factor for the CW power level. Figure 4 displays this length relationship and the distortion caused by the divergence as the line length increases.

Figure 4 also gives a guideline as to the line length to input into the model for microwave frequencies. At microwave frequencies, a maximum physical length of a half-wavelength at the operating frequency generates a model that is unaffected by the divergence issue. This limits the CW power to the transfer capacity at the input of the line rather than the capacity of the entire line.

Most coaxial lines are significantly longer than a half-wavelength, and it is important to include the physical length within the model as this additional material often serves as a limited heat sink. To accomplish this, the entire coaxial line must be divided into parallel segments of a length following Figure 4. Each segment is then modeled using the serial thermal resistance of the layers, as shown in Eq. (12) and (13). The results of each of these segments are then combined using a parallel thermal resistance equation. Starting with the input of the line as "Segment 1" and modeling the adjacent segments up to "Segment n," the parallel model to determine center conductor temperature (in kelvins) based upon the simplified form of Equation 13 is:

$$\Delta T = \sum_{1}^{n} P_{di} \sum_{1}^{n} \left(\frac{1}{R_1} \right)^{-1} + \sum_{1}^{n} P_{dt} \sum_{1}^{n} \left(\frac{1}{R_0} \right)^{-1} \qquad (14)$$

Verification of the Model

To verify the accuracy of this model, experimental data was taken for several different coaxial line constructions, power levels, and ambient environments. Thermocouples were placed at various locations along the jacket of the coaxial lines while connected to an RF power source. The average error between the predicted and measured jacket temperature for all of the models was about 3%. Table 3 shows the measured surface temperatures for a sample of the tests performed.

Further tests were performed with thermocouples built into the coaxial line itself and placed between each of the composite layers surrounding the dielectric core to verify the temperature difference between each layer. The average error between the predicted and measured layer temperatures was about 1%. Table 4 shows the measured internal layer temperatures for one of the tests performed. The accuracy of the model throughout the various test environments was established and justifies the assumptions taken.

Conclusion

This thermal model not only allows for the accurate analysis of the CW power handling of a coaxial line but also gives an engineer the ability to recognize the interaction of each factor involved. There are several software suites available within the industry capable of quickly performing accurate simulations based upon these concepts. With these options available and a clear understanding of the applied principles from this analysis, an engineer will have the necessary tools to design and improve a coaxial line for optimal CW power handling in any operating environment.

Notes

FEP Teflon is a registered trademark of Dupont, Teflon is a registered trademark of Dupont, Kapton is a registered trademark of Dupont, and Fluoroloy H is a registered trademark of Saint Gobain Corp.

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The APPENDIX follows on the next two pages

APPENDIX

Nusselt Number Calculation

The Nusselt Number is based upon two other dimensionless but empirically proven numbers: the Grashof Number and the Prandtl Number. The Grashof Number combines the calculated buoyancy of the fluid based upon the fluid's viscosity and thermal expansion [5]. The Prandtl Number is the ratio of the fluid's dynamic viscosity to its thermal conductivity. Table A1 shows the proper equations to use based upon either a horizontal or vertical orientation of the coaxial line.

	Grashof Number (Gr)	Prandtl Number (Pr)
Horizontal Coaxial Line:	$= \frac{g\gamma\Delta T\varphi^2 D^3}{\eta^2}$ (A1-1)	$= \frac{\eta c_p}{k}$ (A2)
Vertical Coaxial Line:	$= \frac{g\gamma\Delta T\varphi^2 H^3}{\eta^2}$ (A1-2)	

g = Gravitational Acceleration (m/s^2)
γ = Volume Expansion Coefficient ($1/T_a$)
ΔT = Temperature Difference (C)
φ = Fluid Density (kg/m^3)
D = Outer Diameter of Coaxial Line (m)
η = Fluid Dynamic Viscosity (p s $\cdot 10^{-6}$)
c_p = Specific Heat Capacity (kJ/kgK)
k = Fluid Thermal Conductivity (W/mK)

Table A1 (8)

In the case of convective heat transfer into dry air, which is the most conservative factor of heat transmission for standard environments, the values for the fluid density, dynamic viscosity, kinematic viscosity, and thermal conductivity for different temperatures can be found in published data [8].

