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Parametric Analysis of Hollow Conductor Parallel and Coaxial Transmission Lines for High Frequency Space Power Distribution

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ABS: A parametric analysis was performed of transmission cables for transmitting electrical power at high voltage (up to 1000 V) and high frequency (10 to 30 kHz) for high power (100 kW or more) space missions. Large diameter (5 to 30 mm) hollow conductors were considered in closely

PARAMETRIC ANALYSIS OF HOLLOW CONDUCTOR PARALLEL AND COAXIAL TRANSMISSION LINES FOR HIGH FREQUENCY SPACE POWER DISTRIBUTION

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SUMMARY

Power requirements for larger spacecraft, power platforms and space stations are growing toward the 100 to 1000 kW levels. At these power levels, high voltage is desirable to reduce conductor mass and power loss and high frequency is desirable to reduce power processing system mass and power loss. To get full benefit from increasing voltage and frequency, transmission lines have to be tailored for this application.

Three cable configurations were investigated for their capability to transmit high frequency (0 to 30 kHz) ac power. These configurations were coaxial cable, stranded coaxial cable and parallel lines. For all three configurations large diameter (5 to 30 mm) hollow conductors were considered. The coaxial cables used closely spaced conductors to minimize transmission line inductance.

A parametric study of these three cable configurations was performed varying conductor diameter, conductor thickness and alternating current frequency. For each case cable conductance, mass, inductance, capacitance, resistance, power loss, and temperature were evaluated. Curves of these output variables versus cable radius are presented.

Coaxial cable with hollow center conductor is the configuration selected by this study for high frequency distribution of space power. Nearly equal radii of the inner and outer conductor minimize inductance. To provide cable flexibility stranded rather than solid conductors could be used. As an example, a 5 mm inside radius stranded coax cable with 0.5 mm conductor thickness was chosen to transmit 100 kW at a voltage of 1000 V ac for a distance of 50 m. This cable would have a power loss of 1900 W, an inductance of 1.45 μH and a capacitance of 0.07 μF. The figures included in this report could be used to determine characteristics of other cable sizes. The computer programs written for this analysis are listed in the appendix.

INTRODUCTION

As power requirements for larger spacecraft, power platforms, and spacestations grow to the 100 to 1000 kW levels, it becomes apparent that a low voltage (28 V dc), high current power distribution system will not do the job. Raising the dc voltage to 150 V (which is the highest safe operating voltage for low earth orbits due to plasma induced breakdown at the array) will not be

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a simple solution. The problems of switching the large currents and transferring them through sliprings have not been solved.

One logical solution would be a high voltage (1000 V), high frequency power distribution system. This distribution system would convert the 150 V dc solar array voltage to high voltage (1000 V), high frequency (10 to 30 kHz) with a bi-directional four quadrant power converter (ref. 1). The power would then be transferred through a rotary transformer to the transmission line. The high voltage would reduce the current and the high frequency would reduce the mass of the magnetics (transformers, inductors).

The large spacecraft being proposed will probably have many multiple loads (different voltage levels, ac or dc). The ac system is user friendly in that this problem is very easily handled by transformers (step up or down) and rectification for the dc loads. Lower frequencies can also be synthesized from the high frequency if required. The problem of switching large currents in the dc system is avoided for the ac system by switching when the current passes through zero. Development of the rotary transformer would eliminate the slip-ring problem. The ac system has other advantages such as:

- minimum RFI problem
- flexibilty for power expansion
- simple fault protection and isolation
- system voltage not constrained by array or battery
- no switch loss at turn off

One area of concern for the proposed high power ac distribution system is the high voltage, high frequency transmission line. This paper develops computer models for coax and parallel transmission lines. These computer models will enable the system designer to estimate cable size, weight and losses by inserting system parameters (voltage, frequency, current) and system constraints (line inductance, line capacitance, etc.) into the program. The models become design tools that can be used in developing high voltage, high frequency transmission lines for space applications.

ANALYSIS METHOD

As mentioned in the introduction, a computer model was developed to estimate cable size, weight and losses based on system parameters and constraints. This section describes some of the unique features of this computer model.

To accurately determine the resistance and inductance of these configurations, modifications to conventional equations were made adding terms that are significant for these configurations, but negligible for conventional transmission lines. A brief description of the computer model is also included in this section.

Configurations Investigated

In order to efficiently conduct high frequency ac current it is advantageous to greatly reduce cable inductance. Coaxial cable is a natural candidate for this application. Inductance can be minimized by making the ratio of

the outer diameter of the inner conductor to the inner diameter of the outer conductor close to one. This can be achieved by using a large diameter cable with a very thin dielectric between the inner and outer conductor. However, the large diameter inner conductor, if it is a solid rod can be quite heavy. The weight of the cable can be greatly reduced by using a hollow inner conductor. This does not significantly reduce the conductivity because most of the high frequency ac current is conducted near the outer surface of the inner conductor.

Three configurations were considered in this analysis. They are illustrated on figure 1. Figure 1(a) shows a cross section of a hollow coaxial cable. The inside radius of this cable was varied parametrically from 5 to 30 mm. Conductor thickness was the same for the inner and outer conductors, either 0.2 mm or 0.5 mm. The dielectric thickness was 0.5 mm. Figure 1(b) shows a cross section of a hollow coaxial cable in which the conductors consist of strands of fine wires wound in a helix. This design enables the cable to be flexible for ease in installation. A support structure which might be required to prevent collapse of the inner conductor was not included in this analysis. The parameters for the stranded coaxial cable were varied over the same ranges as for the hollow coaxial cable. To differentiate the hollow cable with solid conductors from the hollow cable with stranded conductors, the hollow cable with solid conductors will be referred to as solid coaxial cable in the remainder of this report. Figure 1(c) shows a cross section of a parallel conductor cable. The two conductors are hollow. The parameters for the parallel conductors were varied over the same ranges as the coaxial cables. In addition, the distance between the conductors was varied from 1 to 10 mm.

Formulas

In most cases, standard formulas were used in this analysis. However, because of the unusual configuration (closely spaced, hollow, coaxial conductors) the inductance formula for this analysis includes self inductance terms that are negligible for most other configurations. Also, the conductor thicknesses considered for this application are too thin for the conventional ac formula for resistance to give accurate results and too thick for the conventional dc formula. A more general formula was developed to accurately calculate resistance in this intermediate region. The inductance and resistance formulas used in this analysis are presented below.

Resistance Formula

Current flow versus depth. - High frequency ac current is concentrated near the surface of a conductor and decreases approximately exponentially with depth into the conductor (ref. 2). The distance δ from the surface where the current is reduced by a factor of e from the surface current i_s is called one "skin" depth. Thus the formula for current i_x as a function of depth x into a conductor is:

$$i_x = i_s \, e^{-x/\delta}$$

Total current flow. - The total current flow I_T in an ac conductor of thickness T can be determined by integrating the above formula. Thus:

$$I_T = \int_0^T i_s \, e^{-x/\delta} \, dx = i_s \delta \, (1 - e^{-T/\delta})$$

If the thickness T of the ac conductor is many times the skin depth δ, the term $e^{-T/\delta}$ is very close to zero and the total ac current is approximately:

$$I_T = i_s \delta$$

Thus for an ac conductor that is many skin depths thick, the total current is the surface current times one skin depth. As the surface conductivity for ac is the same as the dc conductivity of the conductor material, the ac conductivity of many skin depths is the dc conductivity of one skin depth. Common ac conductors are many skin depths thick. The above simplified formula is, therefore, commonly used to compute ac resistance.

Skin depth. - The skin depth for ac current is calculated using the following formula (ref. 2).

$$\delta = 503 \sqrt{\rho / f \mu_r}$$

ρ conductor resistivity: copper resistivity = $1.77 \; 10^{-8}$ ohm M^2/M
f frequency, Hz
μ_r relative permeability: close to one for nonmagnetic materials

In computing skin depth for the stranded coaxial cable, resistivity was increased to reflect the portion of the area that was actually filled with conductor material. In this analysis, frequencies of 10, 20, and 30 kHz were considered. The resulting skin depths were 0.6692, 0.4732, and 0.3864 mm for solid conductors and 0.7578, 0.5366, and 0.4413 mm for stranded conductors. As the conductor thickness was parameterized as either 0.2 mm or 0.5 mm, the conductor thickness varied between 0.26 and 1.3 skin depths in this analysis.

Graph of conductance. - Conductance for ac and dc current as a function of conductor thickness is plotted on figure 2. Depth of the conductor is expressed on the x-axis of this figure as multiples of one skin depth at the ac frequency. Conductance on the y-axis is normalized to skin depth times surface conductivity. There are three curves on this figure. The curve labeled "dc formula" represents dc conductivity remaining constant independent of conductor thickness. The curve labeled "ac formula" represents an ac conductor that is many skin depths thick. The curve labeled "general formula" was used in this analysis. It corresponds to the general equation for ac current flow derived above. Note that for the range of conductor thickness encountered in this analysis (0.26 δ to 1.3 δ) the conductance is significantly less using this general formula than using the dc formula or the commonly used ac formula.

dc resistance formulas. - dc resistance of a conductor is the specific resistance ρ of the conductor material times the conductor length 'l' divided by the conductor area A:

$$R_{dc} = \rho \ell / A$$

The round trip dc resistance for a coaxial conductor with inner conductor area A_I and outer conductor area A_O is:

$$R_{dc} = \rho\ell/A_I + \rho\ell/A_O$$

For the stranded coaxial conductor, A_I and A_O are the total cross sectional areas of the strands. The round trip dc resistance for two parallel conductors with conductor area A is:

$$R_{dc} = \partial\rho\ell/A$$

ac resistance formula. - To compute ac resistance for this analysis, the dc resistance R_{dc}, skin depth δ and conductor thickness T were first computed. The following formula was then used to compute the ac resistance:

$$R_{ac} = R_{dc}T/\delta$$

As explained previously, the above commonly used formula is not valid for the range of conductor thicknesses used in this analysis. The following general formula was, therefore, used to correct the ac resistance for conductor thicknesses less than many skin depths:

$$R_{gen} = R_{ac}/(1 - e^{-T/\delta})$$

Coaxial Cable Inductance Formula

The inductance of most conventional coaxial cables is due primarily to the magnetic field in the dielectric between the conductors. This portion of the inductance is represented by the following formula (ref. 3).

$$L = \mu/2\pi \ln (b/a) \sim 2.10^{-7} \ln (b/a)$$

L inductance per unit length of line
μ permeability of dielectric
a,b inner, outer diameters of dielectric

To minimize inductance for efficient transmission of high power at high frequency, large diameter coaxial conductors are closely spaced. This reduces the inductance due to the magnetic field between the conductors. The inductance due to the magnetic field within each of the conductors, although still small, becomes a significant part of the total inductance. The inductances within the conductors are evaluated as follows.

Inductance within inner conductor. - The self inductance of a conductor is evaluated in terms of the self flux linkages ($N\phi$) established by the conductor per unit current flow in the conductor (ref. 2). For a hollow conductor:

$$L_{cond} = \sum \frac{N\phi}{i} = \int_{r_1}^{r_2} \frac{f_x B_x dx}{I}$$

L_{cond}	inductance of conductor, henrys per meter
f_x	fraction of total current within radius x
B_x	$\mu H_x = \mu f x I/2\pi x$ = magnetic flux density at x
μ	permeability of conductor ($4\pi x10^{-7}$, if nonmagnetic)
I	total current in conductor
r_1, r_2	inner, outer radius of conductor, meters

Substituting for B_x in the above formula for L_{cond}

$$L_{cond} = \frac{\mu}{2\pi} \int_{r_1}^{r_2} \frac{f x^2}{x} dx$$

Assuming uniform current density which is valid for dc or low frequency, the following formula was derived for the fraction of current within radius X. X is a variable of integration which varies between r_1 and r_2, the inner and outer radii of the inner conductor as illustrated on figure 1(a).

$$f_x = \frac{X^2 - r_1^2}{r_2^2 - r_1^2}$$

$$L_{cond} = 2.10^{-7} \int_{r_1}^{r_2} \left[\frac{X^2 - r_1^2}{\left(r_2^2 - r_1^2\right)}\right]^2 \frac{dx}{x}$$

$$L_{cond} = \frac{2\ 10^{-7}}{(r_2^2 - r_1^2)} \left[\frac{r_2^2}{4} - \frac{3r_1^2}{4} + \frac{r_1^4 \left(\ln \frac{r_2}{r_1}\right)}{r_2^2 - r_1^2}\right]$$

For high frequency ac, current density was assumed to decrease exponentially with distance into the conductor as explained in the section titled "Resistance Formulas." The resulting formulas for f_x and L_{cond} are:

$$f_x = \frac{e^{(x-r_2)/\delta} - e^{(r_1-r_2)/\delta}}{1 - e^{(r_1-r_2)/\delta}}$$

$$L_{cond} = 2.10^{-7} \int_{r_1}^{r_2} \left[\frac{e^{(x-r_2)/\delta} - e^{(r_1-r_2)/\delta}}{1 - e^{(r_1-r_2)/\delta}}\right]^2 \frac{dx}{x}$$

The above integral was evaluated numerically to determine self-inductance of the inner conductor.

Inductance within outer conductor. - The inductance within the outer conductor would be calculated by the same formula as the inner conductor except

that there is net current flow (due to the inner conductor) within the inner radius of the outer conductor. The current linked by the inside radius (r_3) of the outer conductor is I, the total current of the inner conductor. Assuming the phase difference of the current in the outer conductor compared to the current in the inner conductor is very close to 180°, the net current linked decreases to zero at the outer radius (r_4) of the outer conductor. Thus, assuming uniform current density in the outer conductor, the following formula was derived for the fraction of total current within radius x which is between r_3 and r_4, the inner and outer radii of the outer conductor as illustrated on figure 1(a):

$$f_x = 1 - \frac{x^2 - r_3^2}{r_4^2 - r_3^2}$$

$$f_x = \frac{r_4^2 - x^2}{r_4^2 - r_3^2}$$

and the inductance of the outer conductor is

$$L_{outer} = \frac{\mu}{2\pi} \int_{r_3}^{r_4} \left(\frac{r_4^2 - x^2}{r_4^2 - r_3^2} \right)^2 \frac{dx}{x}$$

$$L_{outer} = \frac{2x10^{-7}}{r_4^2 - r_3^2} \left[\frac{r_3^2}{4} - \frac{3r_4^2}{4} + \frac{r_4^4}{r_4^2 - r_3^2} \ln \frac{r_4}{r_3} \right]$$

For high frequency ac, the current density was again assumed to decrease exponentially with distance into the conductor. The resulting formulas for fx and L for the outer conductor are:

$$f_x = \frac{e^{(r_3-x)/\delta} - e^{(r_3-r_4)/\delta}}{1 - e^{(r_3-r_4)/\delta}}$$

$$L_{outer} = 2x10^{-7} \int_{r_3}^{r_4} \left[\frac{e^{(r_3-x)/\delta} - e^{(r_3-r_4)/\delta}}{1 - e^{(r_3-r_4)/\delta}} \right]^2 \frac{dx}{x}$$

The above integral was evaluated numerically to determine the high frequency self-inductance of the outer conductor.

