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Performance Analysis of Radiation Cooled DC Transmission Lines for High Power Space Systems

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PERFORMANCE ANALYSIS OF RADIATION COOLED DC TRANSMISSION LINES FOR HIGH POWER SPACE SYSTEMS

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SUMMARY

As space power levels increase to meet mission objectives and also as the transmission distance between power source and load increases, the mass, volume, power loss, and operating voltage and temperature become important system design considerations. This analysis develops the dependence of the specific mass and percent power loss on the power and voltage levels, transmission distance, operating temperature and conductor material properties. Only radiation cooling is considered since the transmission line is assumed to operate in a space environment. The results show that the limiting conditions for achieving low specific mass, percent power loss, and volume for a space type dc transmission line are the permissible transmission voltage and operating temperature. Other means to achieve low specific mass includes the judicious choice of conductor materials. The results of this analysis should be immediately applicable to power system trade-off studies including comparisons with ac transmission systems.

INTRODUCTION

Presnet spacecraft distribute low power at low dc voltages over short transmission distances. The power requirements in future space systems, however, will greatly increase. Examples of these increasing power demands include the Space Station (75 kW) and proposed space power systems (100 kW to 1 MW) discussed in reference 1. It can be anticipated as more ambitious space missions unfold, even greater quantities of power will be required to meet missions objectives.

As both the power levels and transmission distances increase, the transmission line becomes a critical element in the power chain between the source and load bus. Thus, the transmission line's design parameters must be characterized so that the effect of these parameters on the total power system can be assessed.

The purpose of this analysis is to determine the dependency of the dc transmission line's mass, loss, and size on the power and voltage levels, operating temperature, transmission distance, and conductor material properties. In particular, the primary objective of this analysis is to make a quantitative assessment of those parameters which have the greatest impact on the mass, loss, and size of the transmission line.

In this analysis the assumption is made that the transmission line is physically located in the space environment and that the only allowable mode of heat transfer is thermal radiation. From this assumption it follows that all heat losses generated by the line are radiated by the line and that none of these losses are conducted to any other part of the spacecraft. Thus, in this analysis, the transmission line not only transmits the power but also acts as its own radiator by directly radiating to space the electrical power losses generated within the transmission line's conductor material.

The geometry of the transmission line analyzed in this paper is a non-insulated solid cylindrical conductor. The expressions derived for the transmission line's mass only include the conductor mass and additional mass such as electrical insulation, line supports and metorite shielding must be taken into consideration by the designer. The assumption that the transmission line is noninsulated not only affects the actual mass of the line, but also, perhaps more importantly, affects the actual operating temperature of the line. For an insulated line the thermal analysis becomes considerably more complex since the thermal gradient across the insulation must be determined and the complexity of the problem increases if multilayers of different types of insulation are used. Thus, the masses and operating temperatures derived in this analysis should be considered as the minimum possible for the geometry and thermal transfer assumed. Once the insulation requirements for the line are specified, then with additional thermal analysis the actual masses and operating temperatures can be determined.

Geometries other than a solid conductor might have to be considered for particular applications. If the transmission line must be flexible for deployment purposes, then a cable composed of fine stranded wire might be required but this requirement will lead to a bulkier transmission line. As the power levels and transmission distances increase and thermal radiation is the only means of heat transfer, then geometries such as thin-walled tubing might have to be considered in order to achieve acceptable operating temperatures by increasing the transmission line's surface area. In any event, the methods used in this analysis to determine the transmission line's characteristics should also be applicable to geometries other than the solid cylindrical conductor geometry used in this analysis.

SYMBOLS

A_c	conductor cross-sectional area, m^2
A_s	conductor surface area, m^2
D	distance between parallel conductors, mm
D_c	conductor density, kg/m^3
d_c	conductor diameter, mm
F	configuration factor, dimensionless
$(1-F)$	view factor to space, dimensionless
I	load current, A
J	current density, A/m^2
j	inverse current density, cir.mils/A
$K(T)$	temperature factor, $(m^2/W)^2$
L	total transmission line length, m
M_c	conductor mass, kg
(M_c/P_G)	specific mass, kg/kW
$(M_c/P_G L)$	normalized specific mass, kg/kWm
P_B	bus power, kW
P_G	dc generator output power, kW
P_L	transmission power loss, kW
Q	radiant heat loss rate, kW
R	conductor resistance, ohms

REG(%)	percent voltage regulation, dimensionless
T	operating or surface temperature, K
T_S	sink temperature, K
T_Z	inferred zero resistance temperature, K
V	dc generator output voltage, V
V_B	bus voltage, V
$\alpha(\%)$	percent power loss, dimensionless
$[\alpha(\%)/L]$	normalized percent power loss, m^{-1}
ϵ	emissivity, dimensionless
$\eta(\%)$	transmission efficiency, dimensionless
$\rho(T)$	conductor resistivity, ohm-m
ρ_0	conductor resistivity at 293 K, Ohm-m
σ	Stefan-Boltzmann constant = 5.67×10^{-8} W/m^2K^4

ANALYSIS

In this analysis section, mathematical expressions are derived for the transmission line's mass, percent power loss, conductor diameter and inverse current density in terms of the power and voltage transmission levels, operating temperature and conductor material properties. Expressions for the normalized specific mass and the normalized percent power loss are also defined. These expressions are used to make plots of the normalized specific mass as a function of the normalized percent power loss with temperature, voltage, power and conductor material as parameters. These plots will enable the system designer to quickly make mass and percent power loss trade-offs for the dc transmission line.

Power Loss

The percent power loss is defined as

$$\alpha(\%) = \frac{P_L}{P_G} \times 10^2 \tag{1}$$

where P_G is the dc generator output power and P_L is the conductor or line loss power. If P_B is the power delivered to the bus via the transmission line from the generator, then the efficiency of power transfer is

$$\eta(\%) = \frac{P_B}{P_G} \times 10^2 = \left(\frac{P_G - P_L}{P_G}\right) \times 10^2 = [100 - \alpha(\%)] \tag{2}$$

If V is the generator output voltage, V_B the bus voltage at the load and R the resistance of the transmission line conductor, then the percent voltage regulation of the line is

$$REG(\%) = \left(\frac{V - V_B}{V}\right) \times 10^2 = \frac{IR}{V} = \frac{P_L}{P_G} \times 10^2 \tag{3}$$

The results of these last three equations shows that

$$\alpha(\%) = REG(\%) = [100 - \eta(\%)] \qquad (4)$$

If we assume a solid conductor with circular cross-sectional area, then the dc resistance of the transmission line conductor is

$$R = \frac{\rho(T)L}{A_c} = \frac{4\rho(T)L \times 10^6}{\pi d_c^2} \quad \text{ohms} \qquad (5)$$

In equation (5), L represents the total length of the transmission line including a return line if such is required. The resistivity of the conductor material is a function of the temperature and in the first approximation is given by

$$\rho(T) = \rho_0 \left[\frac{T - T_z}{293\ K - T_z}\right] \quad \text{ohm m} \qquad (6)$$

where ρ_0 is the resistivity of the conductor at 293 K (20 °C) and T_z is the inferred zero resistance temperature in degrees Kelvin. For copper and aluminum conductors, T_z = 38.5 K (-234.5 °C).

The power loss generated by the conductor is

$$P_L = I^2R \times 10^{-3} = \frac{P_G^{\,2}R \times 10^3}{V^2} \quad \text{kW} \qquad (7)$$

The substitution of equation (5) into equation (7) gives

$$P_L = \frac{4\rho(T)\ L\ P_G^{\,2} \times 10^9}{\pi\ d_c^{\,2}\ V^2} \quad \text{kW} \qquad (8)$$

Heat Balance

In a true space environment the only mode of heat transfer is by radiation. In this analysis it is assumed that the heat generated in the conductor due to the power loss is dissipated to space only by radiative heat transfer. It is also assumed that the conductor has an infinite thermal conductivity so that the surface temperature of the conductor represents the temperature of the entire conductor.

