NASA-TM-83601 19840012571

NASA Technical Memorandum 83601

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

Kent S. Jefferies and David D. Renz
Lewis Research Center
Cleveland, Ohio

March 1984

NASA

```
.45       1       1 RN/NASA-TM-83601
            DISPLAY 45/2/1
        84N20639*#   ISSUE 11   PAGE 1625   CATEGORY 20   RPT#: NASA-TM-83601
        E-2013 NAS 1.15:83601   84/03/00  43 PAGES   UNCLASSIFIED DOCUMENT
UTTL: Parametric analysis of hollow conductor parallel and coaxial transmission
        lines for high frequency space power distribution
AUTH: A/JEFFRIES, K. S.;  B/RENZ, D. D.
CORP: National Aeronautics and Space Administration. Lewis Research Center,
        Cleveland, Ohio.    AVAIL.NTIS   SAP: HC A03/MF A01
MAJS: /*CAPACITANCE/*HIGH FREQUENCIES/*POWER LINES/*TEMPERATURE MEASUREMENT/*
        TRANSMISSION LINES
MINS: / COMPUTER PROGRAMS/ CONDUCTORS/ ELECTRIC POTENTIAL/ INDUCTANCE/ THICKNESS
ABA:  Author
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

Kent S. Jefferies and David D. Renz

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-2013

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 space-stations 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

N84-20639#

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 slipring 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_0 is:

$$R_{dc} = \rho\ell/A_I + \rho\ell/A_0$$

For the stranded coaxial conductor, A_I and A_0 are the total cross sectional areas of the strands. The round trip dc resistance for two parallel conductors with conductor area A is:

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

<u>ac resistance formula</u>. - 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.

<u>Inductance within inner conductor</u>. - 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 ($4\pi x 10^{-7}$, 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.

$$L_{cond} = \frac{2x10^{-7}}{r_2^2 - r_1^2}\left[\frac{r_2^2}{4} - \frac{3r_1^2}{4} + \frac{r_1^4 \ln\,(r_2/r_1)}{(r_2^2 - r_1^2)}\right]$$

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 M 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:

$$C_{coax} = 55.56\mathrm{x}10^{-12}\mathrm{xDiel}_{TEFL}\mathrm{x}\ell/\ln\,(r_3/r_2)$$

$$C_{parallel} = 27.78\mathrm{x}10^{-12}\mathrm{xDiel}_{TEFL}\mathrm{x}\ell/\ln\left[\frac{r_6}{r_2} + \sqrt{\left(\frac{r_6}{r_2}\right)^2 - 1}\right]$$

$Diel_{TEFL}$	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

1. Hansen, I. G.: Advantage of Resonant Power Conversion in Aerospace Applications. NASA TM-83399, 1983.

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(I04,2)
      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)