Parallel Cable Inductance

The standard formula for inductance between parallel conductors is listed below. This is a general formula that is valid even for closely spaced parallel conductors. The distance between the centers of the conductors, r_6, and the outer radius of the conductors, r_2, are illustrated on figure 1(c).

$$L_{parallel} = 4 \times 10^{-7} \times \ln\left(\frac{r_6}{2r_2} + \sqrt{\frac{r_6}{2r_2} - 1}\right)$$

This is applicable for the parallel lines considered herein except an additional term was added to account for the self-inductance of the hollow conductors. This term is the same as the self inductance of the inner conductor of the coaxial cable derived above.

$$L_{cond} = \frac{2\times10^{-7}}{r_2^2 - r_1^2}\left[\frac{r_2^2}{4} - \frac{3r_1^2}{4} + \frac{r_1^4 \ln(r_2/r_1)}{(r_2^2 - r_1^2)}\right]$$

The total inductance of the parallel conductors is:

$$tot = L_{parallel} + 2\,L_{cond}$$

As the self-inductance of the parallel conductors is a much smaller part of the total inductance than the self-inductance of the coaxial conductors is of total coaxial inductance, high frequency self-inductance was not computed for the parallel lines.

Computer Program Description

Three separate computer codes were used for the three configurations (coaxial cable, stranded coaxial cable, and parallel lines) mentioned earlier. These codes are similar with minor differences to reflect the differences between the configurations. Each code consists of a main program and a calculation subroutine. The computer codes used in this analysis are listed in the appendix.

The main programs generate parametric variations of cable size and of alternating current frequency. Cable inside radius values were 5, 10, 15, 20, 25, and 30 mm. Conductor thickness values were 0.2 and 0.5 mm. For parallel lines, spacing between the conductors were 1, 4, 7, and 10 mm. The values of alternating current frequency were 10, 20, and 30 kHz. The main programs generate input to the calculation subroutine for each of the combinations of input parameter values.

The calculation subroutines calculate resistance, conductance, inductance, mass, capacitance and other computed output. These subroutines produce formatted output data for each parametric case generated by the main programs. An example of this output for coaxial cable with inside radius of 15 mm, conductor thickness of 0.5 mm, and ac frequency of 20 kHz is listed on table II. This table is included to show the variety of output produced by this computer

program. Many of the output quantities listed on table II are not discussed or used elsewhere in this report. Note that although the computer program is structured to include a shield around the cable, the shield is omitted in this case by setting the shield outside radius equal to the shield inside radius. There is also a plotting subroutine that is called by the calculation subroutines. The plotting subroutine produces plots of computed output versus cable inside radius. However, the plotting subroutine requires a graphics software package that is only available at NASA Lewis Research Center. Modifications to the plotting subroutine would be required for use with other computer software.

RESULTS

Cable size, mass, and power losses need to be determined based on system parameters (voltage, frequency, and current) and on system constraints (line inductance and line capacitance). However, it is not convenient to determine cable size directly based on system parameters and system constraints. Cable geometry is the logical independent variable. From cable geometry, cable mass, cable resistance, line inductance and line capacitance can be calculated. Power loss is then determined based on voltage, frequency, and current. Interpolating back from the system parameters and constraints, the required cable geometry can then be determined. From the cable geometry the cable mass and power losses are determined.

Cable Mass

Cable mass versus cable inside radius is shown on figure 3(a) for the coaxial configuration, on figure 3(b) for stranded coaxial and on figure 3(c) for parallel lines. On each figure there are six curves. Three curves are for a conductor thickness of 0.5 mm, and three are for a conductor thickness of 0.2 mm. The three curves in each group represent mass of the copper conductors, mass of the teflon dielectrics, and total copper plus teflon mass. Mass of cable support structure and mass of interconnects is not included. Mass increases linearly directly proportional to cable radius for all three types of cable. Mass of the stranded coaxial cable is approximately 25 percent less than of the solid coaxial cable. Mass of the parallel lines is almost the same as the mass of the solid coaxial cable. However, neither the coaxial cable nor the parallel lines were shielded. The magnetic fields of the inner and outer conductors of the coaxial cable tend to cancel each other and shielding may not be required. The parallel lines have an external magnetic field and should be shielded. Shielding the parallel lines would cause them to increase in mass possibly to twice the mass of the unshielded coaxial cable.

Electrical Conductivity

Electrical conductivity is shown on figure 4(a) for the coaxial cable, on figure 4(b) for the stranded coaxial cable and on figure 4(c) for the parallel lines. Conductivity follows the same relationship to cable type and inside radius as the relationships of mass to cable type and inside radius described in the previous section. Conductivity increases linearly directly proportional to radius in each of the three cases. Conductivity of the stranded cable is

approximately 25 percent less than of the solid cable. Conductivity of the parallel lines is almost identical to conductivity of the solid coaxial cable. Unlike cable mass, however, conductivity of the parallel lines does not increase if the parallel lines are shielded. Another difference is that conductivity decreases as the frequency is increased. Mass, of course, stays the same. This is shown by the families of curves on figures 4(a) to (c). On each figure there are curves corresponding to 0 kHz (i.e., direct current), 10, 20, and 30 kHz, and conductor thicknesses of 0.2 and 0.5 mm. Note, that all the curves are linear; conductivity increases directly proportional to cable radius. The ratio of conductivity at each ac frequency to direct current conductivity is a constant independent of cable radius and cable type. This ratio is plotted on figure 5 as a function of conductor thickness computed as the number of skin thicknesses. One skin thickness is the thickness of a dc conductor required to conduct as much current as an infinitely thick ac conductor.

As the ac frequency increases, the resistivity of a conductor increases compared to the resistivity of that same conductor for dc. Thus the current carrying capacity is lower for a conductor carrying high frequency alternating current than for the same conductor carrying direct current. The magnitude of this effect is illustrated for the range of conductor thicknesses and frequencies used in this analysis on figure 5. The extreme case 0.5 mm at 30 kHz has 1.8 times as much electrical resistance as the same size conductor carrying direct current electricity.

To observe the effect of frequency compare the point labeled 0.5 mm at 30 kHz to the point labeled 0.5 mm at 10 kHz. These points correspond to the same physical size conductor. But at the higher frequency, the current is more concentrated near the surface of the conductor. Therefore, the resistance at 30 kHz is 1.8 times the resistance at dc; whereas the resistance at 10 kHz is 1.4 times the resistance at dc. The frequency effect can also be observed by comparing the points labeled 0.2 mm. At 30 kHz the 0.2 mm resistance is 1.3 times the resistance at dc; whereas the resistance at 10 kHz is 1.15 times the resistance at dc.

Comparing different cable thicknesses at the same frequency shows that the ratio of ac resistance to dc resistance increases as the conductor thickness increases. ac resistance and dc resistance both decrease with increasing conductor thickness, but because ac current is concentrated near the conductor surface, the decrease of ac resistance is less than the decrease of dc resistance. At 30 kHz the resistance ratio is 1.8 for a 0.5 mm conductor thickness and 1.3 for a 0.2 mm conductor thickness. At 10 kHz the ratios are 1.4 at 0.5 mm and 1.15 at 0.2 mm. At 0 kHz the ratio of resistance to the resistance for direct current is, of course, 1.0 regardless of the conductor thickness.

Inductance

The inductance of the transmission line is a critical parameter, since the transmission line acts as an integral part of the four quadrant bidirectional converter power stage (ref. 1). Total inductance of the power stage includes the output transformer inductance, the power stage inductor, the transmission line and stray inductances. Maximum inductance is determined by system power, voltage and frequency and by power stage configuration. Current conceptual designs limit the total inductance to 15 to 20 μH. Equations

for computing total inductance and capacitance and example calculations at the 3 kW level are given in reference 4. An objective of this study was to determine the feasibility of designing a 50 Ω transmission line capable of transmitting 100 kW of power with a transmission line inductance less than 5 μH.

The inductance versus cable inside radius is plotted for the coaxial cable on figure 6(a), for the stranded coaxial on figure 6(b), and for parallel lines on figure 6(c). There are eight curves on each of the three figures 6(a) to (c). On figures 6(a) and (b) inductance is plotted for conductor thicknesses of 0.2 and 0.5 mm at the four frequencies, 0, 10, 20, and 30 kHz. The eight curves on figure 6(a) are nearly identical to the eight curves on figure 6(b). For the curves with 0.5 mm conductor thickness and 0 kHz frequency, inductance decreases from 1.5 μH with a 5. mm inside radius to 0.3 μH with a 30 mm inside radius. With 0.2 mm conductor thickness inductance is about 20 percent less for all values of inside radius because, with thinner conductors and the same 0.5 mm dielectric thickness, the currents are closer together. Increasing the frequency also brings the currents somewhat closer to the dielectric; thereby decreasing the inductance by 5 to 10 percent for the 0.5 mm conductors, and by about 1 percent for the 0.2 mm conductors. The decrease of inductance due to increasing frequency is slightly less for the stranded coax because the lower effective conductivity of the stranded coax increases the skin depth.

The inductance of parallel lines is significantly greater than the inductance of coaxial cables. It varies from 27 μH for 5 mm inside radius conductors spaced 10 mm apart to 6 μH for 30 mm inside radius conductors spaced 1 mm apart. The eight curves on figure 6(c) represent four values of spacing between the conductors, 1, 4, 7, and 10 mm, and two values of conductor thickness, 0.2 and 0.5 mm. This is a significant parameter in that increasing the spacing from 1 mm to 10 mm causes the inductance to approximately double. Conductor thickness is a much less significant parameter in that increasing the thickness from 0.2 to 0.5 mm increases the inductance by less than 1 percent. Increasing frequency would reduce inductance by much less than 1 percent. The 30 mm inside radius conductors spaced 1mm apart at 6 μH inductance are close to the objective of 5 μH maximum inductance mentioned earlier but the inductance gets much higher and completely out of the desirable range, if the inside radius is decreased or the spacing is increased.

Capacitance

Capacitance is shown for coaxial cables on figure 7(a), for stranded coax on figure 7(b) and for parallel lines on figure 7(c). The following formulas were used to compute coaxial cable and parallel line capacitance:

$$C_{coax} = 55.56\times10^{-12}\times Diel_{TEFL}\times\ell/\ln\,(r_3/r_2)$$

$$C_{parallel} = 27.78\times10^{-12}\times Diel_{TEFL}\times\ell/\ln\left[\frac{r_6}{r_2}+\sqrt{\left(\frac{r_6}{r_2}\right)^2-1}\right]$$

$Diel_{TEFL}$ dielectric strength of Teflon
ℓ cable length
r_2, r_3, r_6 cable dimensions as shown on figure 1.

These figures show that capacitance increases linearly directly proportional to cable radius. The capacitance (0.07 to 0.4 μF) of both types of coaxial cable is greater than for parallel lines (0.001 to 0.006 μF). However, the cable capacitances are small compared to the several microfarads of capacitance required for the converter power stage. The difference can easily be made up by adding a capacitor to the power stage.

Power Loss

Power loss is shown on figure 8(a) for coaxial cable on figure 8(b) for stranded coax and on figure 8(c) for parallel lines. These curves are based on an assumed 100 A of current flowing through each conductor. On each figure there are curves of power loss versus conductor inside radius for alternating current frequencies of 0 kHz (direct current), 10, 20, and 30 kHz, and for conductor thicknesses of 0.2 and 0.5 mm. Power loss increases with increasing frequency, decreasing conductor thickness, and decreasing conductor inside radius. Power loss varies from 150 W for a solid conductor with 30 mm inside radius conducting dc to 4200 W for a stranded conductor with 5 mm inside radius conducting 30 kHz ac. Stranded coax has about 25 percent more power loss than solid conductor coax. Solid conductor coax and parallel lines are about equal in power loss.

Radiating Temperature

As mentioned in the introduction, this report is concerned with electric cables for spacecraft use. Spacecraft electric power cables must reject the power lost along the cable by radiation to space. Inner conductor temperatures of the cables were computed assuming radiation from the outside surface of the cable to space (sink temperature 273 K) and accounting for the temperature rise across the dielectrics. These inner conductor temperatures are plotted for the coaxial cable on figure 9(a) for the stranded coax on figure 9(b) and for the parallel lines on figure 9(c). The curves show radiating temperature versus inside radius for frequencies of 0, 10, 20, and 30 kHz, and for conductor thicknesses of 0.2 and 0.5 mm. The temperatures range from near 0° C for the 30 mm inside radius to 250° C for the 5 mm inside radius stranded coax with 0.2 mm conductor thickness. Note that the temperatures increase rapidly as the inside radius approaches 5 mm. At 10 mm inside radius the maximum temperature is 130° C.

Transmission Line Example

As an example of using the results of this study in designing a transmission line, consider a transmission line to transmit 100 kW at a voltage of 1000 V ac for a distance of 50 m. The transmission line is to operate with a bi-directional converter at a frequency of 20 kHz and must have a line inductance of not more than 5 μH and a line capacitance of not more than 3 μF. Power loss is to be less than 2 percent of the 100 kW (i.e., 2000W). Stranded coax is desired because of its flexibility (to provide easier installation) and

because of the inherent electromagnetic shielding of coaxial cable. An alternative transmission line is to be chosen to operate at 500 V.

Assuming that power loss is the most severe constraint, cable size is selected based on the power loss requirement using figure 8(b) for the 1000 V case. The 5 mm inside radius stranded coax with 0.5 mm conductor thickness has a loss of 1900 W, which is within the limit of 2000 W. Larger cables have even less power loss. For the 500 V case, 100 kW of power yields 200 A, which is different than the 100 A assumed for figure 8(b). Figure 4(b), "Conductance of Stranded Coax," must, therefore, be used to determine the cable inside radius to keep power loss less than 2000 W. Power loss is current squared divided by conductance. Conductance must, therefore, be greater than 20 mhos to keep power loss less than 2000 W. To achieve this conductance a cable inside radius of 25 mm and a conductor thickness of 0.5 mm was selected from figure 4(b). This results in a conductance of 24 mhos and a power loss of 1667 W which is less than the 2000 W limit.

The 5 mm inside radius cable to operate at 1000 V and 25 mm inside radius cable to operate at 500 V were chosen to satisfy the 2000 W power loss constraint. There are also inductance and capacitance constraints of 5 μH and 3 μF, respectively. From figure 6(b), the inductance of the 5 mm is 1.45 μH and of the 25 mm cable is 0.3 μH. Both these values are within the 5 μH constraint. From figure 7(b), the capacitance of the 5 mm cable is 0.07 μF and of the 25 mm cable is 0.32 μF. These values are within the 3 μF capacitor constraint.