For thermal radiation heat transfer the Stefan-Boltzmann Law applies so that the net radiant heat loss rate Q is

$$Q = \sigma\epsilon\ (1-F)\ A_s\ (T^4 - T_s^{\,4}) \times 10^{-3} \quad \text{kW} \qquad (9)$$

For a circular cross-sectional area conductor, the surface area is

$$A_s = \pi \, d_c \, L \times 10^{-3} \qquad m$$

so that equation (9) becomes

$$Q = \pi \, \sigma \, \epsilon \, (1-F) \, d_c \, L \, (T^4 - T_s^4) \times 10^{-6} \qquad kW \tag{10}$$

For a transmission line with a return, the geometric configuration factor F must be taken into consideration. The geometric configuration factor depends on the geometric orientation of one surface with respect to another surface. The factor F represents the fraction of thermal energy leaving one surface and reaching the other surface. The fraction of energy being transferred to space by the rest of the conductor surface area is then (1-F) and this factor is then defined as the view factor to space.

The configuration factor F for infinitely long semicylinders of equal radi is determined from reference 2 to be

$$F = \frac{2}{\pi} \left\{ \sqrt{(D/d_c)[(D/d_c) + 2]} + \sin^{-1} \left[\frac{1}{(D/d_c) + 1} \right] - (D/d_c) - 1 \right\} \tag{11}$$

In figure 1 the view factor to space (1-F) is plotted against the ratio of the separation distance of the conductors to the conductor diameter. Equation (11) shows that in the limit as D approaches zero or d_c approaches infinity, then (1-F) approaches 0.637 and this represents the worse case. If either D approaches infinity or d_c approaches zero, then (1-F) approaches one. When the separation distance D is equal to the conductor diameter, then (1-F) = 0.84.

Under steady state conditions, the net thermal radiant heat loss rate must be in energy balance with the conductor power loss so that $Q = P_L$. By equation (8) and equation (10) the diameter of the conductor is found to be

$$d_c = \left[\left(\frac{2P_G}{\pi V} \right)^2 \frac{\rho(T)}{\sigma \, \epsilon (1-F)(T^4 - T_s^4)} \right]^{1/3} \times 10^5 \qquad mm \tag{12}$$

For a given power level P_G, equation (12) shows that the conductor can be decreased by either an increase in the transmission voltage or an increase in the conductor temperature. It should be noted though that since the resistivity by equation (6) is a function of temperature, then decreases in the conductor diameter by temperature increases are partially offset by resistivity increases.

For the simplication of later equations, the temperature dependent parameter K(T) is defined as

$$K(T) = \frac{100}{4\pi \, [\sigma \, \epsilon \, (1-F)(T^4 - T_s^4)]^2} \quad (m^2/W)^2 \tag{13}$$

equation (12) then becomes

$$d_c = 2 \left\{ \rho(T) \left[\frac{K(T)}{\pi^3}\right]^{1/2} \left(\frac{P_G}{V}\right)^2 \times 10^{14} \right\}^{1/3} \quad \text{mm} \tag{14}$$

Percent Power Loss

By equation (14) and equation (8), the power loss is

$$P_L = \left[\frac{\rho(T)}{K(T)} \left(\frac{P_G}{V}\right)^2 \times 10^{-1}\right]^{1/3} L \quad \text{kW} \tag{15}$$

By equation (15) and equation (1) the percent power loss is

$$\alpha(\%) = \left[\frac{\rho(T) \times 10^5}{K(T)\ P_G\ V^2}\right]^{1/3} L \tag{16}$$

Equation (16) shows that for a given power and voltage level and transmission distance, increases in temperature always cause increases in the percent power loss. However, for a constant temperature and given power level and transmission distance, increases in voltage level always cause decreases in percent power loss.

Current Density

By definition the current density is the current per unit cross-sectional area so for a solid circular conductor

$$J = \frac{I}{A_c} = \frac{4P_G \times 10^9}{\pi\ V\ d_c^{\ 2}} \quad \text{A/m}^2 \tag{17}$$

By means of equation (14) this last equation becomes

$$J = \left[\frac{V}{10\ K(T)\ \rho(T)^2\ P_G}\right]^{1/3} \quad \text{A/m}^2 \tag{18}$$

Inverse Current Denisty

In practice the wire size required for a certain current is stated in terms of the inverse current density which is expressed in units of circular mils/A. The relation between inverse current density in circular mils/A and current density in A/m^2 is

$$j\ (\text{cir. mils/A}) = \frac{1.9735 \times 10^{9}}{J\ (\text{A/m}^2)} \tag{19}$$

The substitution of equation (18) into equation (19) gives

$$j = 4.252 \times 10^{9} \left[\frac{K(T)\ \rho(T)^2\ P_G}{V} \right]^{1/3} \quad \text{cir.mils/A} \tag{20}$$

Specific Mass

The transmission line's conductor mass for a circular conductor is

$$M_c = \frac{\pi\ D_c\ L\ d_c^{\ 2} \times 10^{-6}}{4} \quad \text{kg} \tag{21}$$

The substitution of equation (14) into equation (21) gives

$$M_c = D_c\ L \left[K(T)\ \rho(T)^2 \left(\frac{P_G}{V} \right)^4 \times 10^{10} \right]^{1/3} \quad \text{kg} \tag{22}$$

Equation (22) shows that the mass will decrease as the temperature increases for a particular conductor material transmitting a given power over a specified transmission distance. Since the resistivity is temperature dependent and since the resistivity appears in the numerator of equation (22), then mass decreases caused by temperature increases are partially offset by resistivity increases. If, however, the operating temperature is maintained constant, then the mass will always decrease for voltage increases for a given power level, transmission distance and conductor material.

The specific mass of the transmission line's conductor is defined as the mass per unit of input power from the source generator. By this definition equation (22) becomes

$$\left(\frac{M_c}{P_G} \right) = D_c\ L \left[\frac{K(T)\ \rho(T)^2\ P_G \times 10^{10}}{V^4} \right]^{1/3} \quad \text{kg/kW} \tag{23}$$

Examination of the Variables

The effect of the transmission distance, power level, voltage, temperature, and conductor material properties on the specific mass, percent power loss, conductor diameter, and inverse current density is determined by equations (23), (16), (14), and (20) respectively.

(1) The diameter and inverse current density are independent of the transmission distance but both the percent loss and specific mass increase linearly with the transmission distance.

(2) The diameter, inverse current density, specific mass and percent power loss are all dependent on the generator output power. The specific mass and inverse current density both increase directly as the cube root of the power level while the percent power loss is inversely proportional to the cube root of the power. The diameter increases as the two-thirds power of the power level. Thus, an order of magnitude increase in power with no change in transmission voltage or operating temperature gives an increase of 2.15 in the specific mass and inverse current density, a 4.64 increase in diameter (a 21.5 increase in conductor volume if transmission distance does not change), and a 54 percent decrease in percent power loss.

(3) The specific mass, percent power loss, diameter, and inverse current density all vary inversely with the voltage; specific mass to the four-thirds, diameter and percent power loss to the two-thirds, and inverse current density to the one-third power. Thus, as the transmission voltage increases all four of these quantities decrease with the specific mass seeing the greatest decrease. For example, if the voltage is increased by a factor of ten with no corresponding increase in power or change in operating temperature, then the specific mass decreases by 95 percent, the percent power loss and diameter decrease by 78 percent and the inverse current density decreases by 54 percent. If both the power and voltage increase by a factor of ten, and again no change in operating temperature, then the specific mass and percent power loss both decrease by 90 percent and the inverse current density and diameter do not change.

(4) As seen by equation (13), K(T) is inversely proportional to the square of the temperature factor $(T^4 - T_s{}^4)$. Thus, the specific mass and inverse current density are inversely proportional to the two-thirds power of the temperature factor while the percent power loss is directly proportional to the two-thirds power and the diameter to the one-third power of the temperature factor. Since the resistivity increases with the temperature, then the decrease in the specific mass and inverse current density are partially offset by increases in the resistivity and the increases in the percent power loss and diameter are compounded by temperature increases due to the resistivity increases. Even though specific mass reductions can be achieved by temperature increases, this perhaps is not the best way to achieve these reductions since they are costly in terms of percent power loss increases.