```
      VSMAX=TSTRNG*RAD(4)*RSLOG
      TCOND=0.
      G=2.*PI*TCOND/RLOG
C     INDUCTANCE OF POWER LINE (HENRYS) AND CAPACITANCE (MFD)
      ER2R1=EXP((RAD(1)-RAD(2))/SKIN)
      SFX2=0.
      DRAD=(RAD(2)-RAD(1))/50.
      DO 50 INT=1,99,2
      RX=RAD(1)+FLOAT(INT)*.5*DRAD
      ER2X=EXP((RX-RAD(2))/SKIN)
      FX=(ER2X-ER2R1)/(1.-ER2R1)
   50 SFX2=SFX2+FX**2/RX
      AINDI=2.E-07*CABL*SFX2*DRAD
      ER4R3=EXP((RAD(3)-RAD(4))/SKIN)
      SFX2=0.
      DRAD=(RAD(4)-RAD(3))/50.
      DO 75 INT=1,99,2
      RX=RAD(3)+FLOAT(INT)*.5*DRAD
      EXR3=EXP((RAD(3)-RX)/SKIN)
      FX=(EXR3-ER4R3)/(1.-ER4R3)
   75 SFX2=SFX2+FX**2/RX
      AINDO=2.E-07*CABL*SFX2*DRAD
      AINDCT=AINDI+2.E-07*RLOG*CABL+AINDO
      R2R1=RAD(2)**2-RAD(1)**2
      DINDI=CABL*(2.E-07/R2R1)*(RAD(1)**4*DLOG(RAD(2)/RAD(1))/R2R1+.25*RAD(2)**2-.75*RAD(1)**2)
      R4R3=RAD(4)**2-RAD(3)**2
      DINDO=CABL*(2.E-07/R4R3)*((RAD(4)**4/R4R3)*DLOG(RAD(4)/RAD(3))+.25*RAD(3)**2-.75*RAD(4)**2)
      DCIND=DINDI+2.E-07*RLOG*CABL+DINDO
      CAP=55.56E-12*TDIEL*CABL/RLOG
C     CHARACTERISTIC IMPEDANCE,Z0; CHARACTERISTIC ADMITTANCE,Y0
      Z0=SQRT(AINDCT/CAP)
      Y0=SQRT(CAP/AINDCT)
C     COMPLEX INDUCTANCE,CIND; COMPLEX CAPACITANCE,CCAP
      COMPLEX CIND,CCAP,J
      DATA J/(0.,1.)/
      CIND=AINDCT+RMAX/(J*2.*PI*FREQ)
      CCAP=CAP+G/(J*2.*PI*FREQ)
  100 FORMAT (1H1,-
     * ' INNER CONDUCTOR RADII         OUTER CONDUCTOR RADII         SHIELD RADII'/-
     * ' INSIDE '3PF9.2,' MM            INSIDE '3PF9.2,' MM           INSIDE '3PF9.2,' MM'/-
     * ' OUTSIDE'3PF9.2,' MM            OUTSIDE'3PF9.2,' MM           OUTSIDE'3PF9.2,' MM'/-
     * ' VOLTAGE             '0PF7.0,' VOLTS'/-
     * ' CURRENT             '0PF7.1,' AMPERES'/-
     * ' FREQUENCY           '0PF7.0,' HERTZ'/-
     * ' POWER               '-3PF7.0,' KILOWATTS'/-
     * ' CABLE LENGTH        '0PF7.1,' METERS'/)
      WRITE (6,100) RAD(1),RAD(3),RAD(5),RAD(2),RAD(4),RAD(6),VOLTS,CURRNT,FREQ,POWER,CABL
  200 FORMAT (-
     * ' COPPER MASS         '-3PF7.1,' KILOGRAMS'/-
     * ' 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'/-
```

Calculation Subroutine for Coax (continued)

```
     * ' 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
      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
```

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(I,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

```
      SUBROUTINE STINT(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 S','TRAN','DED ','COAX','    ',2*0./
      DATA TCHAR2/'COND','UCTA','NCE ','OF 0','.2 M','M ST','RAND','ED C','OAX ',0./
      DATA TMCHR1/'MASS',' OF ','STRA','NDED',' COA','X   ',4*0./
      DATA TMCHR2/'MASS',' OF ','0.2 ','MM S','TRAN','DED ','COAX',3*0./
      DATA TICHR1/'INDU','CTAN','CE O','F ST','RAND','ED C','OAX ',3*0./
      DATA TCCHR1/'CAPA','CITA','NCE ','OF S','TRAN','DED ','COAX','    ',2*0./
      DATA TRCHR1/'RESI','STIV','ITY ','OF S','TRAN','DED ','COAX','    ',2*0./
      DATA TRCHR2/'RESI','STIV','ITY ','OF 0','.2 M','M ST','RAND','ED C','OAX ',0./
      DATA TPCHR1/'POWE','R LO','SS O','F ST','RAND','ED C','OAX ',3*0./
      DATA TPCHR2/'POWE','R LO','SS O','F 0.','2 MM',' STR','ANDE','D CO','AX  ',0./
      DATA TTCHR1/'RADI','ATIN','G TE','MPER','ATUR','E OF',' STR','ANDE','D CO','AX  ',2*0./
      DATA TTCHR2/'RADI','ATIN','G TE','MPER','ATUR','E OF',' 0.2',' MM ','STRA','NDED',' COA','X   '/
      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
      RAD21=RAD(2)-RAD(1)
      NI=2.*PI*RAD(1)/RAD21
      NO=2.*PI*RAD(3)/RAD21
      NS=2.*PI*RAD(5)/RAD21
      AREAI=NI*PI*(RAD21/2.)**2
      AREAO=NO*PI*(RAD21/2.)**2
      AREAS=NS*PI*((RAD(6)-RAD(5))/2.)**2
      CMASS=(AREAI+AREAO+AREAS)*CABL*CDENS
      AREAD=PI*(RAD(5)**2-RAD(1)**2)-(AREAI+AREAO)
      TMASS=AREAD*CABL*TDENS
      RDC=CABL*CRES*(1./AREAI+1./AREAO)
      FS=AREAD/(PI*(RAD(4)**2-RAD(3)**2))
      SKIN=503.*SQRT(CRES/(FS*FREQ))
      RAC=RDC*(RAD21/SKIN)
      RMAX=RAC/(1.-EXP(-RAD21/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
```

Calculation Subroutine for Stranded Coax (continued)