This example has been kept simple for clarity. In designing a specific system a more detailed tradeoff including cable mass, cable temperature, and cable volume is required to specify transmission line optimum sizing. Cable mass can be determined from figure 3(b) and cable temperature from figure 9(b).

CONCLUSIONS

A computer program was developed to evaluate properties of high-power, high-frequency transmission lines. Several transmission line concepts were considered to minimize transmission line inductance and mass. The computer program includes formulas that were derived to accurately compute resistance and inductance for these transmission line designs.

Coaxial cable with hollow center conductor is the configuration selected by this study for high frequency distribution of space power. Nearly equal radii of the inner and outer conductor minimize cable inductance. To provide greater cable flexibility, stranded rather than solid conductors could be used. This would enable deployment or reconfiguration of the power system in orbit. Stranded conductors have approximately 25 percent less mass and 25 percent less electrical conductance than solid conductors of the same overall dimensions.

Parallel transmission lines were also evaluated using this computer program. These lines were also considered to be hollow conductors to minimize mass for high frequency power transmission. Inductance of parallel lines is significantly greater than inductance of the closely space coaxial cable. Parallel line inductance would be too high for the current design of the bidirectional power converter used to generate the high frequency ac power.

Electromagnetic interference might also be a problem with parallel transmission lines. This could increase the mass of the parallel lines with shielding to twice the mass of coaxial cable.

REFERENCES

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2. Ware, Lawrence A.; and Reed, Henry R.: Communication Circuits. Third ed. John Wiley Sons, Inc., 1964.

3. Potter, James I.; and Fich, Sylvan: Theory of Networks and Lines. Prentice-Hall, 1963.

4. Schwarz, F. C.: Bi-Directional Four Quadrant (BDQ4) Power Converter Development. NASA CR-159660, 1979.

APPENDIX - COMPUTER PROGRAMS

The computer codes used in this analysis are listed in this appendix. These codes were described in the section of this report titled "Computer Program Description."

Main Program for Coax

```
C     INNER CONDUCTOR RAD(1),RAD(2); OUTER CONDUCTOR RAD(3),RAD(4)
      DIMENSION RAD(6),R(6)
      DOUBLE PRECISION RAD
      DATA R/.0333375,.034925,.0381,.0396875,.0428625,.04445/
      DO 100 IFREQ=10000,30000,10000
      IR1=5
      ID=1
      DO 50 IR=1,6
   50 RAD(IR)=R(IR)
      FREQ=IFREQ
      CALL TRINT(RAD,FREQ,IR1,IFREQ,ID)
      DO 100 ID=1,2
      DRAD=.0005
      IF(ID.EQ.2) DRAD=.0002
      DO 100 IR1=5,30
      RAD(1)=FLOAT(IR1)*.001
      RAD(2)=RAD(1)+DRAD
      RAD(3)=RAD(2)+.0005
      RAD(4)=RAD(3)+DRAD
      RAD(5)=RAD(4)+.0005
      RAD(6)=RAD(5)+DRAD
C     FOLLOWING CHANGE ELIMINATES SHIELD
      RAD(6)=RAD(5)
      CALL TRINT(RAD,FREQ,IR1,IFREQ,ID)
  100 CONTINUE
      STOP
      END
```

Main Program for Stranded Coax

```
C     INNER CONDUCTOR RAD(1),RAD(2); OUTER CONDUCTOR RAD(3),RAD(4)
      DIMENSION RAD(6),R(6)
      DOUBLE PRECISION RAD
      DATA R/.0333375,.034925,.0381,.0396875,.0428625,.04445/
      DO 100 IFREQ=10000,30000,10000
      IR1=5
      ID=1
      DO 50 IR=1,6
   50 RAD(IR)=R(IR)
      FREQ=IFREQ
      CALL STINT(RAD,FREQ,IR1,IFREQ,ID)
      DO 100 ID=1,2
      DRAD=.0005
      IF(ID.EQ.2) DRAD=.0002
      DO 100 IR1=5,30
      RAD(1)=FLOAT(IR1)*.001
      RAD(2)=RAD(1)+DRAD
      RAD(3)=RAD(2)+.0005
      RAD(4)=RAD(3)+DRAD
      RAD(5)=RAD(4)+.0005
      RAD(6)=RAD(5)+DRAD
C     FOLLOWING CHANGE ELIMINATES SHIELD
      RAD(6)=RAD(5)
      CALL STINT(RAD,FREQ,IR1,IFREQ,ID)
  100 CONTINUE
      STOP
      END
```

Main Program for Parallel Lines

```
C     INNER CONDUCTOR RAD(1),RAD(2); SHIELD RAD(3),RAD(4)
C     CENTER TO CENTER DISTANCE RAD(6)
      DIMENSION RAD(6),R(6)
      DOUBLE PRECISION RAD
      DATA R/.0333375,.034925,.0381,.0381,.0381,.1016/
      DO 50 IR=1,6
   50 RAD(IR)=R(IR)
      IR1=5
      ID=1
      IFREQ=10000
      FREQ=10000.
      SPACE=.001
      CALL PRLINT(RAD,FREQ,IR1,IFREQ,ID,1)
      DO 100 LSPACE=1,4
      SPACE=FLOAT(LSPACE*3-2)*.001
      DO 100 IFREQ=10000,30000,10000
      FREQ=IFREQ
      DO 100 ID=1,2
      DRAD=.0005
      IF(ID.EQ.2) DRAD=.0002
      DO 100 IR1=5,30
      RAD(1)=FLOAT(IR1)*.001
      RAD(2)=RAD(1)+DRAD
      RAD(3)=RAD(2)+.0005
      RAD(4)=RAD(3)
      RAD(6)=2.*RAD(4)+SPACE
      CALL PRLINT(RAD,FREQ,IR1,IFREQ,ID,LSPACE)
  100 CONTINUE
      STOP
      END
```

Calculation Subroutine for Coax

```
      SUBROUTINE TRINT(RAD,FREQ,IR1,IFREQ,ID)
      DIMENSION RAD(6),ERAD(6)
      DIMENSION X(26),Y(104,2),YM(78,2),YI(104,2),TICHR1(10),YC(26,2),TPCHR1(10),TPCHR2(10),YP(104,2)
      DIMENSION TCHAR1(10),TCHAR2(10),TMCHR1(10),TMCHR2(10),TCCHR1(10),TCCHR2(10)
      DIMENSION TRCHR1(10),TRCHR2(10),YR(104,2),TTCHR1(12),TTCHR2(12),YT(104,2)
      DATA TCHAR1/'COND','UCTA','NCE ','OF C','OPPE','R CO','AX  ','    ',2*0./
      DATA TCHAR2/'COND','UCTA','NCE ','OF 0','.2 M','M CO','PPER',' COA','X   ',0./
      DATA TMCHR1/'MASS',' OF ','COPP','ER C','OAX ','    ',4*0./
      DATA TMCHR2/'MASS',' OF ','0.2 ','MM C','OPPE','R CO','AX  ',3*0./
      DATA TICHR1/'INDU','CTAN','CE O','F CO','PPER',' COA','X   ',3*0./
      DATA TCCHR1/'CAPA','CITA','NCE ','OF C','OPPE','R CO','AX  ','    ',2*0./
      DATA TRCHR1/'RESI','STIV','ITY ','OF C','OPPE','R CO','AX  ','    ',2*0./
      DATA TRCHR2/'RESI','STIV','ITY ','OF 0','.2 M','M CO','PPER',' COA','X   ',0./
      DATA TPCHR1/'POWE','R LO','SS O','F CO','PPER',' COA','X   ',3*0./
      DATA TPCHR2/'POWE','R LO','SS O','F 0.','2 MM',' COP','PER ','COAX','    ',0./
      DATA TTCHR1/'RADI','ATIN','G TE','MPER','ATUR','E OF',' COP','PER ','COAX','    ',2*0./
      DATA TTCHR2/'RADI','ATIN','G TE','MPER','ATUR','E OF',' 0.2',' MM ','COPP','ER C','OAX ','    '/
      DOUBLE PRECISION RAD,R2R1,R4R3
   10 CABL=50.
      PI=3.1416
C     RESISTIVITY OHM METER;DENSITY GRAM/CUBIC METER
      DATA CRES,CDENS/1.77E-08,8.96E06/
C     TEFLON DENSITY GRAM/CUBIC METER; RELATIVE DIELECTRIC CONSTANT; DIELECTRIC STRENGTH VOLTS/METER
      DATA TDENS,TDIEL,TSTRNG/2.2E06,2.2,16.9E06/
C     THERMAL CONDUCTIVITY WATTS/METER/DEG C
      DATA TTCND/.25/
      VOLTS=1000.
      CURRNT=100.
      POWER=VOLTS*CURRNT
      AREAI=PI*(RAD(2)**2-RAD(1)**2)
      AREAO=PI*(RAD(4)**2-RAD(3)**2)
      AREAS=PI*(RAD(6)**2-RAD(5)**2)
      CMASS=(AREAI+AREAO+AREAS)*CABL*CDENS
      AREAD=PI*(RAD(3)**2-RAD(2)**2)+PI*(RAD(5)**2-RAD(4)**2)
      TMASS=AREAD*CABL*TDENS
      RDC=CABL*CRES*(1./AREAI+1./AREAO)
      SKIN=503.*SQRT(CRES/FREQ)
      RAC=RDC*(RAD(2)-RAD(1))/SKIN
      RMAX=RAC/(1.-EXP(-(RAD(2)-RAD(1))/SKIN))
      CONDCT=1./RMAX
      PWRRES=RMAX*CURRNT**2
      PWRRAT=PWRRES/POWER
      PWRPM=PWRRES/CABL
      RLOG=ALOG(RAD(3)/RAD(2))
      RSLOG=ALOG(RAD(5)/RAD(4))
      PWRPMI=PWRPM*RAD(3)/(RAD(2)+RAD(3))
      DTEMP=(PWRPMI*RLOG+PWRPM*RSLOG)/(2.*PI*TTCND)
      EMIS=0.5
      SIG=5.67E-08
      TSINK=273.
      TRADK=DTEMP+SQRT(SQRT(TSINK**4+PWRPM/(2.*PI*RAD(6)*EMIS*SIG)))
      TRADC=TRADK-273.
      TSINKC=TSINK-273.
      VMAX=TSTRNG*RAD(2)*RLOG
```

Calculation Subroutine for Coax (continued)

```
0005500          VSMAX=TSTRNG*RAD(4)*RSLOG
0005600          TCOND=0.
0005700          G=2.*PI*TCOND/RLOG
0005800 C        INDUCTANCE OF POWER LINE (HENRYS) AND CAPACITANCE (MFD)
0005900          ER2R1=EXP((RAD(1)-RAD(2))/SKIN)
0006000          SFX2=0.
0006100          DRAD=(RAD(2)-RAD(1))/50.
0006200          DO 50 INT=1,99,2
0006300          RX=RAD(1)+FLOAT(INT)*.5*DRAD
0006400          ER2X=EXP((RX-RAD(2))/SKIN)
0006500          FX=(ER2X-ER2R1)/(1.-ER2R1)
0006600       50 SFX2=SFX2+FX**2/RX
0006700          AINDI=2.E-07*CABL*SFX2*DRAD
0006800          ER4R3=EXP((RAD(3)-RAD(4))/SKIN)
0006900          SFX2=0.
0007000          DRAD=(RAD(4)-RAD(3))/50.
0007100          DO 75 INT=1,99,2
0007200          RX=RAD(3)+FLOAT(INT)*.5*DRAD
0007300          EXR3=EXP((RAD(3)-RX)/SKIN)
0007400          FX=(EXR3-ER4R3)/(1.-ER4R3)
0007500       75 SFX2=SFX2+FX**2/RX
0007600          AINDO=2.E-07*CABL*SFX2*DRAD
0007700          AINDCT=AINDI+2.E-07*RLOG*CABL+AINDO
0007800          R2R1=RAD(2)**2-RAD(1)**2
0007900          DINDI=CABL*(2.E-07/R2R1)*(RAD(1)**4*DLOG(RAD(2)/RAD(1))/R2R1+.25*RAD(2)**2-.75*RAD(1)**2)
0008000          R4R3=RAD(4)**2-RAD(3)**2
0008100          DINDO=CABL*(2.E-07/R4R3)*((RAD(4)**4/R4R3)*DLOG(RAD(4)/RAD(3))+.25*RAD(3)**2-.75*RAD(4)**2)
0008200          DCIND=DINDI+2.E-07*RLOG*CABL+DINDO
0008300          CAP=55.56E-12*TDIEL*CABL/RLOG
0008400 C        CHARACTERISTIC IMPEDANCE,Z0; CHARACTERISTIC ADMITTANCE,Y0
0008500          Z0=SQRT(AINDCT/CAP)
0008600          Y0=SQRT(CAP/AINDCT)
0008700 C        COMPLEX INDUCTANCE,CIND; COMPLEX CAPACITANCE,CCAP
0008800          COMPLEX CIND,CCAP,J
0008900          DATA J/(0.,1.)/
0009000          CIND=AINDCT+RMAX/(J*2.*PI*FREQ)
0009100          CCAP=CAP+G/(J*2.*PI*FREQ)
0009200      100 FORMAT (1H1,-
0009300         * ' INNER CONDUCTOR RADII          OUTER CONDUCTOR RADII          SHIELD RADII'/-
0009400         * ' INSIDE '3PF9.2,' MM             INSIDE '3PF9.2,' MM             INSIDE '3PF9.2,' MM'/-
0009500         * ' OUTSIDE'3PF9.2,' MM             OUTSIDE'3PF9.2,' MM             OUTSIDE'3PF9.2,' MM'/-
0009600         * ' VOLTAGE                 '0PF7.0,' VOLTS'/-
0009700         * ' CURRENT                 '0PF7.1,' AMPERES'/-
0009800         * ' FREQUENCY               '0PF7.0,' HERTZ'/-
0009900         * ' POWER                   '-3PF7.0,' KILOWATTS'/-
0010000         * ' CABLE LENGTH            '0PF7.1,' METERS'/)
0010100          WRITE (6,100) RAD(1),RAD(3),RAD(5),RAD(2),RAD(4),RAD(6),VOLTS,CURRNT,FREQ,POWER,CABL
0010200      200 FORMAT (-
0010300         * ' COPPER MASS            '-3PF7.1,' KILOGRAMS'/-
0010400         * ' TEFLON MASS            '-3PF7.1,' KILOGRAMS'/-
0010500         * ' DC FORMULA RESISTANCE'0PF6.4,' OHMS'/-
0010600         * ' AC FORMULA RESISTANCE'0PF6.4,' OHMS'/-
0010700         * ' RESISTANCE              '0PF7.4,' OHMS'/-
0010800         * ' CONDUCTANCE             '0PF7.3,' MHOS'/-
```