(5) The diameter, percent power loss, and inverse current density are only dependent on the conductor material's resistivity while the specific mass depends on both the density and resistivity of the conductor material. The diameter and percent power loss vary directly as the one-third power of the resistivity while the inverse current density varies directly as the two-thirds power of the resistivity. The specific mass, however, varies directly as the product of the conductor density and two-thirds power of the resistivity. In table I, this product is calculated for various types of conductor materials. From the table it is seen from a specific mass consideration that gold would not be a good conductor choice and that copper is somewhat better than silver but that aluminum is the best choice since its value is less than one-half that of either copper or silver. From the table it is also seen that from a percent power loss, inverse current density and diameter consideration, a silver or copper conductor would be the best choice. Thus, the choice of conductor material depends on whether low specific mass or low percent power loss are the most important consideration.

From the above analysis, it becomes quite clear that only increases in the transmission voltage cause reductions in the specific mass, percent power loss, and conductor diameter. Increases in temperature cause reductions in specific mass but at the expense of increases in the percent power loss and conductor diameter. The analysis also clearly shows that as the transmission distance and power level increase, then so also must the transmission voltage if low specific masses are to be realized.

Relationship Between Specific Mass and Percent Power Loss

From the previous discussion it is seen that both the specific mass and percent power loss decrease with increases in the transmission voltages. The relationship between them can be established by eliminating the voltage from the specific mass expression given by equation (23). By normalizing both the specific mass and percent power loss with respect to the transmission line length and solving equation (16) for the voltage we obtain

$$V = \left[\frac{\rho(T) \times 10^5}{K(T)\ P_G}\right]^{1/2} \left[\alpha(\%)/L\right]^{-3/2} \quad V \qquad (24)$$

The substitution of equation (24) into equation (23) then gives the desired result.

$$\left(M_c/P_G\ L\right) = D_c\ K(T)\ P_G\ [\alpha(\%)/L]^2 \quad kg/kW\ m \qquad (25)$$

This last set of equations shows the following:

(1) For a given conductor material and normalized percent power loss, high power levels or large values of $K(T)$ due to low operating temperatures increase the normalized specific mass and decrease the voltage level.

(2) For a given conductor material and normalized percent power loss, low power levels or small values of $K(T)$ due to high operating temperatures decrease the normalized specific mass and increase the transmission voltage.

(3) For a given conductor material, power level, and $K(T)$, small values of normalized specific mass can only be obtained with small values of normalized percent power loss. But by equation (24), it is clearly seen that small values of normalized percent power loss require very high transmission voltages. Thus, the only limit to obtaining both low normalized specific mass and percent power loss and also low operating temperatures is the permissible transmission voltage.

Equation (25) is the equation of a parabola with vertex at the point (0,0). A family of parabolas is generated by changing the value of the product $D_c\ K(T)P_G$. Changes in either the conductor material, operating and sink temperatures or power level will cause this product to change. It is convenient to plot the normalized specific mass against the normalized percent power loss on log-log paper since a straight line results with a slope of two and a vertical axis intercept of $D_c\ K(T)P_G$. That is

$$\log\ M_c/P_G\ L = 2\log\,[\alpha(\%)/L] + \log\ D_c\ K(T)\ P_G \quad kg/kWm \qquad (26)$$

Equation (26) is plotted in figure 2 for a copper conductor and in figure 3 for an aluminum conductor. Four different power levels and two different operating temperatures are used so that the effects of temperature and power level can be seen. For instance, in both figures, the 1 MW line at 500 K is very close to being identical with the 100 kW line at 400 K. Since equation (26) is independent of the voltage, equation (24) must be used to find the voltage corresponding to a particular normalized percent power loss. In these two figures, six voltages are also shown so that the approximate voltage level required to obtain given normalized specific masses or percent power losses can be identified.

A comparison of figures 2 and 3 shows that the curves of figure 3 are obtained by merely shifting the curves of figure 2 to the right. By equation (25), it is found that for identical power levels, temperatures, and normalized percent power losses, the ratio of the normalized specific mass of an aluminum to copper conductor is equal to the ratio of the aluminum to copper densities. By table I, this ratio is 0.304. Thus, the normalized specific mass of aluminum is obtained by multiplying the normalized specific mass of copper by the factor 0.304. For identical normalized specific masses, power levels, and temperatures, then again by equation (25), the ratio of the normalized percent power loss of an aluminum to copper conductor is equal to the reciprocal of the aluminum to copper densities. By table I this ratio is 3.29 so that for identical power levels, temperatures, and normalized specific masses, multiplication of the copper normalized percent power loss by 3.29 gives the aluminum percent power loss.

Figure 4 combines some of the information in figures 2 and 3 for two different power levels and only one operating temperature. This figure not only enables a comparison of a copper and aluminum conductor's relative normalized specific masses and percent power losses for identical power levels and temperatures, but also allows a comparison of the voltage levels for the two conductors. Thus, for identical normalized percent power losses the required voltages are quite close but for identical normalized specific masses, the required voltages for the copper conductor are considerably greater than those for the aluminum conductor. Solving equation (23) for the voltage gives

$$V = \left[\frac{D_C^{\,3}\ K(T)\ \rho(T)^2\ P_G \times 10^{10}}{\left(M_C/P_G\ L\right)^3}\right]^{1/4} \quad V \qquad (27)$$

By equation (24) it is found that for identical power levels and temperatures, the aluminum conductor must be operated at 1.28 times the copper conductor voltage in order to have equal normalized percent power losses. By equation (27) it is found that for identical power levels and temperatures, the copper conductor's voltage must be 1.91 times the aluminum conductor's voltage in order to have equal normalized specific masses.

The only way to have the normalized specific masses equal and also the normalized percent power losses equal for a copper and aluminum conductor is to operate both conductors at different voltages and different temperatures. For these conditions and also for equal power levels, then by equation (25) we obtain

$$\frac{K(T)_{Al}}{K(T)_{Cu}} = \frac{(D_c)_{Cu}}{(D_c)_{Al}} \tag{28}$$

If the emissivity and view factor are the same for each conductor, then by the use of equation (13), equation (28) becomes

$$T_{cu} = \left[\left(T_s^4\right)_{C_u} + \sqrt{\frac{(D_c)_{Cu}}{(D_c)_{Al}}} \left(T^4 - T_s^4\right)_{Al}\right]^{1/4} \quad K \tag{29}$$

The resultant voltage ratio of the copper to aluminum transmission voltages can be obtained by substituting equation (28) into either equation (24) or equation (27) to get

$$\frac{V_{Cu}}{V_{Al}} = \left[\frac{\rho(T)_{Cu}\ (D_c)_{Cu}}{\rho(T)_{Al}\ (D_c)_{Al}}\right]^{1/2} \tag{30}$$

For example, if the operating temperature for the aluminum conductor is 400 K and the sink temperature for both the copper and the aluminum conductors is 273 K, then by equation (29), T_{Cu} = 452.5 K. By equation (30) (V_{Cu}/V_{Al}) = 1.52 so if the aluminum operating voltage is 200 V then the required copper operating voltage is 303 V. From this example it is seen that both the copper temperature and operating voltage must be greater than those quantities for the aluminum conductor if equal normalized specific masses and equal normalized percent power losses are to be obtained.