```
      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
      VSMAX=TSTRNG*RAD(4)*RSLOG
      TCOND=0.
      G=2.*PI*TCOND/RLOG
C     INDUCTANCE OF POWER LINE (HENRYS) AND CAPACITANCE (MFD)
      ER2R1=EXP((RAD(1)-RAD(2))/SKIN)
      SFX2=0.
      DRAD=(RAD(2)-RAD(1))/50.
      DO 50 INT=1,99,2
      RX=RAD(1)+FLOAT(INT)*.5*DRAD
      ER2X=EXP((RX-RAD(2))/SKIN)
      FX=(ER2X-ER2R1)/(1.-ER2R1)
   50 SFX2=SFX2+FX**2/RX
      AINDI=2.E-07*CABL*SFX2*DRAD
      ER4R3=EXP((RAD(3)-RAD(4))/SKIN)
      SFX2=0.
      DRAD=(RAD(4)-RAD(3))/50.
      DO 75 INT=1,99,2
      RX=RAD(3)+FLOAT(INT)*.5*DRAD
      EXR3=EXP((RAD(3)-RX)/SKIN)
      FX=(EXR3-ER4R3)/(1.-ER4R3)
   75 SFX2=SFX2+FX**2/RX
      AINDO=2.E-07*CABL*SFX2*DRAD
      AINDCT=AINDI+2.E-07*RLOG*CABL+AINDO
      R2R1=RAD(2)**2-RAD(1)**2
      DINDI=CABL*(2.E-07/R2R1)*(RAD(1)**4*DLOG(RAD(2)/RAD(1))/R2R1+.25*RAD(2)**2-.75*RAD(1)**2)
      R4R3=RAD(4)**2-RAD(3)**2
      DINDO=CABL*(2.E-07/R4R3)*((RAD(4)**4/R4R3)*DLOG(RAD(4)/RAD(3))+.25*RAD(3)**2-.75*RAD(4)**2)
      DCIND=DINDI+2.E-07*RLOG*CABL+DINDO
      CAP=55.56E-12*TDIEL*CABL/RLOG
C     CHARACTERISTIC IMPEDANCE,Z0; CHARACTERISTIC ADMITTANCE,Y0
       Z0=SQRT(AINDCT/CAP)
      Y0=SQRT(CAP/AINDCT)
C     COMPLEX INDUCTANCE,CIND; COMPLEX CAPACITANCE,CCAP
      COMPLEX CIND,CCAP,J
      DATA J/(0.,1.)/
      CIND=AINDCT+RMAX/(J*2.*PI*FREQ)
      CCAP=CAP+G/(J*2.*PI*FREQ)
  100 FORMAT (1H1,-
     * ' INNER CONDUCTOR RADII         OUTER CONDUCTOR RADII         SHIELD RADII'/-
     * ' INSIDE '3PF9.2,' MM            INSIDE '3PF9.2,' MM           INSIDE '3PF9.2,' MM'/-
     * ' OUTSIDE'3PF9.2,' MM            OUTSIDE'3PF9.2,' MM           OUTSIDE'3PF9.2,' MM'/-
     * ' VOLTAGE             '0PF7.0,' VOLTS'/-
     * ' CURRENT             '0PF7.1,' AMPERES'/-
     * ' FREQUENCY           '0PF7.0,' HERTZ'/-
     * ' POWER               '-3PF7.0,' KILOWATTS'/-
     * ' CABLE LENGTH        '0PF7.1,' METERS'/)
      WRITE (6,100) RAD(1),RAD(3),RAD(5),RAD(2),RAD(4),RAD(6),VOLTS,CURRNT,FREQ,POWER,CABL
  200 FORMAT (-
     * ' 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.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 Parallel Lines

```
      SUBROUTINE PRLINT(RAD,FREQ,IR1,IFREQ,ID,LSPACE)
      DIMENSION RAD(6),ERAD(6)
      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)
      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 P','ARAL','LEL ','LINE','S   ',2*0./
      DATA TCHAR2/'COND','UCTA','NCE ','OF 0','.2 M','M PA','RALL','EL L','INES',0./
      DATA TMCHR1/'MASS',' OF ','PARA','LLEL',' LIN','ES  ',4*0./
      DATA TMCHR2/'MASS',' OF ','0.2 ','MM P','ARAL','LEL ','LINE','S   ',2*0./
      DATA TICHR1/'INDU','CTAN','CE O','F PA','RALL','EL L','INES',3*0./
      DATA TCCHR1/'CAPA','CITA','NCE ','OF P','ARAL','LEL ','LINE','S   ',2*0./
      DATA TRCHR1/'RESI','STIV','ITY ','OF P','ARAL','LEL ','LINE','S   ',2*0./
      DATA TRCHR2/'RESI','STIV','ITY ','OF 0','.2 M','M PA','RALL','EL L','INES',0./
      DATA TPCHR1/'POWE','R LO','SS O','F PA','RALL','EL L','INES',3*0./
      DATA TPCHR2/'POWE','R LO','SS O','F 0.','2 MM',' PAR','ALLE','L LI','NES ',0./
      DATA TTCHR1/'RADI','ATIN','G TE','MPER','ATUR','E OF',' PAR','ALLE','L LI','NES ',2*0./
      DATA TTCHR2/'RADI','ATIN','G TE','MPER','ATUR','E OF',' 0.2',' MM ','PARA','LLEL',' LIN','ES  '/
      DOUBLE PRECISION RAD,R2R1
C     RAD(1) INNER RADIUS OF CONDUCTORS; RAD(2) OUTER RADIUS OF CONDUCTORS
C     RAD(3) OUTER RADIUS OF DIELECTRICS; RAD(6)  CENTER TO CENTER SPACING
   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/
      DATA EMIS,SIG,TSINK/0.5,5.67E-08,273./
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)
      AREAS=PI*(RAD(4)**2-RAD(3)**2)
      CMASS=2.*(AREAI+AREAS)*CABL*CDENS
      AREAD=PI*(RAD(3)**2-RAD(2)**2)
      TMASS=2.*AREAD*CABL*TDENS
      RDC=2.*CABL*CRES/AREAI
      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))
      DTEMP=PWRPM*RLOG/(4.*PI*TTCND)
      TRADK=DTEMP+SQRT(SQRT(TSINK**4+PWRPM/(4.*PI*RAD(4)*EMIS*SIG)))
      TRADC=TRADK-273.
      TSINKC=TSINK-273.
      VMAX=TSTRNG*RAD(2)*RLOG
      TCOND=0.
      G=PI*TCOND/RLOG
C     INDUCTANCE OF POWER LINE (HENRYS) AND CAPACITANCE (MFD)
```