Calculation Subroutine for Coax (continued)

```
0010900      * ' RESISTIVE POWER      '0PF7.1,' WATTS'/-
0011000      * ' PERCENT POWER LOST   '2PF7.2,' PERCENT'/-
0011100      * ' POWER PER METER      '0PF7.2,' WATTS'/-
0011200      * ' TEMPERATURE RISE     '0PF7.2,' DEG C'/-
0011300      * ' RADIANT TEMPERATURE '0PF7.1,' DEG C'/-
0011400      * ' SINK TEMPERATURE     '0PF7.1,' DEG C'/-
0011500      * ' DIELECTRIC STRENGTH '0PF7.1,' VOLTS'/-
0011600      * ' SHIELD DIEL STRENGTH'0PF7.1,' VOLTS'/)
0011700       WRITE (6,200) CMASS,TMASS,RDC,RAC,RMAX,CONDCT,PWRRES,PWRRAT,PWRPM,DTEMP,TRADC,TSINKC,VMAX,VSMAX
0011800   300 FORMAT(-
0011900      * ' SHUNT CONDUCTANCE    '0PF7.6, ' MHOS'/-
0012000      * ' INDUCTANCE           '6PF7.3,' MICROHENRYS'/-
0012100      * ' CAPACITANCE          '6PF7.3,' MICROFARADS'/-
0012200      * ' DEPTH OF PENETRATION'3PF7.4,' MM'/-
0012300      * ' INNER INDUCTANCE     '6PF7.3,' MICROHENRYS'/-
0012400      * ' OUTER INDUCTANCE     '6PF7.3,' MICROHENRYS'/)
0012500       WRITE (6,300)G,AINDCT,CAP,SKIN,AINDI,AINDO
0012600   400 FORMAT(-
0012700      * ' CHAR. IMPEDANCE      '0PF7.3,' OHMS'/-
0012800      * ' CHAR. ADMITTANCE     '0PF7.3,' MHOS'/-
0012900      * ' COMPLEX INDUCTANCE  '6PF7.3,6PF7.3,' MICROHENRYS'/-
0013000      * ' COMPLEX CAPACITANCE '6PF7.3,6PF7.3,' MICROFARADS'/)
0013100       WRITE (6,400) Z0,Y0,CIND,CCAP
0013200 C     CONVERSION TO ENGLISH UNITS
0013300       DO 425 I=1,6
0013400   425 ERAD(I)=39.37*RAD(I)
0013500       PWRPF=PWRPM*12./39.37
0013600       ECMASS=CMASS/454
0013700       ETMASS=TMASS/454
0013800       ESKIN=39.37*SKIN
0013900       TRADF=TRADC*1.8+32.
0014000   500 FORMAT (-
0014100      * ' INNER CONDUCTOR RADII          OUTER CONDUCTOR RADII          SHIELD RADII'/-
0014200      * ' INSIDE '0PF9.4,  ' INCH          INSIDE '0PF9.4,  ' INCH          INSIDE '0PF9.4,  ' INCH'/-
0014300      * ' OUTSIDE'0PF9.4,  ' INCH          OUTSIDE'0PF9.4,  ' INCH          OUTSIDE'0PF9.4,  ' INCH'/-
0014400      * ' COPPER MASS          '0PF7.1,' POUNDS'/-
0014500      * ' TEFLON MASS          '0PF7.1,' POUNDS'/-
0014600      * ' POWER PER FOOT       '0PF7.3,' WATTS'/-
0014700      * ' RADIANT TEMPERATURE '0PF7.1,' DEG F'/-
0014800      * ' DEPTH OF PENETRATION'0PF7.4,' INCH')
0014900       WRITE (6,500) ERAD(1),ERAD(3),ERAD(5),ERAD(2),ERAD(4),ERAD(6),ECMASS,ETMASS,PWRPF,TRADF,ESKIN
0015000       IP=IR1-4
0015100       JP=IR1-4+26*IFREQ/10000
0015200       IF(IFREQ.GT.10000.) GO TO 550
0015300       X(IP)=1000.*RAD(1)
0015400       Y(IP,ID)=1./RDC
0015500       YI(IP,ID)=DCIND*1.E06
0015600       YR(IP,ID)=RDC
0015700       YP(IP,ID)=RDC*CURRNT**2
0015800       YM(IP,ID)=TMASS/1000.+CMASS/1000.
0015900       YT(IP,ID)=SQRT(SQRT(TSINK**4+RDC*CURRNT**2/(CABL*2*PI*RAD(6)*EMIS*SIG)))-273.
0016000       YM(IP+26,ID)=CMASS/1000.
0016100       YM(IP+52,ID)=TMASS/1000.
0016200   550 Y(JP,ID)=CONDCT
```

Calculation Subroutine for Coax (concluded)

```
      YI(JP,ID)=AINDCT*1.E06
      YC(IP,ID)=CAP*1.E06
      YR(JP,ID)=RMAX
      YP(JP,ID)=PURRES
      YT(JP,ID)=TRADC
      IF(IFREQ.NE.30000. .OR. IP.NE.26 .OR. ID.NE.2) RETURN
  600 CALL PLT26(X,Y(1,1),TCHAR1,1)
      CALL PLT26(X,YM(1,1),TMCHR1,2)
      CALL PLT26(X,YI(1,1),TICHR1,3)
      CALL PLT26(X,YC(1,1),TCCHR1,4)
      CALL PLT26(X,YR(1,1),TRCHR1,5)
      CALL PLT26(X,YP(1,1),TPCHR1,6)
      CALL PLT26(X,YT(1,1),TTCHR1,7)
      RETURN
      END
```

Calculation Subroutine for Stranded Coax

```
0000100          SUBROUTINE STINT(RAD,FREQ,IR1,IFREQ,ID)
0000200          DIMENSION RAD(6),ERAD(6)
0000300          DIMENSION X(26),Y(104,2),YM(78,2),YI(104,2),TICHR1(10),YC(26,2),TPCHR1(10),TPCHR2(10),YP(104,2)
0000400          DIMENSION TCHAR1(10),TCHAR2(10),TMCHR1(10),TMCHR2(10),TCCHR1(10),TCCHR2(10)
0000500          DIMENSION TRCHR1(10),TRCHR2(10),YR(104,2),TTCHR1(12),TTCHR2(12),YT(104,2)
0000600          DATA TCHAR1/'COND','UCTA','NCE ','OF S','TRAN','DED ','COAX','    ',2*0./
0000700          DATA TCHAR2/'COND','UCTA','NCE ','OF 0','.2 M','M ST','RAND','ED C','OAX ',0./
0000800          DATA TMCHR1/'MASS',' OF ','STRA','NDED',' COA','X   ',4*0./
0000900          DATA TMCHR2/'MASS',' OF ','0.2 ','MM S','TRAN','DED ','COAX',3*0./
0001000          DATA TICHR1/'INDU','CTAN','CE 0','F ST','RAND','ED C','OAX ',3*0./
0001100          DATA TCCHR1/'CAPA','CITA','NCE ','OF S','TRAN','DED ','COAX','    ',2*0./
0001200          DATA TRCHR1/'RESI','STIV','ITY ','OF S','TRAN','DED ','COAX','    ',2*0./
0001300          DATA TRCHR2/'RESI','STIV','ITY ','OF 0','.2 M','M ST','RAND','ED C','OAX ',0./
0001400          DATA TPCHR1/'POWE','R LO','SS 0','F ST','RAND','ED C','OAX ',3*0./
0001500          DATA TPCHR2/'POWE','R LO','SS 0','F 0.','2 MM',' STR','ANDE','D CO','AX  ',0./
0001600          DATA TTCHR1/'RADI','ATIN','G TE','MPER','ATUR','E OF',' STR','ANDE','D CO','AX  ',2*0./
0001700          DATA TTCHR2/'RADI','ATIN','G TE','MPER','ATUR','E OF',' 0.2',' MM ','STRA','NDED',' COA','X   '/
0001800          DOUBLE PRECISION RAD,R2R1,R4R3
0001900       10 CABL=50.
0002000          PI=3.1416
0002100 C        RESISTIVITY OHM METER;DENSITY GRAM/CUBIC METER
0002200          DATA CRES,CDENS/1.77E-08,8.96E06/
0002300 C        TEFLON DENSITY GRAM/CUBIC METER; RELATIVE DIELECTRIC CONSTANT; DIELECTRIC STRENGTH VOLTS/METER
0002400          DATA TDENS,TDIEL,TSTRNG/2.2E06,2.2,16.9E06/
0002500 C        THERMAL CONDUCTIVITY WATTS/METER/DEG C
0002600          DATA TTCND/.25/
0002700          VOLTS=1000.
0002800          CURRNT=100.
0002900          POWER=VOLTS*CURRNT
0003000          RAD21=RAD(2)-RAD(1)
0003100          NI=2.*PI*RAD(1)/RAD21
0003200          NO=2.*PI*RAD(3)/RAD21
0003300          NS=2.*PI*RAD(5)/RAD21
0003400          AREAI=NI*PI*(RAD21/2.)**2
0003500          AREAO=NO*PI*(RAD21/2.)**2
0003600          AREAS=NS*PI*((RAD(6)-RAD(5))/2.)**2
0003700          CMASS=(AREAI+AREAO+AREAS)*CABL*CDENS
0003800          AREAD=PI*(RAD(5)**2-RAD(1)**2)-(AREAI+AREAO)
0003900          TMASS=AREAD*CABL*TDENS
0004000          RDC=CABL*CRES*(1./AREAI+1./AREAO)
0004100          FS=AREAO/(PI*(RAD(4)**2-RAD(3)**2))
0004200          SKIN=503.*SQRT(CRES/(FS*FREQ))
0004300          RAC=RDC*(RAD21/SKIN)
0004400          RMAX=RAC/(1.-EXP(-RAD21/SKIN))
0004500          CONDCT=1./RMAX
0004600          PWRRES=RMAX*CURRNT**2
0004700          PWRRAT=PWRRES/POWER
0004800          PWRPM=PWRRES/CABL
0004900          RLOG=ALOG(RAD(3)/RAD(2))
0005000          RSLOG=ALOG(RAD(5)/RAD(4))
0005100          PWRPMI=PWRPM*RAD(3)/(RAD(2)+RAD(3))
0005200          DTEMP=(PWRPMI*RLOG+PWRPM*RSLOG)/(2.*PI*TTCND)
0005300          EMIS=0.5
0005400          SIG=5.67E-08
```

Calculation Subroutine for Stranded Coax (continued)

```
0005500        TSINK=273.
0005600        TRADK=DTEMP+SQRT(SQRT(TSINK**4+PWRPM/(2.*PI*RAD(6)*EMIS*SIG)))
0005700        TRADC=TRADK-273.
0005800        TSINKC=TSINK-273.
0005900        VMAX=TSTRNG*RAD(2)*RLOG
0006000        VSMAX=TSTRNG*RAD(4)*RSLOG
0006100        TCOND=0.
0006200        G=2.*PI*TCOND/RLOG
0006300 C      INDUCTANCE OF POWER LINE (HENRYS) AND CAPACITANCE (MFD)
0006400        ER2R1=EXP((RAD(1)-RAD(2))/SKIN)
0006500        SFX2=0.
0006600        DRAD=(RAD(2)-RAD(1))/50.
0006700        DO 50 INT=1,99,2
0006800        RX=RAD(1)+FLOAT(INT)*.5*DRAD
0006900        ER2X=EXP((RX-RAD(2))/SKIN)
0007000        FX=(ER2X-ER2R1)/(1.-ER2R1)
0007100     50 SFX2=SFX2+FX**2/RX
0007200        AINDI=2.E-07*CABL*SFX2*DRAD
0007300        ER4R3=EXP((RAD(3)-RAD(4))/SKIN)
0007400        SFX2=0.
0007500        DRAD=(RAD(4)-RAD(3))/50.
0007600        DO 75 INT=1,99,2
0007700        RX=RAD(3)+FLOAT(INT)*.5*DRAD
0007800        EXR3=EXP((RAD(3)-RX)/SKIN)
0007900        FX=(EXR3-ER4R3)/(1.-ER4R3)
0008000     75 SFX2=SFX2+FX**2/RX
0008100        AINDO=2.E-07*CABL*SFX2*DRAD
0008200        AINDCT=AINDI+2.E-07*RLOG*CABL+AINDO
0008300        R2R1=RAD(2)**2-RAD(1)**2
0008400        DINDI=CABL*(2.E-07/R2R1)*(RAD(1)**4*DLOG(RAD(2)/RAD(1))/R2R1+.25*RAD(2)**2-.75*RAD(1)**2)
0008500        R4R3=RAD(4)**2-RAD(3)**2
0008600        DINDO=CABL*(2.E-07/R4R3)*((RAD(4)**4/R4R3)*DLOG(RAD(4)/RAD(3))+.25*RAD(3)**2-.75*RAD(4)**2)
0008700        DCIND=DINDI+2.E-07*RLOG*CABL+DINDO
0008800        CAP=55.56E-12*TDIEL*CABL/RLOG
0008900 C      CHARACTERISTIC IMPEDANCE,Z0; CHARACTERISTIC ADMITTANCE,Y0
0009000         Z0=SQRT(AINDCT/CAP)
0009100        Y0=SQRT(CAP/AINDCT)
0009200 C      COMPLEX INDUCTANCE,CIND; COMPLEX CAPACITANCE,CCAP
0009300        COMPLEX CIND,CCAP,J
0009400        DATA J/(0.,1.)/
0009500        CIND=AINDCT+RMAX/(J*2.*PI*FREQ)
0009600        CCAP=CAP+G/(J*2.*PI*FREQ)
0009700    100 FORMAT (1H1,-
0009800       * ' INNER CONDUCTOR RADII          OUTER CONDUCTOR RADII          SHIELD RADII'/-
0009900       * ' INSIDE '3PF9.2,' MM             INSIDE '3PF9.2,' MM             INSIDE '3PF9.2,' MM'/-
0010000       * ' OUTSIDE'3PF9.2,' MM             OUTSIDE'3PF9.2,' MM             OUTSIDE'3PF9.2,' MM'/-
0010100       * ' VOLTAGE                 '0PF7.0,' VOLTS'/-
0010200       * ' CURRENT                 '0PF7.1,' AMPERES'/-
0010300       * ' FREQUENCY               '0PF7.0,' HERTZ'/-
0010400       * ' POWER                   '-3PF7.0,' KILOWATTS'/-
0010500       * ' CABLE LENGTH            '0PF7.1,' METERS'/)
0010600        WRITE (6,100) RAD(1),RAD(3),RAD(5),RAD(2),RAD(4),RAD(6),VOLTS,CURRNT,FREQ,POWER,CABL
0010700    200 FORMAT (-
0010800       * ' COPPER MASS            '-3PF7.1,' KILOGRAMS'/-
```