In comparing different conductor materials it is probably more appropriate to make the transmission voltages the same and then observe how the normalized specific masses and percent power losses compare. If the power levels, transmission distances, and operating and sink temperatures are also made the same for the two conductors, then by equation (14) and equation (16) we have

$$\frac{\alpha(\%)_1}{\alpha(\%)_2} = \frac{(d_c)_1}{(d_c)_2} = \left[\frac{(\rho_o)_1}{(\rho_o)_2}\right]^{1/3} \tag{31}$$

By equation (23) we have

$$\frac{\left(M_c/P_G\right)_1}{\left(M_c/P_G\right)_2} = \left[\frac{(D_c)_1}{(D_c)_2}\right]\left[\frac{(\rho_o)_1}{(\rho_o)_2}\right]^{2/3} \tag{32}$$

If conductor 1 is an aluminum conductor and conductor 2 is a copper conductor then by equation (31) the percent power loss and diameter of the aluminum conductor are 1.18 times these quantities for the copper conductor.

But by equation (32) the aluminum specific mass is 0.422 times the copper's specific mass. Thus, for identical operating voltages, temperatures, and transmission distances, the advantage of an aluminum conductor transmission line over a copper line are clearly seen since the aluminum conductor gives a 58 percent specific mass reduction for only an 18 percent diameter and percent power loss increase. It should be noted though, that since the volume of the aluminum conductor is directly proportional to the square of the diameter, then the volume of the aluminum conductor for equal transmission lengths is 38 percent greater than the copper conductor's volume. If the means to transport the transmission line to space is volume limited rather than weight limited, then some of the advantages of the aluminum conductor over a copper conductor begin to disappear.

Relationship Between Conductor Diameter and Percent Power Loss

The relationship between the conductor diameter and percent power loss is obtained by substituting equation (24) into equation (14).

$$d_c = 2\ P_G \left[\frac{K(T)}{\pi}\right]^{1/2} [\alpha(\%)/L] \times 10^3 \text{ mm} \tag{33}$$

Equation (33) is a straight line with slope of $2 \times 10^3\ P_G[K(T)/\pi]^{1/2}$. For different power levels and operating temperatures, the slope changes value so that equation (33) represents a family of straight lines all intercepting the origin. In equation (33) it should be noted that the diameter is dependent only on the power level and operating temperature and is independent of the conductor's material properties. Thus, a copper and aluminum conductor will give identical curves.

If log-log paper is used to plot equation (33), then this equation is written in the form

$$\log d_c = \log [\alpha(\%)/L] + \log 2 \times 10^3\ P_G\ [K(T)/\pi]^{1/2} \text{ mm} \tag{34}$$

A plot of equation (34) is shown in figure 5 for four different power levels and two different operating temperatures. Also, six different voltages are shown so that the voltage required for a given diameter or normalized percent power loss can be identified. The voltages given in figure 5 are for an aluminum conductor since by equation (24) the voltage is dependent on the conductor material's resistivity. If the corresponding voltages for a copper conductor are wanted, then as seen by equation (24), the voltages in figure 5 must be multiplied by the square root of the ratio of the copper to aluminum resistivities. In this case the multiplying factor is 0.78.

Either figure 5 or an analysis of equations (24) and (33) shows that for a given power level and identical voltages, the diameter decreases and the normalized percent power losses increase as the temperature increases. For a given temperature and identical voltages, the diameter increases and the normalized percent power losses decrease as the power level increases.

If in figure 5 the horizontal scale is multiplied by the required transmission distance, then the conductor diameter required for different power levels and operating temperatures can be readily determined. For example, for a 300 kW power level and a 100 m transmission distance including return, a 1 percent power loss requires an aluminum conductor diameter of 12.5 mm (which is roughly equivalent to a number 4/0 wire) operating at a temperature of 400 K and a voltage of 1000 V.

Relationship Between Mass and Percent Power Loss

If the horizontal and vertical scales in figures 2 to 4 are multiplied by the total length of the transmission line, then these figures become plots of the specific mass versus the percent power loss. If, in addition, the vertical scale of these figures is also multiplied by the power level, then these figures give the conductor mass as a function of the percent power loss for the specified power level.

In figures 6 and 7, the mass for an aluminum and copper conductor is plotted against the percent power loss for two different operating temperatures. Figure 6 is for a 100 kW power level while figure 7 is for a 1 MW power level. The transmission distance for each figure is 50 m including return. Five voltage levels are also shown in order to indicate the effect of the transmission voltage on the mass and percent power loss.

For example, transmitting 100 kW at 300 V for a 400 K operating temperature gives a mass of 45 kg and a loss of 1.4 percent for a copper conductor and a mass of 19 kg and a loss of 1.6 percent for an aluminum conductor. If for this same transmission voltage the operating temperature is increased to 500 K, then the copper conductor's mass decreases to 26 kg and its loss increases to 3.0 percent while the aluminum conductor's mass decreases to 11 kg and its loss increases to 3.5 percent.

If the power is increased an order of magnitude to 1 MW but the transmission voltage stays at 300 V, then for a 400 K operating temperature, the copper conductors mass is 960 kg and its loss is 0.63 percent while the aluminum conductors mass is 405 kg and its loss is 0.75 percent. If for this 1 MW power level the transmission voltage is increased to 1000 V and the operating temperature is increased to 500 K, then the copper conductor's mass is reduced to 115 kg and its loss reduced to 0.61 percent while the aluminum conductors mass is reduced to 48 kg and its loss is reduced to 0.72 percent. Thus, as the power level increases, moderate increases in the transmission voltage and operating temperature buy significant reductions in mass without causing a percent power loss penalty.

If particular energy sources require long distances between the power source and the load bus, or if particular missions require multimegawatts of power, then high voltage transmission becomes mandatory if reasonable transmission line masses are to be realized. In figure 8 the mass for an aluminum transmission line operating at 400 K is plotted against the power level with transmission voltage as parameter. In this figure, the transmission distance is only 50 m including return, but unless high voltage transmission is used for very high power levels, then the mass of the transmission line begins to match the mass carrying capacity of the Shuttle. Additional mass reductions can be achieved at the expense of increased percent power losses by increasing the operating temperature.

NUMERICAL EXAMPLES

To further illustrate some of the results derived in the analysis section, three examples are given. These examples give a numerical demonstration of how the transmission line's characteristics respond to certain specified conditions. In Example 1 the transmission line is required to meet a specific mass goal while in Example 2 the line is required to meet a percent power loss goal. Example 3 examines the condition when the transmission voltage is specified. The expressions needed to obtain these numerical results for the specified conditions are obtained by simple manipulation of expressions previously derived in the analysis section of this paper.

EXAMPLES

Example 1. - If an upper limit is placed on the specific mass and, in addition, the power level, sink and operating temperatures and transmission distance are given, then the transmission line's conductor mass, diameter, percent power loss, voltage level, and inverse current density are determined as follows.

$$M_c = (M_c/P_G)\ P_G \qquad \text{kg} \tag{35}$$

Equation (21) is solved for d_c to give the conductor diameter.

$$d_c = \left(\frac{4M_c}{\pi D_c L}\right)^{1/2} \times 10^3 \ \text{mm} \tag{36}$$

Solving equation (25) for the percent power loss gives

$$\alpha(\%) = \left[\frac{M_c\ L}{P_G^{\,2}\ D_c\ K(T)}\right]^{1/2} \tag{37}$$

equation (27) is used to give the voltage.

$$V = P_G\left[K(T)\ \rho(T)^2 \left(\frac{D_c\ L}{M_c}\right)^3 \times 10^{10}\right]^{1/4} \ \text{V} \tag{38}$$

The inverse current density is found by substituting equation (38) into equation (20) to give

$$j = 6.241\times10^8 \left[\frac{M_c\ K(T)\ \rho(T)^2}{D_c\ L}\right]^{1/4} \qquad \text{cir.mils/A} \tag{39}$$

For a specific mass limit of 1 kg/kW, the use of the above equations give the results shown in table II for a 100 kW power level transmitted over two different distances for two different operating temperatures. Both a copper and an aluminum conductor are shown for comparative purposes.

From table II the following is seen.

(1) A fourfold increase in the transmission distance requires a factor of 2.83 increase in the voltage, a doubling of the percent power loss, a halving of the diameter and a decrease in the inverse current density by a factor of 0.707.