The Nusselt Number is calculated from the product of the Grashof and Prandtl numbers along with two other constant relationships. The Nusselt Number formula is shown in Table A2 for both horizontal and vertical orientations of a coaxial line.

	$10^4 < Gr \cdot Pr < 10^9$	$10^9 < Gr \cdot Pr < 10^{12}$
Horizontal Coaxial Line Nusselt Number	$= .53\sqrt[4]{Gr \cdot Pr}$ (A3-1)	$= .13\sqrt[4]{Gr \cdot Pr}$ (A3-2)
Vertical Coaxial Line Nusselt Number	$= .56\sqrt[4]{Gr \cdot Pr}$ (A4-1)	$= .13\sqrt[3]{Gr \cdot Pr}$ (A4-2)

Table A2 (2)

The above values and equations allow for accurate modeling of the convective boundary layer present around the outer diameter of a coaxial line during free convection. To adjust for the effects of altitude, established derating curves offer a very quick and highly safe prediction of what the system will be able to handle. Figure A1 (on the following page) gives two examples of these curves, the first from a military specification governing Aerospace Wiring [17] and the second from a Dept. of Navy study [7] of coaxial cable in 1971.

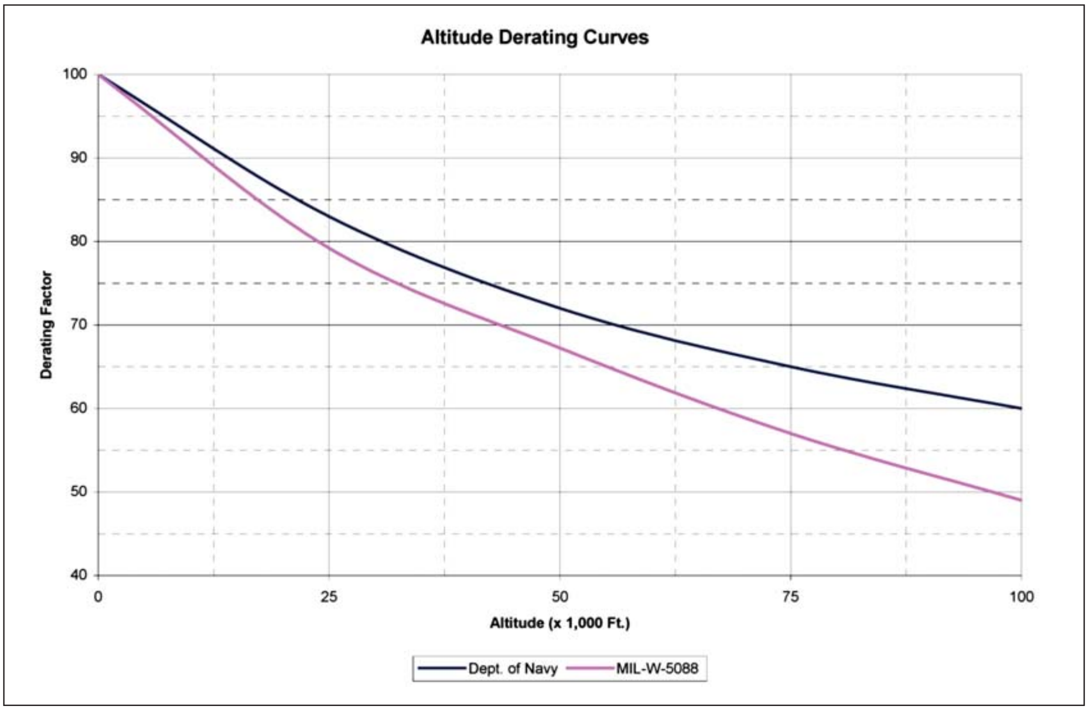

Figure A-1

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