Calculation Subroutine for Stranded Coax (continued)

```
     * ' TEFLON MASS          '-3PF7.1,' KILOGRAMS'/-
     * ' DC FORMULA RESISTANCE'0PF6.4,' OHMS'/-
     * ' AC FORMULA RESISTANCE'0PF6.4,' OHMS'/-
     * ' RESISTANCE           '0PF7.4,' OHMS'/-
     * ' CONDUCTANCE          '0PF7.3,' MHOS'/-
     * ' RESISTIVE POWER      '0PF7.1,' WATTS'/-
     * ' PERCENT POWER LOST   '2PF7.2,' PERCENT'/-
     * ' POWER PER METER      '0PF7.2,' WATTS'/-
     * ' TEMPERATURE RISE     '0PF7.2,' DEG C'/-
     * ' RADIANT TEMPERATURE '0PF7.1,' DEG C'/-
     * ' SINK TEMPERATURE     '0PF7.1,' DEG C'/-
     * ' DIELECTRIC STRENGTH '0PF7.1,' VOLTS'/-
     * ' SHIELD DIEL STRENGTH'0PF7.1,' VOLTS'/)
      WRITE (6,200) CMASS,TMASS,RDC,RAC,RMAX,CONDCT,PWRRES,PWRRAT,PWRPM,DTEMP,TRADC,TSINKC,VMAX,VSMAX
  300 FORMAT(-
     * ' SHUNT CONDUCTANCE    '0PF7.6, ' MHOS'/-
     * ' INDUCTANCE           '6PF7.3,' MICROHENRYS'/-
     * ' CAPACITANCE          '6PF7.3,' MICROFARADS'/-
     * ' DEPTH OF PENETRATION'3PF7.4,' MM'/-
     * ' INNER INDUCTANCE     '6PF7.3,' MICROHENRYS'/-
     * ' OUTER INDUCTANCE     '6PF7.3,' MICROHENRYS'/)
      WRITE (6,300)G,AINDCT,CAP,SKIN,AINDI,AINDO
  400 FORMAT(-
     * ' CHAR. IMPEDANCE      '0PF7.3,' OHMS'/-
     * ' CHAR. ADMITTANCE     '0PF7.3,' MHOS'/-
     * ' COMPLEX INDUCTANCE  '6PF7.3,6PF7.3,' MICROHENRYS'/-
     * ' COMPLEX CAPACITANCE '6PF7.3,6PF7.3,' MICROFARADS'/)
      WRITE (6,400) Z0,Y0,CIND,CCAP
C     CONVERSION TO ENGLISH UNITS
      DO 425 I=1,6
  425 ERAD(I)=39.37*RAD(I)
      PWRPF=PWRPM*12./39.37
      ECMASS=CMASS/454
      ETMASS=TMASS/454
      ESKIN=39.37*SKIN
      TRADF=TRADC*1.8+32.
  500 FORMAT (-
     * ' INNER CONDUCTOR RADII          OUTER CONDUCTOR RADII          SHIELD RADII'/-
     * ' INSIDE '0PF9.4,  ' INCH          INSIDE '0PF9.4,  ' INCH          INSIDE '0PF9.4,  ' INCH'/-
     * ' OUTSIDE'0PF9.4,  ' INCH          OUTSIDE'0PF9.4,  ' INCH          OUTSIDE'0PF9.4,  ' INCH'/-
     * ' COPPER MASS          '0PF7.1,' POUNDS'/-
     * ' TEFLON MASS          '0PF7.1,' POUNDS'/-
     * ' POWER PER FOOT       '0PF7.3,' WATTS'/-
     * ' RADIANT TEMPERATURE '0PF7.1,' DEG F'/-
     * ' DEPTH OF PENETRATION'0PF7.4,' INCH')
      WRITE (6,500) ERAD(1),ERAD(3),ERAD(5),ERAD(2),ERAD(4),ERAD(6),ECMASS,ETMASS,PWRPF,TRADF,ESKIN
      IP=IR1-4
      JP=IR1-4+26*IFREQ/10000
      IF(IFREQ.GT.10000.) GO TO 550
      X(IP)=1000.*RAD(1)
      Y(IP,ID)=1./RDC
      YI(IP,ID)=DCIND*1.E06
      YR(IP,ID)=RDC
      YP(IP,ID)=RDC*CURRNT**2
```

Calculation Subroutine for Stranded Coax (concluded)

```
      YM(IP,ID)=TMASS/1000.+CMASS/1000.
      YT(IP,ID)=SQRT(SQRT(TSINK**4+RDC*CURRNT**2/(CABL*2*PI*RAD(6)*EMIS*SIG)))-273.
      YM(IP+26,ID)=CMASS/1000.
      YM(IP+52,ID)=TMASS/1000.
  550 Y(JP,ID)=CONDCT
      YI(JP,ID)=AINDCT*1.E06
      YC(IP,ID)=CAP*1.E06
      YR(JP,ID)=RMAX
      YP(JP,ID)=PWRRES
      YT(JP,ID)=TRADC
      IF(IFREQ.NE.30100. .OR. IP.NE.26 .OR. ID.NE.2) RETURN
  600 CALL PLT26(X,Y(1,1),TCHAR1,1)
      CALL PLT26(X,YM(1,1),TMCHR1,2)
      CALL PLT26(X,YI(1,1),TICHR1,3)
      CALL PLT26(X,YC(1,1),TCCHR1,4)
      CALL PLT26(X,YR(1,1),TRCHR1,5)
      CALL PLT26(X,YP(1,1),TPCHR1,6)
      CALL PLT26(X,YT(1,1),TTCHR1,7)
      RETURN
      END
```

Calculation Subroutine for Parallel Lines

```
0000100        SUBROUTINE PRLINT(RAD,FREQ,IR1,IFREQ,ID,LSPACE)
0000200        DIMENSION RAD(6),ERAD(6)
0000300        DIMENSION X(26),Y(104,2),YM(78,2),YI(26,4,2),TICHR1(10),YC(26,4,2),TPCHR1(10),TPCHR2(10),YP(104,2)
0000400        DIMENSION TCHAR1(10),TCHAR2(10),TMCHR1(10),TMCHR2(10),TCCHR1(10),TCCHR2(10)
0000500        DIMENSION TRCHR1(10),TRCHR2(10),YR(104,2),TTCHR1(12),TTCHR2(12),YT(104,2)
0000600        DATA TCHAR1/'COND','UCTA','NCE ','OF P','ARAL','LEL ','LINE','S   ',2*0./
0000700        DATA TCHAR2/'COND','UCTA','NCE ','OF 0','.2 M','M PA','RALL','EL L','INES',0./
0000800        DATA TMCHR1/'MASS',' OF ','PARA','LLEL',' LIN','ES  ',4*0./
0000900        DATA TMCHR2/'MASS',' OF ','0.2 ','MM P','ARAL','LEL ','LINE','S   ',2*0./
0001000        DATA TICHR1/'INDU','CTAN','CE O','F PA','RALL','EL L','INES',3*0./
0001100        DATA TCCHR1/'CAPA','CITA','NCE ','OF P','ARAL','LEL ','LINE','S   ',2*0./
0001200        DATA TRCHR1/'RESI','STIV','ITY ','OF P','ARAL','LEL ','LINE','S   ',2*0./
0001300        DATA TRCHR2/'RESI','STIV','ITY ','OF 0','.2 M','M PA','RALL','EL L','INES',0./
0001400        DATA TPCHR1/'POWE','R LO','SS O','F PA','RALL','EL L','INES',3*0./
0001500        DATA TPCHR2/'POWE','R LO','SS O','F 0.','2 MM',' PAR','ALLE','L LI','NES ',0./
0001600        DATA TTCHR1/'RADI','ATIN','G TE','MPER','ATUR','E OF',' PAR','ALLE','L LI','NES ',2*0./
0001700        DATA TTCHR2/'RADI','ATIN','G TE','MPER','ATUR','E OF',' 0.2',' MM ','PARA','LLEL',' LIN','ES  '/
0001800        DOUBLE PRECISION RAD,R2R1
0001900 C      RAD(1) INNER RADIUS OF CONDUCTORS; RAD(2) OUTER RADIUS OF CONDUCTORS
0002000 C      RAD(3) OUTER RADIUS OF DIELECTRICS; RAD(6)  CENTER TO CENTER SPACING
0002100     10 CABL=50.
0002200        PI=3.1416
0002300 C      RESISTIVITY OHM METER;DENSITY GRAM/CUBIC METER
0002400        DATA CRES,CDENS/1.77E-08,8.96E06/
0002500 C      TEFLON DENSITY GRAM/CUBIC METER; RELATIVE DIELECTRIC CONSTANT; DIELECTRIC STRENGTH VOLTS/METER
0002600        DATA TDENS,TDIEL,TSTRNG/2.2E06,2.2,16.9E06/
0002700        DATA EMIS,SIG,TSINK/0.5,5.67E-08,273./
0002800 C      THERMAL CONDUCTIVITY WATTS/METER/DEG C
0002900        DATA TTCND/.25/
0003000        VOLTS=1000.
0003100        CURRNT=100.
0003200        POWER=VOLTS*CURRNT
0003300        AREAI=PI*(RAD(2)**2-RAD(1)**2)
0003400        AREAS=PI*(RAD(4)**2-RAD(3)**2)
0003500        CMASS=2.*(AREAI+AREAS)*CABL*CDENS
0003600        AREAD=PI*(RAD(3)**2-RAD(2)**2)
0003700        TMASS=2.*AREAD*CABL*TDENS
0003800        RDC=2.*CABL*CRES/AREAI
0003900        SKIN=503.*SQRT(CRES/FREQ)
0004000        RAC=RDC*((RAD(2)-RAD(1))/SKIN)
0004100        RMAX=RAC/(1.-EXP(-(RAD(2)-RAD(1))/SKIN))
0004200        CONDCT=1./RMAX
0004300        PWRRES=RMAX*CURRNT**2
0004400        PWRRAT=PWRRES/POWER
0004500        PWRPM=PWRRES/CABL
0004600        RLOG=ALOG(RAD(3)/RAD(2))
0004700        DTEMP=PWRPM*RLOG/(4.*PI*TTCND)
0004800        TRADK=DTEMP+SQRT(SQRT(TSINK**4+PWRPM/(4.*PI*RAD(4)*EMIS*SIG)))
0004900        TRADC=TRADK-273.
0005000        TSINKC=TSINK-273.
0005100        VMAX=TSTRNG*RAD(2)*RLOG
0005200        TCOND=0.
0005300        G=PI*TCOND/RLOG
0005400 C      INDUCTANCE OF POWER LINE (HENRYS) AND CAPACITANCE (MFD)
```

Calculation Subroutine for Parallel Lines (continued)

```
0005500        ER2R1=EXP((RAD(1)-RAD(2))/SKIN)
0005600        SFX2=0.
0005700        DRAD=(RAD(2)-RAD(1))/50.
0005800        DO 50 INT=1,99,2
0005900        RX=RAD(1)+FLOAT(INT)*.5*DRAD
0006000        ER2X=EXP((RX-RAD(2))/SKIN)
0006100        FX=(ER2X-ER2R1)/(1.-ER2R1)
0006200     50 SFX2=SFX2+FX**2/RX
0006300        AINDI=2.E-07*CABL*SFX2*DRAD
0006400        DCOSH=ALOG(RAD(6)/(2.*RAD(2))+SQRT((RAD(6)/(2.*RAD(2)))**2-1.))
0006500        AINDCT=2.*AINDI+4.E-07*DCOSH*CABL
0006600        CAP=27.78E-12*CABL/DCOSH
0006700 C      CHARACTERISTIC IMPEDANCE,Z0; CHARACTERISTIC ADMITTANCE,Y0
0006800        Z0=SQRT(AINDCT/CAP)
0006900        Y0=SQRT(CAP/AINDCT)
0007000 C      COMPLEX INDUCTANCE,CIND; COMPLEX CAPACITANCE,CCAP
0007100        COMPLEX CIND,CCAP,J
0007200        DATA J/(0.,1.)/
0007300        CIND=AINDCT+RMAX/(J*2.*PI*FREQ)
0007400        CCAP=CAP+G/(J*2.*PI*FREQ)
0007500 C      FORCE BETWEEN CONDUCTORS
0007600        FMAG=2.E-07*CURRNT**2/RAD(6)
0007700        FEMAG=FMAG*(2.2/9.8)*(12./39.37)
0007800    100 FORMAT (1H1,-
0007900       * ' INNER CONDUCTOR RADII          SHIELD RADII'/-
0008000       * ' INSIDE '3PF9.2,' MM             INSIDE '3PF9.2,' MM'/-
0008100       * ' OUTSIDE'3PF9.2,' MM             OUTSIDE'3PF9.2,' MM'/-
0008200       * ' CENTER - CENTER DIST'3PF7.2,' MM'/-
0008300       * ' VOLTAGE              '0PF7.0,' VOLTS'/-
0008400       * ' CURRENT              '0PF7.1,' AMPERES'/-
0008500       * ' FREQUENCY            '0PF7.0,' HERTZ'/-
0008600       * ' POWER                '-3PF7.0,' KILOWATTS'/-
0008700       * ' CABLE LENGTH         '0PF7.1,' METERS'/)
0008800        WRITE (6,100) RAD(1),RAD(3),RAD(2),RAD(4),RAD(6),VOLTS,CURRNT,FREQ,POWER,CABL
0008900    200 FORMAT (-
0009000       * ' COPPER MASS          '-3PF7.1,' KILOGRAMS'/-
0009100       * ' TEFLON MASS          '-3PF7.1,' KILOGRAMS'/-
0009200       * ' DC FORMULA RESISTANCE '0PF5.4,' OHMS'/-
0009300       * ' AC FORMULA RESISTANCE '0PF5.4,' OHMS'/-
0009400       * ' RESISTANCE           '0PF7.4,' OHMS'/-
0009500       * ' CONDUCTANCE          '0PF7.3,' MHOS'/-
0009600       * ' RESISTIVE POWER      '0PF7.1,' WATTS'/-
0009700       * ' PERCENT POWER LOST   '2PF7.2,' PERCENT'/-
0009800       * ' POWER PER METER      '0PF7.2,' WATTS'/-
0009900       * ' TEMPERATURE RISE     '0PF7.2,' DEG C'/-
0010000       * ' RADIANT TEMPERATURE '0PF7.1,' DEG C'/-
0010100       * ' SINK TEMPERATURE     '0PF7.1,' DEG C'/-
0010200       * ' DIELECTRIC STRENGTH '0PF7.1,' VOLTS'/)
0010300        WRITE (6,200) CMASS,TMASS,RDC,RAC,RMAX,CONDCT,PWRRES,PWRRAT,PWRPM,DTEMP,TRADC,TSINKC,VMAX
0010400    300 FORMAT(-
0010500       * ' SHUNT CONDUCTANCE   '0PF7.6, ' MHOS'/-
0010600       * ' INDUCTANCE          '6PF7.3,' MICROHENRYS'/-
0010700       * ' CAPACITANCE         '6PF7.3,' MICROFARADS'/-
0010800       * ' DEPTH OF PENETRATION'3PF7.4,' MM'/-
```