(2) An increase in the operating temperature from 400 to 500 K with no change in the transmission distance causes both the voltage and inverse current density to decrease by a factor of 0.67, causes the percent power loss to increase by a factor of 2.84 and causes no change in the conductor diameter.

If the power level in table II is increased by a factor of 10, then the masses increase by a factor of 10, the voltages and inverse current densities increase by a factor of 1.78, the diameters increase by a factor of 3.16 and the percent losses decrease by a factor of 0.316.

Example 2. - If now an upper limit is placed on the percent power loss rather than on the specific mass and, if in addition the power level, sink and operating temperature, and transmission distance are given, then the transmission line's conductor mass, diameter, voltage level, and inverse current density are determined as follows.

$$M_c = (M_c/P_G L)\ P_G L \qquad \text{kg} \tag{40}$$

The normalized specific mass, $(M_c/P_G L)$ is calculated from equation (25). The diameter is calculated from equation (36) given in Example 1, and the voltage level is determined from equation (24). The inverse current density is found by substituting equation (24) into equation (20) to give

$$j = 6.241\times10^8 \left[\frac{K(T)\ \rho(T)\ P_G\ \alpha(\%)}{L}\right]^{1/2} \text{cir.mils/A} \tag{41}$$

For a percent power loss of 2 percent, the use of the above equations give the results shown in table III for a 100 kW power level transmitted over two different distances for two different operating temperatures. Again, both a copper and aluminum conductor are shown for comparative purposes.

From table III the following is seen:

(1) A fourfold increase in the transmission distance causes an eightfold increase in the voltage, a decrease of one-half in the inverse current density, and a decrease of one-fourth in the mass and diameter.

(2) An increase in conductor surface temperature from 400 to 500 K increases the voltage by a factor of 3.2, decreases the inverse current density by a factor of 0.40, decreases the diameter by a factor of 0.35 and decreases the mass by a factor of 0.12.

If the power level in table III is increased to 1 MW, then the masses and diameters increase by a factor of 10, the inverse current densities increase by a factor of 3.16, and the voltages decrease by a factor of 0.316.

Example 3. - In both Examples 1 and 2, the operating temperature, transmission distance, and power level were specified and then for either a given specific mass (Example 1) or percent power loss (Example 2) the transmission voltage, conductor diameter and inverse current density were calculated. In this example let the voltage level, percent power loss, power level and transmission distance be specified, and then determine the operating temperature, conductor diameter and mass, and the inverse current density.

The procedure to accomplish the above objective is as follows. Solve equation (16) for K(T) and substitute this value into equation (25) to get

$$\left(M_c/P_G L\right) = \frac{D_c\ \rho(T) \times 10^5}{V^2\ [\alpha(\%)/L]} \tag{42}$$

Even though the power and voltage level, transmission distance, percent power loss, and conductor material are specified, the mass cannot be calculated until the temperature is known since the resistivity is a function of the temperature. When the above expression determined for K(T) from equation (16) is set equal to equation (13), the resultant expression for the operating temperature is

$$T = \left[\frac{V}{\sigma\ \epsilon\ (1-F)}\sqrt{\frac{P_G[\alpha(\%)/L]^3 \times 10^{-3}}{4\pi\ \rho(T)}} + T_s^{\ 4}\right]^{1/4} \quad K \tag{43}$$

It should be noted that equation (43) is also a function of the temperature dependent resistivity. Thus, equation (43) must be solved by an iterative process and equation (6) must be used in this process. After the temperature is determined, then the mass is readily calculated from equation (42) and the conductor diameter from equation (36). The inverse current density can be calculated from either equation (39) or equation (41).

Table IV gives the calculated values of the operating temperature, conductor mass and diameter and inverse current density for various power and voltage levels, percent power losses, and transmission distances. In particular, table IV(a) is for a copper conductor transmitting 100 kW while table IV(b) is for an aluminum conductor transmitting 100 kW. Tables IV(c) and IV(d) are similiar to IV(a) and IV(b), respectively, except the power level is increased by a factor of 10 to 1000 kW.

From the results given in these tables, the following conclusions can be made:

(1) For a given voltage level, as the percent power loss increases, so also does the operating temperature but the mass, diameter, and inverse current density decrease. It should be noted that an aluminum conductor gives lower operating temperatures and masses but larger diameters and inverse current

densities, than a copper conductor of like voltage and percent loss. In addition, it should be noted that increasing the power level increases both the operating temperature and mass but increasing the transmission distance causes the operating temperature to decrease and the mass to increase.

(2) For a given percent power loss an increase in the voltage level causes an increase in the operating temperature but a significant decrease in the conductor mass, diameter and inverse current density.

This example clearly shows that reductions in the transmission line's conductor mass can be achieved by either an increase in the transmission voltage or the percent power loss but that these increases always cause the operating temperature to increase. As the power level increases, mass reductions by percent power loss increases approaches a limit which is the melting point of the conductor material. Thus, as the power level increases, the voltage level must also increase and the percent power loss decrease in order to obtain acceptable operating temperatures. The penalty for doing this though is increased conductor mass and volume.

As the transmission distance increases, an increase in the voltage level is necessary in order to achieve an acceptable mass. However, since increases in transmission distance cause decreases in the operating temperature, additional mass reductions can be achieved by increases in the percent power loss with resultant acceptable operating temperatures.

CONCLUSION

The results of this analysis clearly shows that the limiting condition in achieving low specific mass, low percent power loss, low operating temperatures and low cable volumes for a space-type dc transmission line is the permissible transmission voltage. If the transmission distance between power source and load bus increases or the demands for load power increases due to mission requirements, then in order to avoid heavy, bulky, and lossy transmission lines, the transmission voltage must also necessarily increase.

As shown in this analysis for radiative type cooling, both the specific mass and the percent power loss of the transmission line are a function of the power level; the percent power loss decreases inversely with the cube root of the power level while the specific mass increases directly with the cube root of the power level. Thus, the mass of the transmission line increases with the power transmitted to the four-thirds power. This result of mass increase with power increase is opposite to what occurs in power transformers (3) where the mass of the transformer is directly proportional to the three-fourths power of the transformer's kVA rating.

The analysis shows that low transmission line mass can be achieved in three ways: (1) operating the line at high voltage; (2) operating the line at high temperature; and (3) using conductor materials with low $[D_c P(T)^{2/3}]$ values. Operation at high temperature though increases the percent power loss, whereas operation at high voltage decreases the percent power loss. As shown in table I, conductor materials with high resistivity can have low density so that the product $[D_c P(T)^{2/3}]$ is low. Because of these material property characteristics, conductors exhibiting such characteristics will give transmission lines with low mass but high losses because of the higher resistivity values. Thus, depending on the circumstances, a trade-off between mass, volume and percent power loss in terms of voltage level, operating temperature, and conductor material properties will most likely be required when the entire power system is considered. The results derived in this analysis will enable such an analysis to be made rather rapidly with respect to the transmission line.

It must be recognized that reductions in the transmission line mass through higher operating temperatures with resultant higher percent power losses will require increases in the source power to offset these transmission line losses. Thus, an increase in the transmission line's percent power loss causes a decrease in the transmission line's mass but an increase in the power source's mass. To determine the optimum operating point necessary to achieve minimum total mass for the source and transmission line will require a system trade-off study. Again, the results developed in this paper should find immediate application to such a trade-off study.

If the dc source voltage has an upper limit due to the power conversion process used, then a dc to ac inversion process using a transformer to step up the source voltage to an acceptable transmission voltage will be required. The inversion frequency should be in the 10 to 20 kHz range in order to obtain low mass and high efficiency power magnetics (3). If a dc to ac inversion is required, then an analysis of high frequency, high voltage transmission will be necessary to determine whether ac transmission has any clear advantages over dc transmission.