Calculation Subroutine for Parallel Lines (continued)

```
      ER2R1=EXP((RAD(1)-RAD(2))/SKIN)
      SFX2=0.
      DRAD=(RAD(2)-RAD(1))/50.
      DO 50 INT=1,99,2
      RX=RAD(1)+FLOAT(INT)*.5*DRAD
      ER2X=EXP((RX-RAD(2))/SKIN)
      FX=(ER2X-ER2R1)/(1.-ER2R1)
   50 SFX2=SFX2+FX**2/RX
      AINDI=2.E-07*CABL*SFX2*DRAD
      DCOSH=ALOG(RAD(6)/(2.*RAD(2))+SQRT((RAD(6)/(2.*RAD(2)))**2-1.))
      AINDCT=2.*AINDI+4.E-07*DCOSH*CABL
      CAP=27.78E-12*CABL/DCOSH
C     CHARACTERISTIC IMPEDANCE,Z0; CHARACTERISTIC ADMITTANCE,Y0
      Z0=SQRT(AINDCT/CAP)
      Y0=SQRT(CAP/AINDCT)
C     COMPLEX INDUCTANCE,CIND; COMPLEX CAPACITANCE,CCAP
      COMPLEX CIND,CCAP,J
      DATA J/(0.,1.)/
      CIND=AINDCT+RMAX/(J*2.*PI*FREQ)
      CCAP=CAP+G/(J*2.*PI*FREQ)
C     FORCE BETWEEN CONDUCTORS
      FMAG=2.E-07*CURRNT**2/RAD(6)
      FEMAG=FMAG*(2.2/9.8)*(12./39.37)
  100 FORMAT (1H1,-
     * ' INNER CONDUCTOR RADII         SHIELD RADII'/-
     * ' INSIDE '3PF9.2,' MM            INSIDE '3PF9.2,' MM'/-
     * ' OUTSIDE'3PF9.2,' MM            OUTSIDE'3PF9.2,' MM'/-
     * ' CENTER - CENTER DIST'3PF7.2,' MM'/-
     * ' VOLTAGE             '0PF7.0,' VOLTS'/-
     * ' CURRENT             '0PF7.1,' AMPERES'/-
     * ' FREQUENCY           '0PF7.0,' HERTZ'/-
     * ' POWER               '-3PF7.0,' KILOWATTS'/-
     * ' CABLE LENGTH        '0PF7.1,' METERS'/)
      WRITE (6,100) RAD(1),RAD(3),RAD(2),RAD(4),RAD(6),VOLTS,CURRNT,FREQ,POWER,CABL
  200 FORMAT (-
     * ' COPPER MASS         '-3PF7.1,' KILOGRAMS'/-
     * ' TEFLON MASS         '-3PF7.1,' KILOGRAMS'/-
     * ' DC FORMULA RESISTANCE '0PF5.4,' OHMS'/-
     * ' AC FORMULA RESISTANCE '0PF5.4,' 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'/)
      WRITE (6,200) CMASS,TMASS,RDC,RAC,RMAX,CONDCT,PWRRES,PWRRAT,PWRPM,DTEMP,TRADC,TSINKC,VMAX
  300 FORMAT(-
     * ' SHUNT CONDUCTANCE   '0PF7.6, ' MHOS'/-
     * ' INDUCTANCE          '6PF7.3,' MICROHENRYS'/-
     * ' CAPACITANCE         '6PF7.3,' MICROFARADS'/-
     * ' 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 YCHARI/'COND','UCTA','NCE ','OF 5','OM C','ABLE',' MHO','S   ',2*0./
      CALL TITLE (3,29,15,YCHARI)
      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)