Calculation Subroutine for Parallel Lines (concluded)

```
     * ' INNER INDUCTANCE    '6PF7.3,' MICROHENRYS'/)
      WRITE (6,300)G,AINDCT,CAP,SKIN,AINDI
  400 FORMAT(-
     * ' CHAR. IMPEDANCE     '0PF7.3,' OHMS'/-
     * ' CHAR. ADMITTANCE    '0PF7.3,' MHOS'/-
     * ' COMPLEX INDUCTANCE  '6PF7.3,6PF7.3,' MICROHENRYS'/-
     * ' COMPLEX CAPACITANCE '6PF7.3,6PF7.3,' MICROFARADS'/-
     * ' MAGNETIC FORCE      '0PF7.5,' N/M'/-
     * ' MAGNETIC FORCE      '0PF7.5,' LBS/FT'/)
      WRITE (6,400) Z0,Y0,CIND,CCAP,FMAG,FEMAG
C     CONVERSION TO ENGLISH UNITS
      DO 425 I=1,6
  425 ERAD(I)=39.37*RAD(I)
      PWRPF=PWRPM*12./39.37
      ECMASS=CMASS/454
      ETMASS=TMASS/454
      ESKIN=39.37*SKIN
      TRADF=TRADC*1.8+32.
  500 FORMAT (-
     * ' INNER CONDUCTOR RADII          SHIELD RADII'/-
     * ' INSIDE '0PF9.4,  ' INCH          INSIDE '0PF9.4,  ' INCH'/-
     * ' OUTSIDE'0PF9.4,  ' INCH          OUTSIDE'0PF9.4,  ' INCH'/-
     * ' CENTER - CENTER DIST'0PF7.4,' INCH'/-
     * ' COPPER MASS          '0PF7.1,' POUNDS'/-
     * ' TEFLON MASS          '0PF7.1,' POUNDS'/-
     * ' POWER PER FOOT       '0PF7.3,' WATTS'/-
     * ' RADIANT TEMPERATURE '0PF7.1,' DEG F'/-
     * ' DEPTH OF PENETRATION'0PF7.4,' INCH')
      WRITE (6,500) ERAD(1),ERAD(3),ERAD(2),ERAD(4),ERAD(6),ECMASS,ETMASS,PWRPF,TRADF,ESKIN
      IP=IR1-4
      JP=IR1-4+26*IFREQ/10000
      IF(IFREQ.GT.10000.) GO TO 550
      X(IP)=1000.*RAD(1)
      Y(IP,ID)=1./RDC
      YR(IP,ID)=RDC
      YP(IP,ID)=RDC*CURRNT**2
      YM(IP,ID)=TMASS/1000.+CMASS/1000.
      YT(IP,ID)=SQRT(SQRT(TSINK**4+RDC*CURRNT**2/(CABL*4.*PI*RAD(4)*EMIS*SIG)))-273.
      YM(IP+26,ID)=CMASS/1000.
      YM(IP+52,ID)=TMASS/1000.
  550 Y(JP,ID)=CONDCT
      YI(IP,LSPACE,ID)=AINDCT*1.E06
      YC(IP,LSPACE,ID)=CAP*1.E06
      YR(JP,ID)=RMAX
      YP(JP,ID)=PWRRES
      YT(JP,ID)=TRADC
      IF(IFREQ.NE.30000. .OR. IP.NE.26 .OR. ID.NE.2) RETURN
      IF(LSPACE.NE.4) RETURN
  600 CALL PLT26(X,Y(1,1),TCHAR1,1)
      CALL PLT26(X,YM(1,1),TMCHR1,2)
      CALL PLT26(X,YI(1,1,1),TICHR1,8)
      CALL PLT26(X,YC(1,1,1),TCCHR1,9)
      CALL PLT26(X,YR(1,1),TRCHR1,5)
      CALL PLT26(X,YP(1,1),TPCHR1,6)
      CALL PLT26(X,YT(1,1),TTCHR1,7)
      RETURN
      END
```

Plotting Subroutine for all Configurations

```
      SUBROUTINE PLT26(X,Y,TCHAR1,K)
      DIMENSION X(1),Y(1),IVARS1(7),TCHAR1(10),TCHAR2(10),XCHAR1(10)
      DIMENSION VARSX(5),VARSY(5),SIDE(40),SIDEP(5,8),VARSC(5),VARSR(5),VARSP(5),VARSI(5),VARST(5)
      DIMENSION SIDEM(30),SIDEI(14)
      DIMENSION YCHARR(8),YCHARI(10),YCHARM(10),YCHARI(9),YCHARC(9),YCHARP(8),YCHART(10)
      DIMENSION COP5(6),COP2(6),TEF5(6)
      DATA VARSX/5.,-1.,0.,5.,30./
      DATA VARSY/5.,-1.,90.,0.,100./
      DATA IVARS1/7,26,2,115,5,15,0/
      DATA SIDE/Z40404073,'  0 ','KHZ ','0.5 ','MM  ',Z40404074,' 10 ','KHZ ','0.5 ','MM  ',-
     *          Z40404075,' 20 ','KHZ ','0.5 ','MM  ',Z40404076,' 30 ','KHZ ','0.5 ','MM  ',-
     *          Z40404077,'  0 ','KHZ ','0.2 ','MM  ',Z40404078,' 10 ','KHZ ','0.2 ','MM  ',-
     *          Z40404079,' 20 ','KHZ ','0.2 ','MM  ',Z4040407A,' 30 ','KHZ ','0.2 ','MM  '/
      DATA SIDEM/Z40404073,'   T','OTAL',' MAS','S   ',Z40404074,'  CO','PPER',' MAS','S   ',-
     *           Z40404075,'  TE','FLON',' MAS','S   ',Z40404076,'   T','OTAL',' MAS','S   ',-
     *           Z40404077,'  CO','PPER',' MAS','S   ',Z40404078,'  TE','FLON',' MAS','S   '/
      DATA SIDEI/Z40404073,' 0.5',' MM ','COPP','ER C','ONDU','CTOR',-
     *           Z40404074,' 0.2',' MM ','COPP','ER C','ONDU','CTOR'/
      DATA SIDEP/Z40404073,'  1 ','MM  ','0.5 ','MM  ',Z40404074,'  4 ','MM  ','0.5 ','MM  ',-
     *          Z40404075,'  7 ','MM  ','0.5 ','MM  ',Z40404076,' 10 ','MM  ','0.5 ','MM  ',-
     *          Z40404077,'  1 ','MM  ','0.2 ','MM  ',Z40404078,'  4 ','MM  ','0.2 ','MM  ',-
     *          Z40404079,'  7 ','MM  ','0.2 ','MM  ',Z4040407A,' 10 ','MM  ','0.2 ','MM  '/
      DATA COP5/'0.5 ','MM C','OPPE','R CO','NDUC','TOR '/
      DATA TEF5/'0.5 ','MM T','EFLO','N DI','ELEC','TRIC'/
      DATA COP2/'0.2 ','MM C','OPPE','R CO','NDUC','TOR '/
      CALL COLOR(1,0,1,0,0,0,0)
      IF(K.EQ.2) GO TO 200
      IF(K.EQ.3) GO TO 300
      IF(K.EQ.4) GO TO 400
      IF(K.EQ.5) GO TO 500
      IF(K.EQ.6) GO TO 600
      IF(K.EQ.7) GO TO 700
      IF(K.EQ.8) GO TO 800
      IF(K.EQ.9) GO TO 900
C
C     PLOT CONDUCTANCE
C
      CALL TITLE (0,32,20,TCHAR1)
      DATA XCHAR1/'INSI','DE R','ADIU','S, M','M   ',5*0./
      CALL TITLE (4,17,15,XCHAR1)
      DATA YCHAR1/'COND','UCTA','NCE ','OF 5','OM C','ABLE',' MHO','S   ',2*0./
      CALL TITLE (3,29,15,YCHAR1)
      CALL XAXIS(-1.,-1.,VARSX)
      CALL YAXIS(-1.,-1.,VARSY)
      CALL CHARS(24,COP5,0.,6.,8.30,15)
      CALL CHARS(24,TEF5,0.,6.,8.05,15)
      CALL CHARS(24,COP2,0.,6.,6.3,15)
      CALL CHARS(24,TEF5,0.,6.,6.05,15)
      DO 100 I=1,8
      IY=26*I-25
      IVARS1(4)=114+I
      YSIDE=8.-.25*FLOAT(I)
      IF(I.GT.4) YSIDE=YSIDE-1.
      ISIDE=5*I-4
```

Plotting Subroutine for all Configurations (continued)

```
0005500          NC1=I
0005600          IF(I.GT.3) NC1=I-4
0005700          CALL COLOR(1,NC1,1,0,0,0,0)
0005800          CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
0005900      100 CALL GPLOT (X,Y(IY),IVARS1)
0006000          CALL DISPLA(1)
0006100          RETURN
0006200 C
0006300 C        PLOT MASS OF CABLE
0006400 C
0006500      200 CALL TITLE(0,24,20,TCHAR1)
0006600          CALL TITLE(4,17,15,XCHAR1)
0006700          DATA YCHARM/'MASS',' OF ','50M ','CABL','E KG',5*0./
0006800          CALL TITLE(3,20,15,YCHARM)
0006900          CALL XAXIS(-1.,-1.,VARSX)
0007000          CALL YAXIS(-1.,-1.,VARSY)
0007100          CALL CHARS(24,COP5,0.,6.,8.30,15)
0007200          CALL CHARS(24,TEF5,0.,6.,8.05,15)
0007300          CALL CHARS(24,COP2,0.,6.,6.55,15)
0007400          CALL CHARS(24,TEF5,0.,6.,6.3,15)
0007500          DO 250 I=1,6
0007600          IY=26*I-25
0007700          IVARS1(4)=114+I
0007800          YSIDE=8.-.25*FLOAT(I)
0007900          IF(I.GT.3) YSIDE=YSIDE-1.
0008000          ISIDE=5*I-4
0008100          NC1=I
0008200          IF(I.GT.3) NC1=I-4
0008300          CALL COLOR(1,NC1,1,0,0,0,0)
0008400          CALL CHARS(19,SIDEM(ISIDE),0.,7.,YSIDE,15)
0008500      250 CALL GPLOT(X,Y(IY),IVARS1)
0008600          CALL DISPLA(1)
0008700          RETURN
0008800 C
0008900 C        PLOT INDUCTANCE OF COAXIAL CABLE
0009000 C
0009100      300 CALL TITLE (0,28,20,TCHAR1)
0009200          CALL TITLE (4,17,15,XCHAR1)
0009300          DATA YCHARI/'INDU','CTAN','CE O','F 50','M CA','BLE ','MICR','OHEN','RYS '/
0009400          CALL TITLE (3,35,15,YCHARI)
0009500          CALL XAXIS(-1.,-1.,VARSX)
0009600          DATA VARSI/5.,-1.,90.,0.,2./
0009700          CALL YAXIS(-1.,-1.,VARSI)
0009800          CALL CHARS(24,COP5,0.,6.,8.30,15)
0009900          CALL CHARS(24,TEF5,0.,6.,8.05,15)
0010000          CALL CHARS(24,COP2,0.,6.,6.3,15)
0010100          CALL CHARS(24,TEF5,0.,6.,6.05,15)
0010200          DO 350 I=1,8
0010300          IY=26*I-25
0010400          IVARS1(4)=114+I
0010500          YSIDE=8.-.25*FLOAT(I)
0010600          IF(I.GT.4) YSIDE=YSIDE-1.
0010700          ISIDE=5*I-4
0010800          NC1=I
```

Plotting Subroutine for all Configurations (continued)

```
0010900          IF(I.GT.3) NC1=I-4
0011000          CALL COLOR(1,NC1,1,0,0,0,0)
0011100          CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
0011200      350 CALL GPLOT (X,Y(IY),IVARS1)
0011300          CALL DISPLA(1)
0011400          RETURN
0011500 C
0011600 C         PLOT CAPACITANCE OF COAXIAL CABLE
0011700 C
0011800      400 CALL TITLE(0,29,20,TCHAR1)
0011900          CALL TITLE (4,17,15,XCHAR1)
0012000          DATA YCHARC/'CAPA','CITA','NCE ','OF 5','OM C','ABLE',' MIC','ROFA','RADS'/
0012100          CALL TITLE (3,36,15,YCHARC)
0012200          CALL XAXIS(-1.,-1.,VARSX)
0012300          DATA VARSC/5.,-1.,90.,0.,.5/
0012400 C        FOLLOWING CHANGE FOR PARALLEL ONLY
0012500 C        VARSC(5)=.015
0012600          CALL YAXIS(-1.,-1.,VARSC)
0012700          CALL CHARS(24,TEF5,0.,6.,8.05,15)
0012800          DO 450 I=1,2
0012900          IY=26*I-25
0013000          IVARS1(4)=114+I
0013100          YSIDE=8.-.25*FLOAT(I)
0013200          ISIDE=7*I-6
0013300          NC1=I
0013400          IF(I.GT.3) NC1=I-4
0013500          CALL COLOR(1,NC1,1,0,0,0,0)
0013600          CALL CHARS(28,SIDEI(ISIDE),0.,5.5,YSIDE,15)
0013700      450 CALL GPLOT(X,Y(IY),IVARS1)
0013800          CALL DISPLA(1)
0013900          RETURN
0014000 C
0014100 C        PLOT RESISTIVITY
0014200 C
0014300      500 CALL TITLE(0,28,20,TCHAR1)
0014400          CALL TITLE(4,17,15,XCHAR1)
0014500          DATA YCHARR/'RESI','STIV','ITY ','OF 5','OM C','ABLE',' OHM','S   '/
0014600          CALL TITLE (3,29,15,YCHARR)
0014700          CALL XAXIS (-1.,-1.,VARSX)
0014800          DATA VARSR/5.,-1.,90.,0.,.5/
0014900          CALL YAXIS (-1.,-1.,VARSR)
0015000          CALL CHARS(24,COP5,0.,6.,8.30,15)
0015100          CALL CHARS(24,TEF5,0.,6.,8.05,15)
0015200          CALL CHARS(24,COP2,0.,6.,6.3,15)
0015300          CALL CHARS(24,TEF5,0.,6.,6.05,15)
0015400          DO 550 I=1,8
0015500          IY=26*I-25
0015600          IVARS1(4)=114+I
0015700          YSIDE=8.-.25*FLOAT(I)
0015800          IF(I.GT.4) YSIDE=YSIDE-1.
0015900          ISIDE=5*I-4
0016000          NC1=I
0016100          IF(I.GT.3) NC1=I-4
0016200          CALL COLOR(1,NC1,1,0,0,0,0)
```