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Table 1. - Material Properties

Material	$\rho(T)$ (Ohm-m)[a]	Dc (kg/m^3)	Dc $\rho(T)^{2/3}$ (Ohm$^{2/3}$ kg/m$^{7/3}$)
Aluminum	2.828×10^{-8}	2.699×10^3	25.05×10^3
Copper	1.724×10^{-8}	8.89×10^3	59.33×10^3
Silver	1.593×10^{-8}	10.492×10^3	66.43×10^3
Gold	2.44×10^{-8}	19.26x103	162.0×10^3

[a]Resistivity at 293 K.

Table 2. - Results of Example 1

T(K)	(L/2)(m)	M_c(kg)	V(V)	α(%)	j(cir.mils/A)	d_c(mm)
Copper conductor						
400	25	100	165	2.0	725	16.9
400	100	100	465	4.0	515	8.5
500	25	100	110	5.8	490	16.9
500	100	100	310	11.6	345	8.5
Aluminum conductor						
400	25	100	85	3.7	1255	30.7
400	100	100	245	7.4	885	15.4
500	25	100	60	10.5	840	30.7
500	100	100	160	21.0	595	15.4

$(M_c/P_G) = 1$ kg/kW

$P_G = 100$ kW

$T_s = 273$ K

$\epsilon = 0.8$

$(1-F) = 0.84$

Table 3. - Results of Example 2

T(K)	(L/2)(m)	M_c(kg)	V(V)	j(cir.mils/A)	d_c(mm)
Copper conductor					
400	25	100	165	725	16.8
400	100	25	1320	360	4.2
500	25	12	540	290	6.0
500	100	3	4320	145	1.5
Aluminum conductor					
400	25	30	215	925	16.8
400	100	7.5	1720	460	4.2
500	25	3.6	690	365	6.0
500	100	0.9	5520	180	1.5

$\alpha(\%) = 2$

$P_G = 100$ kW

$T_s = 273$ K

$\epsilon = 0.8$

$(1-F) = 0.84$

Table 4(a). - Results of Example 3

Copper conductor

(L/2)(m)	V(V)	α(%)	T(K)	M_c(kg)	d_c(mm)	j(cir.mils/A)
25	100	1	319	420	34.8	1875
		2	367	245	26.6	1095
		5	470	130	19.3	580
	500	1	404	22	7.9	490
		2	492	14	6.3	305
		5	657	7.5	4.6	105
50	500	1	342	73	10.2	815
		2	404	44	7.9	490
		5	528	24	5.8	260
	1000	1	380	21	5.4	460
		2	460	13	4.3	280
		5	610	6.9	3.1	155

$P_G = 100$ kW

$\epsilon = 0.8$

$(1-F) = 0.84$

$T_s = 273$ K

Table 4(b). - Results of Example 3

Aluminum conductor

(L/2)(m)	V(V)	α(%)	T(K)	M_c(kg)	d_c(mm)	j(cir.mils/A)
25	100	1	311	204	43.9	2990
		2	353	118	33.4	1730
		5	448	61.4	24.1	900
	500	1	387	10.5	9.9	760
		2	469	6.5	7.8	470
		5	623	3.5	5.8	260
50	500	1	331	35	12.9	1290
		2	387	21	9.9	760
		5	501	11	7.2	410
	1000	1	365	2.0	3.0	720
		2	438	6.0	5.3	440
		5	579	3.2	3.9	235

P_G = 100 kW

ε = 0.8

(1-F) = 0.84

T_s = 273 K

Table 4(c). - Results of Example 3

Copper conductor

(L/2)(m)	V(V)	α(%)	T(K)	M_c(kg)	d_c(mm)	j(cir.mils/A)
25	500	1	504	280	28.3	620
		2	626	177	22.5	395
		5	844	97	16.7	215
	1000	1	582	82	15.3	365
		2	727	52	12.2	230
		5	982	28	9.0	125
50	500	1	412	899	35.9	1000
		2	504	561	28.3	620
		5	673	306	20.9	340
	1000	1	470	260	19.3	580
		2	582	164	15.3	365
		5	782	90	11.3	200

P_G = 1000 kW

ε = 0.8

(1-F) = 0.84

T_s = 273 K

Table 4(d). - Results of Example 3

Aluminum conductor

(L/2)(m)	V(V)	α(%)	T(K)	M_c(kg)	d_c(mm)	j(cir.mils/A)
25	500	1	479	132	35.3	970
		2	594	83	28.1	610
		5	800	46	20.8	335
	1000	1	552	39	19.1	565
		2	689	24	15.2	360
		5	[a]930	13	11.2	195
50	500	1	394	428	44.9	2220
		2	479	265	35.3	1375
		5	638	144	26.1	745
	1000	1	448	123	24.1	1270
		2	552	77	19.1	800
		5	741	42	14.1	435

[a]Melting point of aluminum is 933 K.

P_G = 1000 kW

ϵ = 0.8

(1-F) = 0.84

T_s = 273 K

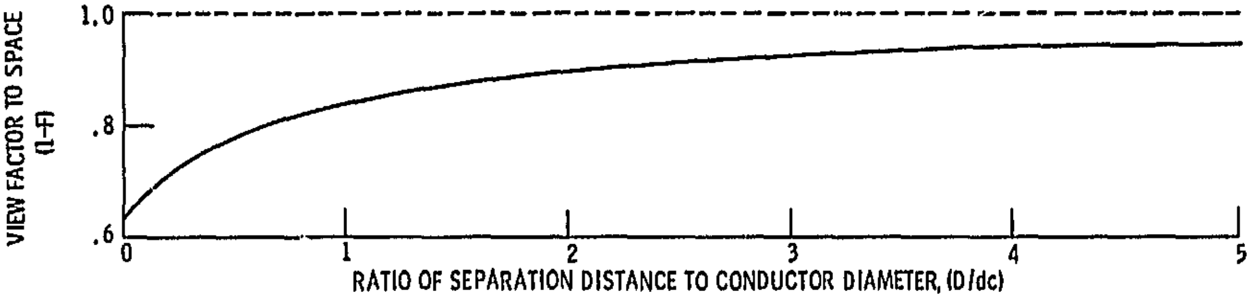

Figure 1. - View factor to space for infinitely long cylindrical conductors of equal radius versus ratio of separation distance to conductor diameter.

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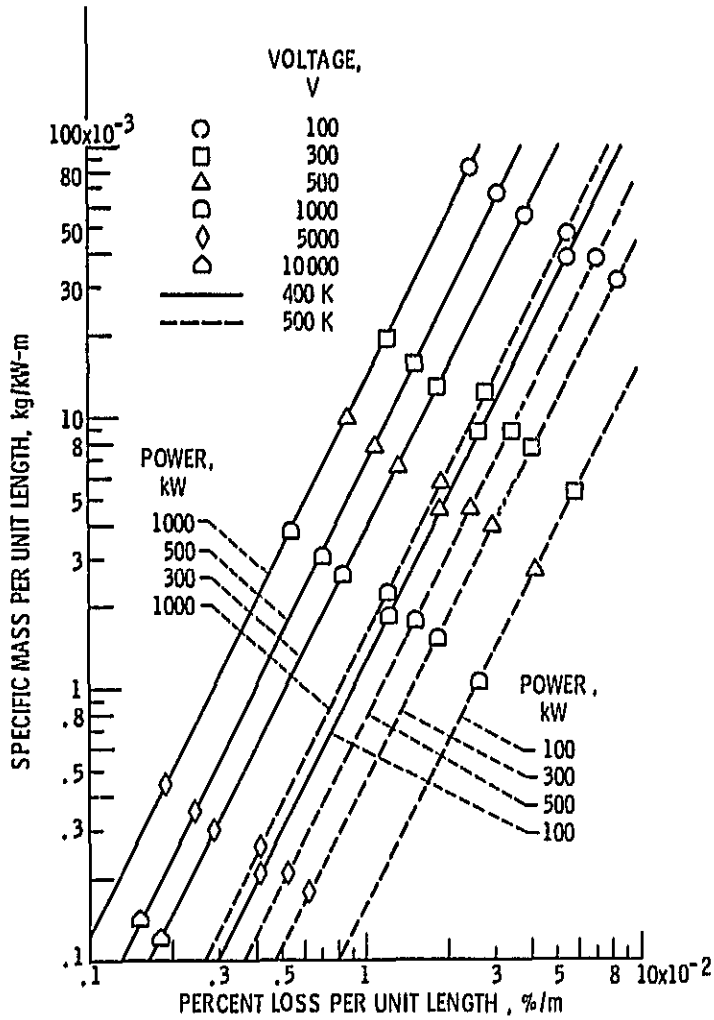

Figure 2. - Normalized specific mass vs normalized percent power loss for a noninsulated solid cylindrical copper conductor dc transmission line; power level and operating temperature as parameters where ε = 0.8; 1 - F = 0.84 and T_S = 273 K.