```
      NC1=I
      IF(I.GT.3) NC1=I-4
      CALL COLOR(1,NC1,1,0,0,0,0)
      CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
  100 CALL GPLOT (X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT MASS OF CABLE
C
  200 CALL TITLE(0,24,20,TCHAR1)
      CALL TITLE(4,17,15,XCHAR1)
      DATA YCHARM/'MASS',' OF ','50M ','CABL','E KG',5*0./
      CALL TITLE(3,20,15,YCHARM)
      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.,6.55,15)
      CALL CHARS(24,TEF5,0.,6.,6.3,15)
      DO 250 I=1,6
      IY=26*I-25
      IVARS1(4)=114+I
      YSIDE=8.-.25*FLOAT(I)
      IF(I.GT.3) YSIDE=YSIDE-1.
      ISIDE=5*I-4
      NC1=I
      IF(I.GT.3) NC1=I-4
      CALL COLOR(1,NC1,1,0,0,0,0)
      CALL CHARS(19,SIDEM(ISIDE),0.,7.,YSIDE,15)
  250 CALL GPLOT(X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT INDUCTANCE OF COAXIAL CABLE
C
  300 CALL TITLE (0,28,20,TCHAR1)
      CALL TITLE (4,17,15,XCHAR1)
      DATA YCHARI/'INDU','CTAN','CE O','F 50','M CA','BLE ','MICR','OHEN','RYS '/
      CALL TITLE (3,35,15,YCHARI)
      CALL XAXIS(-1.,-1.,VARSX)
      DATA VARSI/5.,-1.,90.,0.,2./
      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 350 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
      NC1=I
```

Plotting Subroutine for all Configurations (continued)