Plotting Subroutine for all Configurations (continued)

```
0016300          CALL CHARS (12,SIDE(ISIDE),0.,7.,YSIDE,15)
0016400      550 CALL GPLOT (X,Y(IY),IVARS1)
0016500          CALL DISPLA(1)
0016600          RETURN
0016700 C
0016800 C        PLOT POWER LOSS
0016900 C
0017000      600 CALL TITLE(0,28,20,TCHAR1)
0017100          CALL TITLE (4,17,15,XCHAR1)
0017200          DATA YCHARP/'POWE','R LO','SS O','F 50','M CA','BLE ','WATT','S   '/
0017300          CALL TITLE (3,29,15,YCHARP)
0017400          CALL XAXIS (-1.,-1.,VARSX)
0017500          DATA VARSP/5.,-1.,90.,0.,5000./
0017600          CALL YAXIS(-1.,-1.,VARSP)
0017700          CALL CHARS(24,COP5,0.,6.,8.30,15)
0017800          CALL CHARS(24,TEF5,0.,6.,8.05,15)
0017900          CALL CHARS(24,COP2,0.,6.,6.3,15)
0018000          CALL CHARS(24,TEF5,0.,6.,6.05,15)
0018100          DO 650 I=1,8
0018200          IY=26*I-25
0018300          IVARS1(4)=114+I
0018400          YSIDE=8.-.25*FLOAT(I)
0018500          IF(I.GT.4) YSIDE=YSIDE-1.
0018600          ISIDE=5*I-4
0018700          NC1=I
0018800          IF(I.GT.3) NC1=I-4
0018900          CALL COLOR(1,NC1,1,0,0,0,0)
0019000          CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
0019100      650 CALL GPLOT(X,Y(IY),IVARS1)
0019200          CALL DISPLA(1)
0019300          RETURN
0019400 C
0019500 C        PLOT TEMPERATURE
0019600 C
0019700      700 CALL TITLE(0,40,20,TCHAR1)
0019800          CALL TITLE(4,17,15,XCHAR1)
0019900          DATA YCHART/'INNE','R CO','NDUC','TOR ','TEMP','ERAT','URE ','DEG ','C   ','    '/
0020000          CALL TITLE(3,33,15,YCHART)
0020100          CALL XAXIS(-1.,-1.,VARSX)
0020200          DATA VARST/5.,-1.,90.,0.,250./
0020300          CALL YAXIS(-1.,-1.,VARST)
0020400          CALL CHARS(24,COP5,0.,6.,8.30,15)
0020500          CALL CHARS(24,TEF5,0.,6.,8.05,15)
0020600          CALL CHARS(24,COP2,0.,6.,6.3,15)
0020700          CALL CHARS(24,TEF5,0.,6.,6.05,15)
0020800          DO 750 I=1,8
0020900          IY=26*I-25
0021000          IVARS1(4)=114+I
0021100          YSIDE=8.-.25*FLOAT(I)
0021200          IF(I.GT.4) YSIDE=YSIDE-1.
0021300          ISIDE=5*I-4
0021400          NC1=I
0021500          IF(I.GT.3) NC1=I-4
0021600          CALL COLOR(1,NC1,1,0,0,0,0)
```

Plotting Subroutine for all Configurations

(concluded)

```
      CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
  750 CALL GPLOT(X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT INDUCTANCE OF PARALLEL LINES
C
  800 CALL TITLE (0,28,20,TCHAR1)
      CALL TITLE (4,17,15,XCHAR1)
      CALL TITLE (3,35,15,YCHARI)
      CALL XAXIS(-1.,-1.,VARSX)
      VARSI(5)=30.
      CALL YAXIS(-1.,-1.,VARSI)
      CALL CHARS(24,COP5,0.,6.,8.30,15)
      CALL CHARS(24,TEF5,0.,6.,8.05,15)
      CALL CHARS(24,COP2,0.,6.,6.3,15)
      CALL CHARS(24,TEF5,0.,6.,6.05,15)
      DO 850 I=1,8
      IY=26*I-25
      IVARS1(4)=114+I
      YSIDE=8.-.25*FLOAT(I)
      IF(I.GT.4) YSIDE=YSIDE-1.
      ISIDE=3*I-2
      IF(I.EQ.5) CALL COLOR(1,1,1,0,0,0,0)
      CALL CHARS(12,SIDEP(1,I),0.,7.,YSIDE,15)
  850 CALL GPLOT (X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT CAPACITANCE OF PARALLEL LINES
C
  900 CALL TITLE(0,29,20,TCHAR1)
      CALL TITLE (4,17,15,XCHAR1)
      CALL TITLE (3,36,15,YCHARC)
      CALL XAXIS(-1.,-1.,VARSX)
      VARSC(5)=.0075
      CALL YAXIS(-1.,-1.,VARSC)
      CALL CHARS(24,COP5,0.,6.,8.30,15)
      CALL CHARS(24,TEF5,0.,6.,8.05,15)
      CALL CHARS(24,COP2,0.,6.,6.3,15)
      CALL CHARS(24,TEF5,0.,6.,6.05,15)
      DO 950 I=1,8
      IY=26*I-25
      IVARS1(4)=114+I
      YSIDE=8.-.25*FLOAT(I)
      IF(I.GT.4) YSIDE=YSIDE-1.
      ISIDE=3*I-2
      IF(I.EQ.5) CALL COLOR(1,1,1,0,0,0,0)
      CALL CHARS(12,SIDEP(1,I),0.,7.,YSIDE,15)
  950 CALL GPLOT(X,Y(IY),IVARS1)
      CALL DISPLA(1)
 1000 RETURN
      END
```

TABLE I. - RANGES OF PARAMETERS

Inside radius, mm	5 to 30
Thickness, mm	
Copper conductor	0.2 and 0.5
Teflon dielectric	0.5
Geometries	Coaxial, stranded coaxial, and parallel lines
Frequencies, kHz	10, 20 and 30
Distance between parallel lines, mm	1, 4, 7, and 10
Power (1000 V at 100 A), kW	100
Line length, m	50

TABLE II. - EXAMPLE OF COMPUTER OUTPUT

INNER CONDUCTOR RADII		OUTER CONDUCTOR RADII		SHIELD RADII	
INSIDE	15.00 MM	INSIDE	16.00 MM	INSIDE	17.00 MM
OUTSIDE	15.50 MM	OUTSIDE	16.50 MM	OUTSIDE	17.00 MM

VOLTAGE	1000.	VOLTS
CURRENT	100.0	AMPERES
FREQUENCY	20000.	HERTZ
POWER	100.	KILOWATTS
CABLE LENGTH	50.0	METERS
COPPER MASS	44.3	KILOGRAMS
TEFLON MASS	11.2	KILOGRAMS
DC FORMULA RESISTANCE	0.0358	OHMS
AC FORMULA RESISTANCE	0.0378	OHMS
RESISTANCE	0.0580	OHMS
CONDUCTANCE	17.242	MHOS
RESISTIVE POWER	580.0	WATTS
PERCENT POWER LOST	0.58	PERCENT
POWER PER METER	11.60	WATTS
TEMPERATURE RISE	0.34	DEG C
RADIANT TEMPERATURE	38.6	DEG C
SINK TEMPERATURE	0.0	DEG C
DIELECTRIC STRENGTH	8316.6	VOLTS
SHIELD DIEL STRENGTH	8324.5	VOLTS
SHUNT CONDUCTANCE	.000000	MHOS
INDUCTANCE	0.478	MICROHENRYS
CAPACITANCE	0.192	MICROFARADS
DEPTH OF PENETRATION	0.4732	MM
INNER INDUCTANCE	0.082	MICROHENRYS
OUTER INDUCTANCE	0.078	MICROHENRYS
CHAR. IMPEDANCE	1.576	OHMS
CHAR. ADMITTANCE	0.635	MHOS
COMPLEX INDUCTANCE	0.478	-0.462 MICROHENRYS
COMPLEX CAPACITANCE	0.192	0.000 MICROFARADS

INNER CONDUCTOR RADII		OUTER CONDUCTOR RADII		SHIELD RADII	
INSIDE	0.5905 INCH	INSIDE	0.6299 INCH	INSIDE	0.6693 INCH
OUTSIDE	0.6102 INCH	OUTSIDE	0.6496 INCH	OUTSIDE	0.6693 INCH

COPPER MASS	97.7	POUNDS
TEFLON MASS	24.7	POUNDS
POWER PER FOOT	3.536	WATTS
RADIANT TEMPERATURE	101.5	DEG F
DEPTH OF PENETRATION	0.0186	INCH

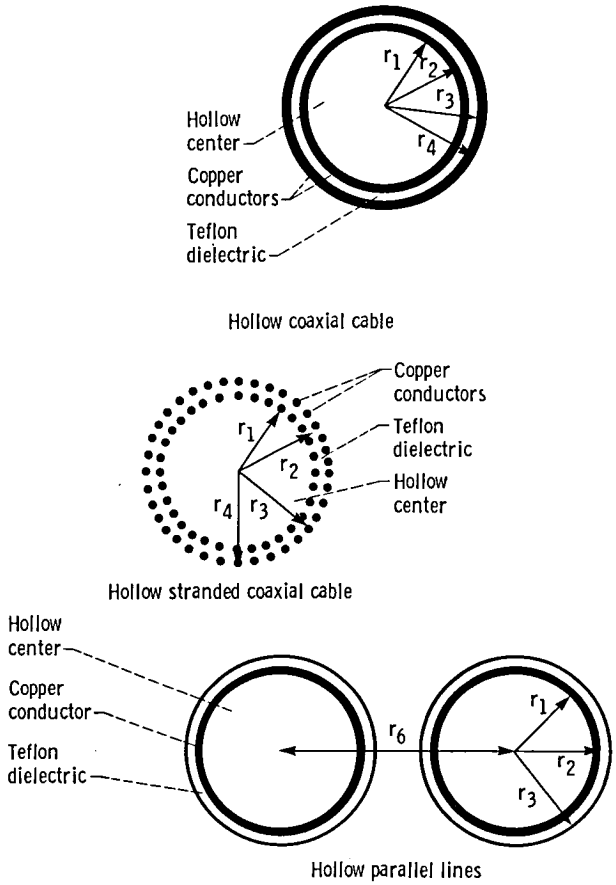


Figure 1. - Configurations investigated.

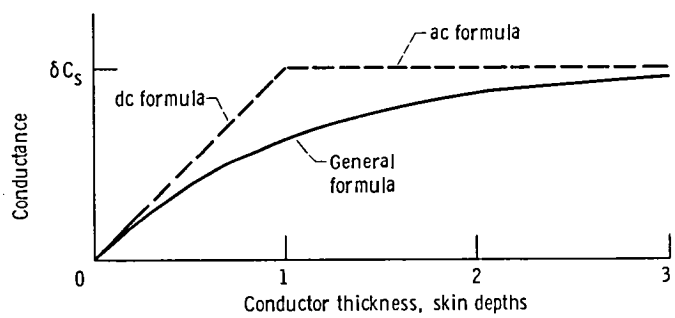
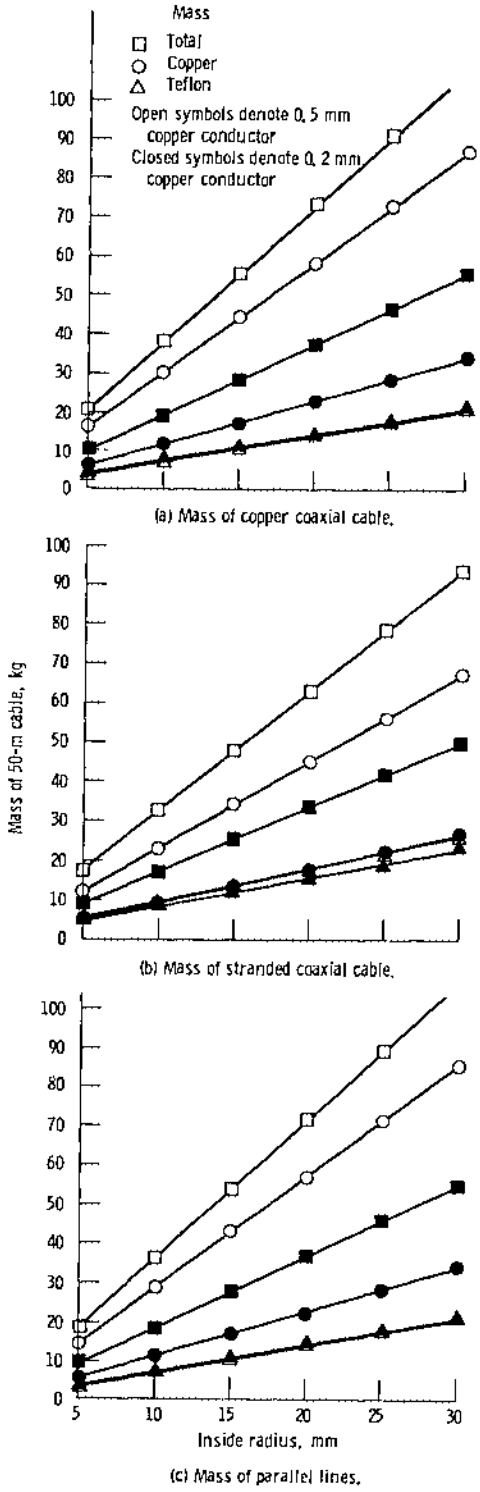


Figure 2. - Conductance versus conductor thickness.



(a) Mass of copper coaxial cable.

(b) Mass of stranded coaxial cable.

(c) Mass of parallel lines.

Figure 3. - Mass of copper conductor, mass of Teflon dielectric and total mass of transmission lines. Diameter of Teflon dielectric, 0.5 mm.