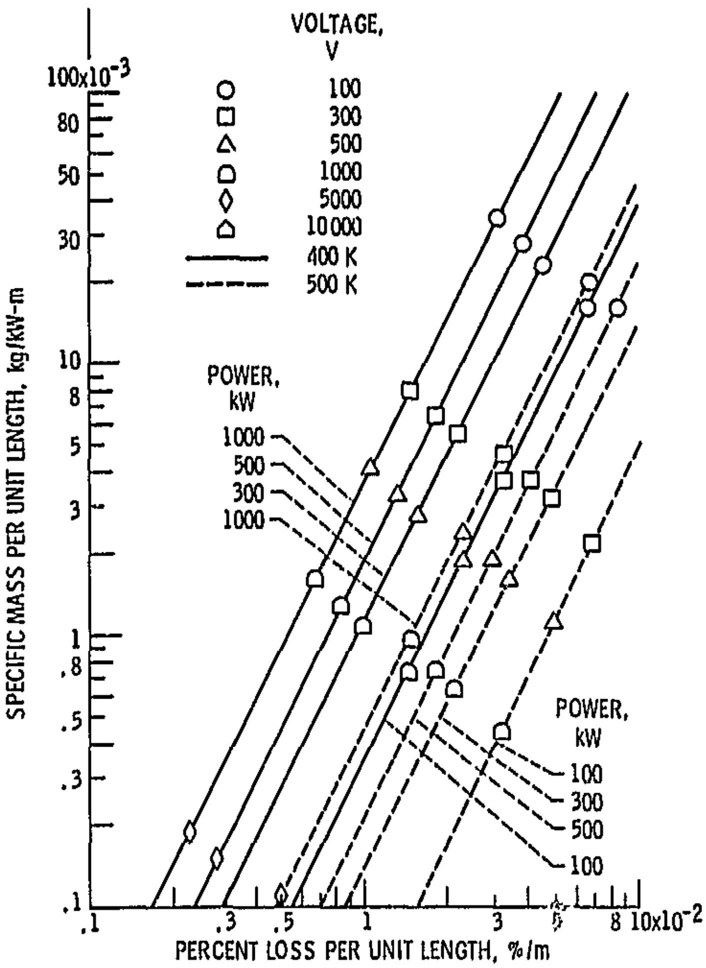

Figure 3. - Normalized specific mass vs normalized percent power loss for a noninsulated solid cylindrical aluminum conductor dc transmission line; power level and operating temperature as parameters where $\varepsilon = 0.8$; $1-F = 0.84$; and $T_S = 273$ K.

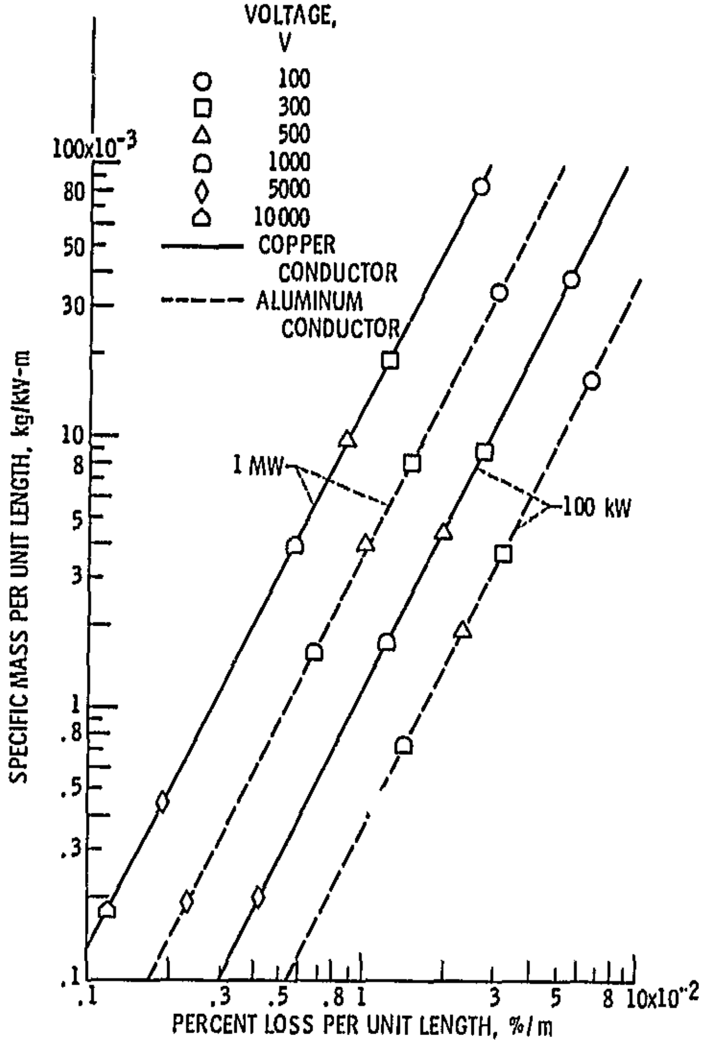

Figure 4. - Comparison of normalized specific mass vs normalized percent power loss for a noninsulated solid cylindrical copper and aluminum conductor dc transmission line; power level as parameter where $\varepsilon = 0.8$; $1-F = 0.84$; $T = 400$ K; and $T_s = 273$ K.

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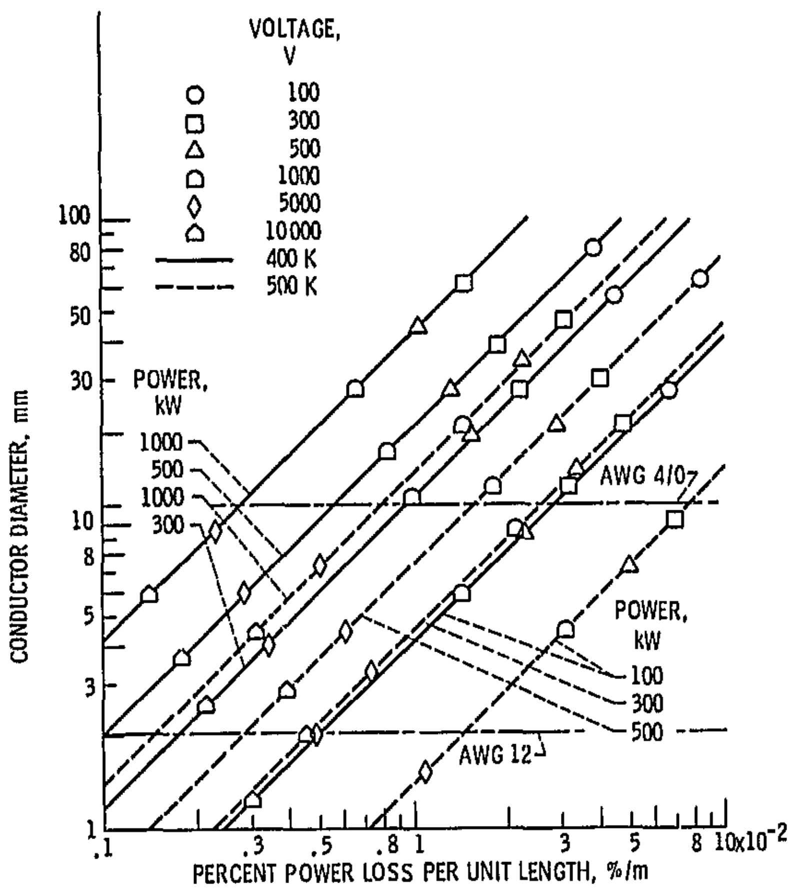

Figure 5. - Diameter vs normalized percent power loss for a non-insulated solid cylindrical aluminum conductor dc transmission line; power level and operating temperature as parameters where $\varepsilon = 0.8$; $1-F = 0.84$; and $T_S = 273$ K.