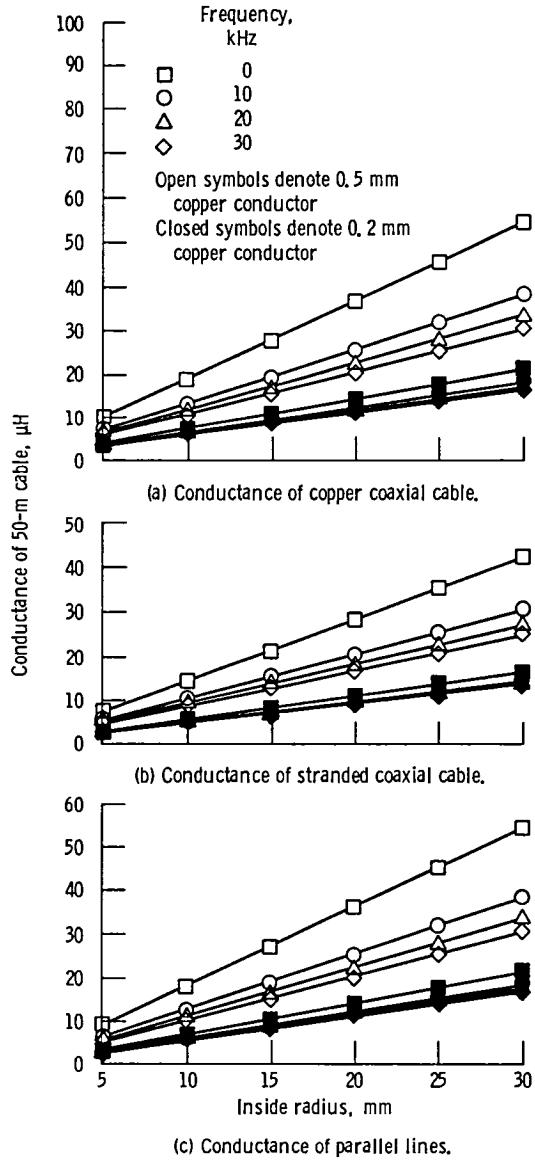


Figure 4. - Conductance of transmission lines. Diameter of Teflon dielectric, 0.5 mm.

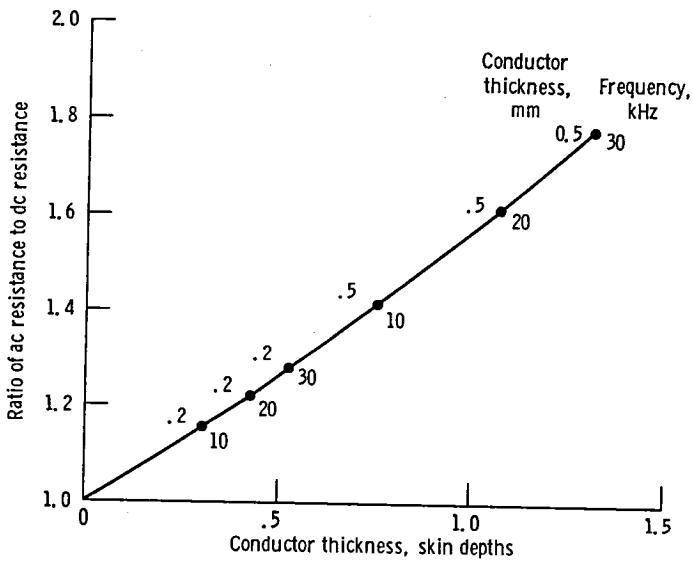
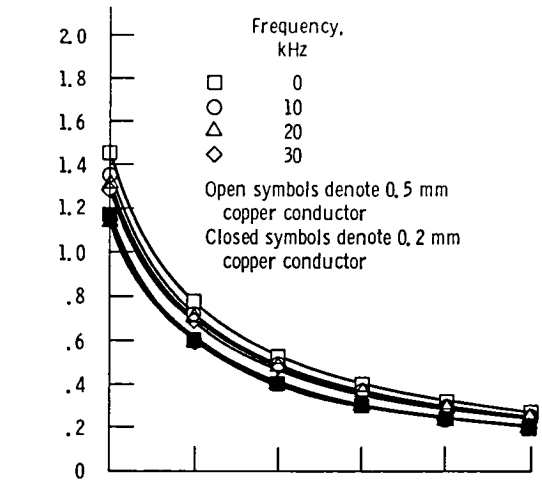
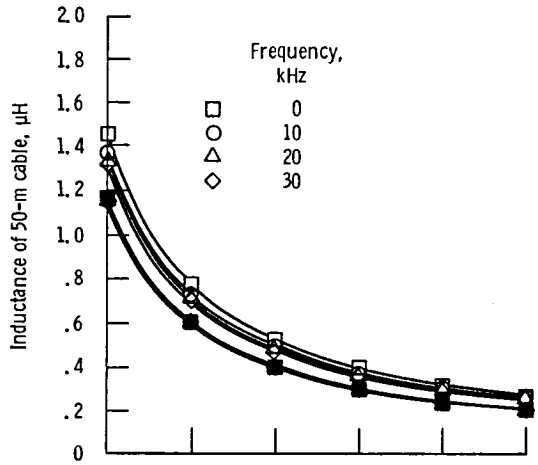


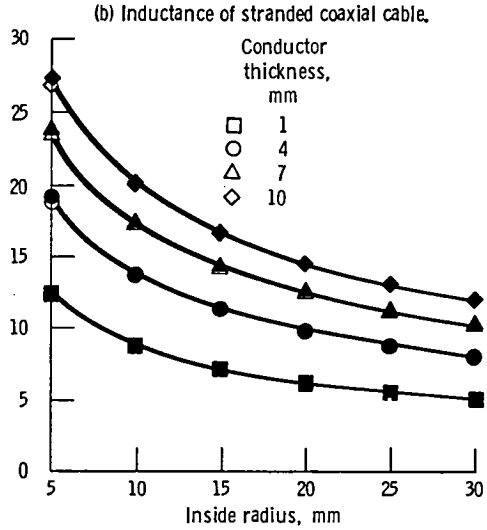
Figure 5. - Increases of ac/dc resistance ratio due to increasing conductor thickness and increasing frequency.



(a) Inductance of copper coaxial cable.



(b) Inductance of stranded coaxial cable.



(c) Inductance of parallel lines.

Figure 6. - Inductance of transmission lines. Diameter of Teflon dielectric, 0.5 mm.

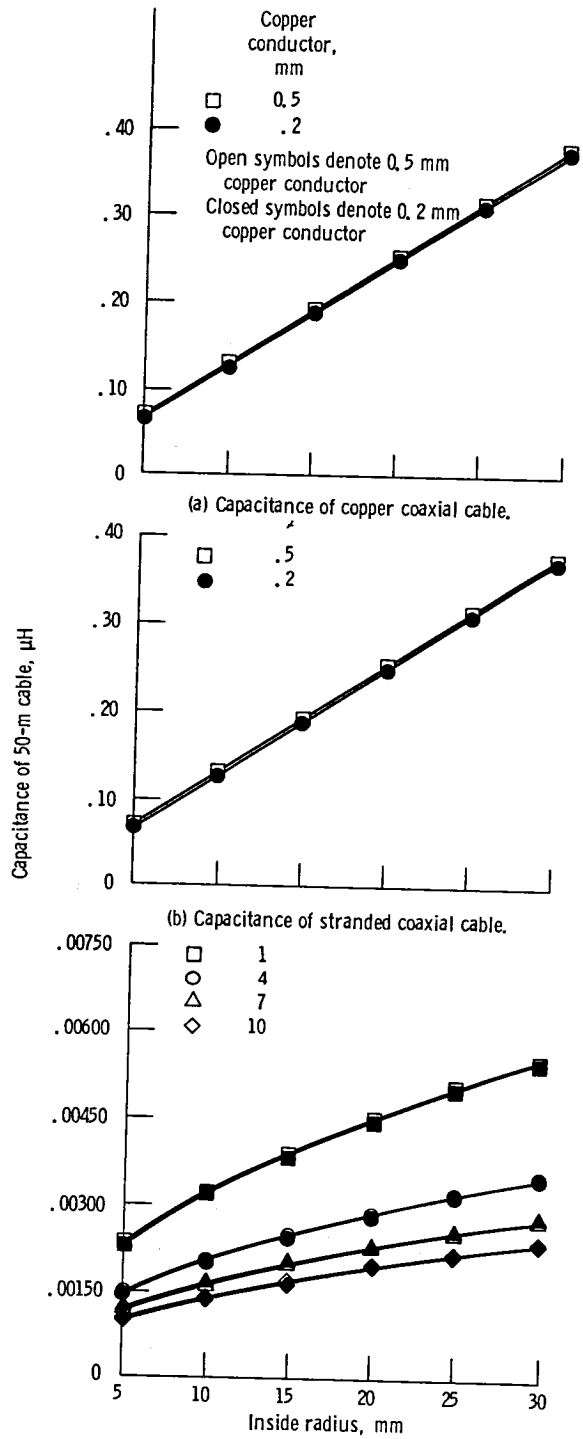
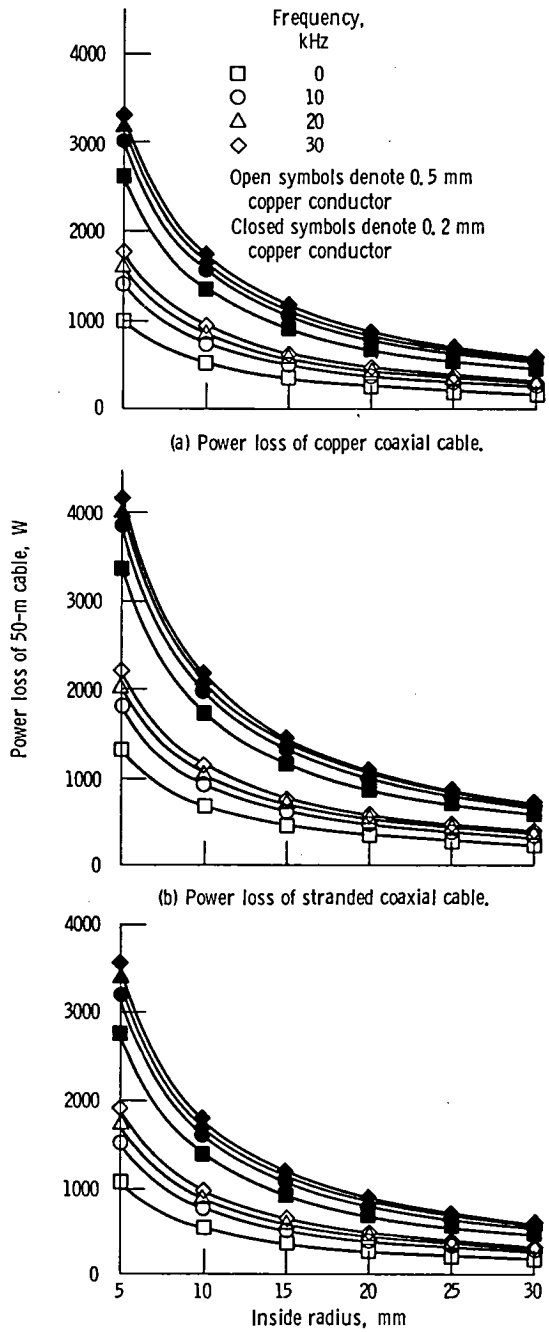


Figure 7. - Capacitance of transmission lines. Diameter of Teflon dielectric, 0.5 mm.

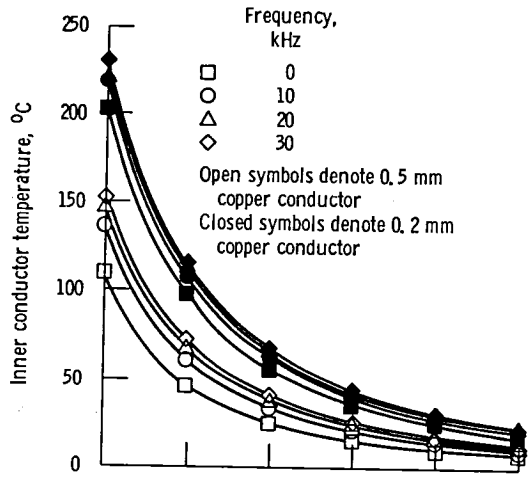


(a) Power loss of copper coaxial cable.

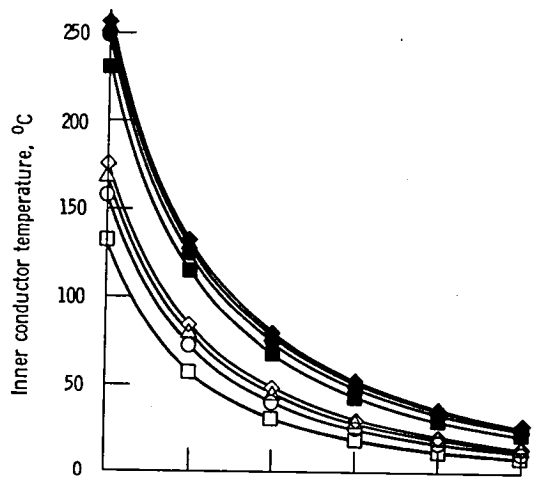
(b) Power loss of stranded coaxial cable.

(c) Power loss of parallel lines.

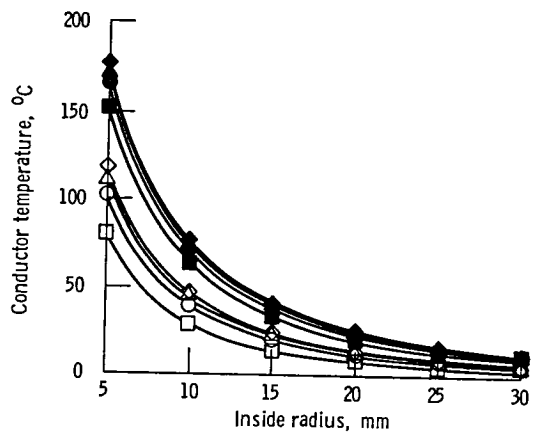
Figure 8. - Power loss of transmission lines. Diameter of Teflon dielectric, 0.5 mm.



(a) Inner conductor temperature of copper coaxial cable.



(b) Inner conductor temperature of stranded coaxial cable.



(c) Conductor temperature of parallel lines.

Figure 9. - Temperatures of transmission line conductors. Diameter of Teflon dielectric, 0.5 mm.

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15. Supplementary Notes

16. Abstract

A parametric analysis was performed of transmission cables for transmitting electrical power at high voltage (up to 1000 V) and high frequency (10 to 30 kHz) for high power (100 kW or more) space missions. Large diameter (5 to 30 mm) hollow conductors were considered in closely spaced coaxial configurations and in parallel lines. Formulas were derived to calculate inductance and resistance for these conductors. Curves of cable conductance, mass, inductance, capacitance, resistance, power loss, and temperature were plotted for various conductor diameters, conductor thicknesses, and alternating current frequencies. An example 5 mm diameter coaxial cable with 0.5 mm conductor thickness was calculated to transmit 100 kW at 1000 V ac, 50 m with a power loss of 1900 W, an inductance of 1.45 μH and a capacitance of 0.07 μF. The computer programs written for this analysis are listed in the appendix.

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