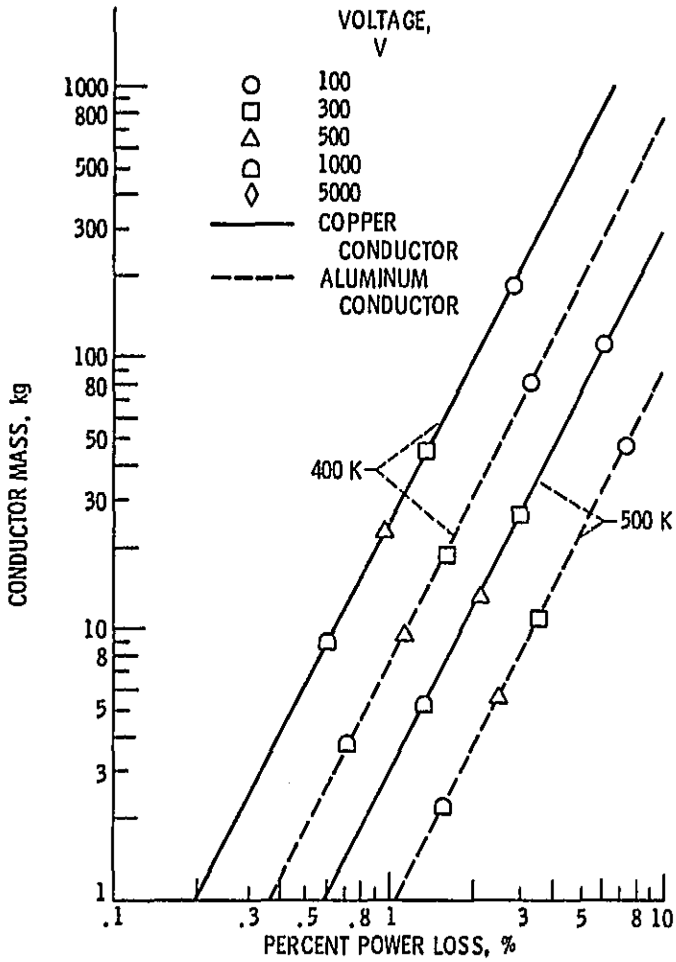

Figure 6. - Mass vs percent power loss for a noninsulated solid conductor dc transmission line where $\varepsilon = 0.8$; $1-F = 0.84$; $T_s = 273$ K; $P_G = 100$ kW; and $L = 50$ m.

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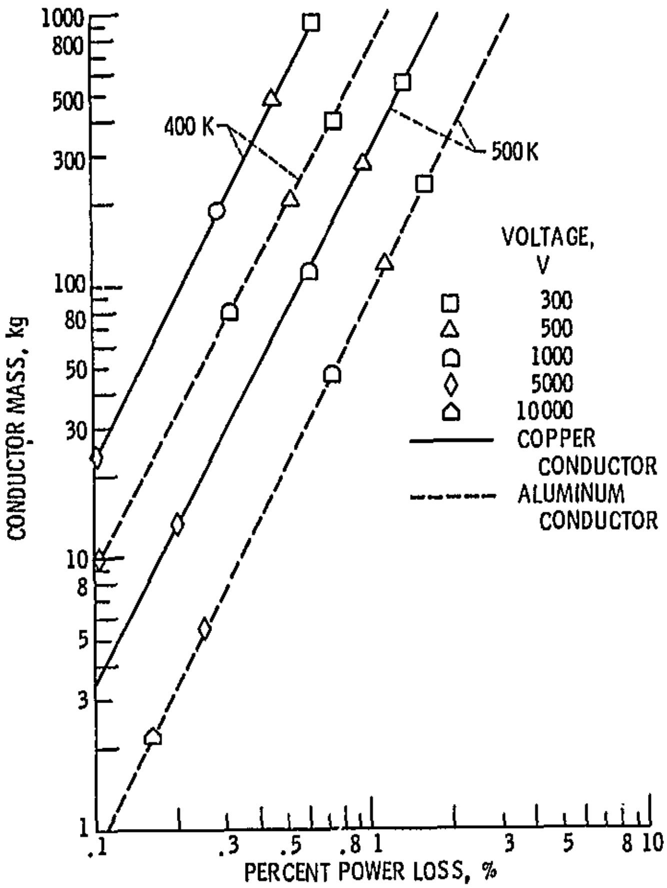

Figure 7. - Mass vs percent power loss for a noninsulated solid conductor dc transmission line where $\varepsilon = 0.8$; $1-F = 0.84$; $T_S = 273$ K; $P_G = 1$ MW; and $L = 50$ m.

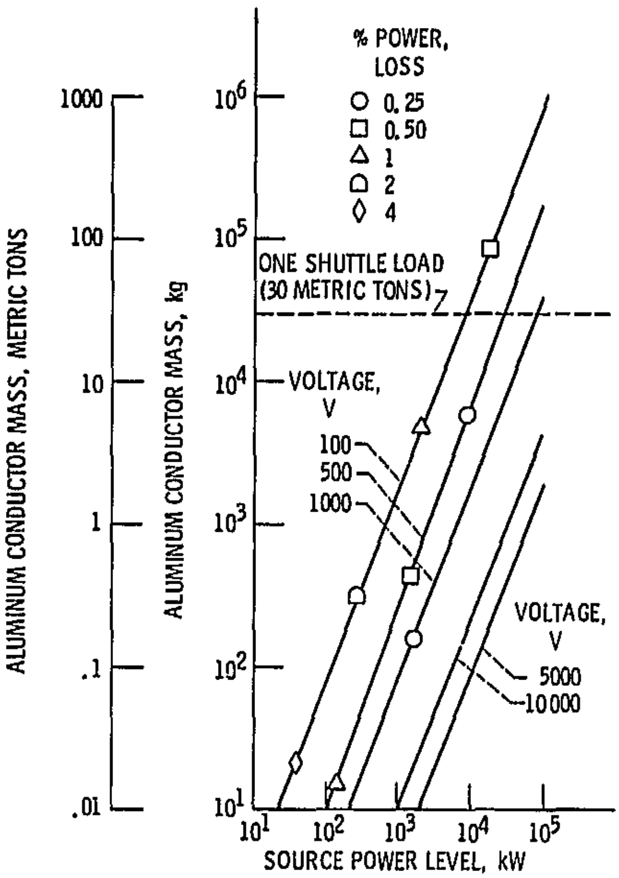

Figure 8. - Mass vs power level for noninsulated solid aluminum conductor dc transmission line; voltage as parameter where $\varepsilon = 0.8$; $1-F = 0.84$; $T = 400$ K; $T_s = 273$ K; and $L = 50$ m.

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16. Abstract
As space power levels increase to meet mission objectives and also as the transmission distance between power source and load increases, the mass, volume, power loss, and operating voltage and temperature become important system design considerations. This analysis develops the dependence of the specific mass and percent power loss on the power and voltage levels, transmission distance, operating temperature and conductor material properties. Only radiation cooling is considered since the transmission line is assumed to operate in a space environment. The results show that the limiting conditions for achieving low specific mass, percent power loss, and volume for a space-type dc transmission line are the permissible transmission voltage and operating temperature. Other means to achieve low specific mass includes the judicious choice of conductor materials. The results of this analysis should be immediately applicable to power system trade-off studies including comparisons with ac transmission systems.

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