```
      IF(I.GT.3) NC1=I-4
      CALL COLOR(1,NC1,1,0,0,0,0)
      CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
  350 CALL GPLOT (X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C      PLOT CAPACITANCE OF COAXIAL CABLE
C
  400 CALL TITLE(0,29,20,TCHAR1)
      CALL TITLE (4,17,15,XCHAR1)
      DATA YCHARC/'CAPA','CITA','NCE ','OF 5','0M C','ABLE',' MIC','ROFA','RADS'/
      CALL TITLE (3,36,15,YCHARC)
      CALL XAXIS(-1.,-1.,VARSX)
      DATA VARSC/5.,-1.,90.,0.,.5/
C     FOLLOWING CHANGE FOR PARALLEL ONLY
C     VARSC(5)=.015
      CALL YAXIS(-1.,-1.,VARSC)
      CALL CHARS(24,TEF5,0.,6.,8.05,15)
      DO 450 I=1,2
      IY=26*I-25
      IVARS1(4)=114+I
      YSIDE=8.-.25*FLOAT(I)
      ISIDE=7*I-6
      NC1=I
      IF(I.GT.3) NC1=I-4
      CALL COLOR(1,NC1,1,0,0,0,0)
      CALL CHARS(28,SIDEI(ISIDE),0.,5.5,YSIDE,15)
  450 CALL GPLOT(X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT RESISTIVITY
C
  500 CALL TITLE(0,28,20,TCHAR1)
      CALL TITLE(4,17,15,XCHAR1)
      DATA YCHARR/'RESI','STIV','ITY ','OF 5','0M C','ABLE',' OHM','S   '/
      CALL TITLE (3,29,15,YCHARR)
      CALL XAXIS (-1.,-1.,VARSX)
      DATA VARSR/5.,-1.,90.,0.,.5/
      CALL YAXIS (-1.,-1.,VARSR)
      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 550 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
      NC1=I
      IF(I.GT.3) NC1=I-4
      CALL COLOR(1,NC1,1,0,0,0,0)
```

Plotting Subroutine for all Configurations (continued)

```
      CALL CHARS (12,SIDE(ISIDE),0.,7.,YSIDE,15)
  550 CALL GPLOT (X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT POWER LOSS
C
  600 CALL TITLE(0,28,20,TCHAR1)
      CALL TITLE (4,17,15,XCHAR1)
      DATA YCHARP/'POWE','R LO','SS O','F 50','M CA','BLE ','WATT','S   '/
      CALL TITLE (3,29,15,YCHARP)
      CALL XAXIS (-1.,-1.,VARSX)
      DATA VARSP/5.,-1.,90.,0.,5000./
      CALL YAXIS(-1.,-1.,VARSP)
      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 650 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
      NC1=I
      IF(I.GT.3) NC1=I-4
      CALL COLOR(1,NC1,1,0,0,0,0)
      CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
  650 CALL GPLOT(X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT TEMPERATURE
C
  700 CALL TITLE(0,40,20,TCHAR1)
      CALL TITLE(4,17,15,XCHAR1)
      DATA YCHART/'INNE','R CO','NDUC','TOR ','TEMP','ERAT','URE ','DEG ','C   ','    '/
      CALL TITLE(3,33,15,YCHART)
      CALL XAXIS(-1.,-1.,VARSX)
      DATA VARST/5.,-1.,90.,0.,250./
      CALL YAXIS(-1.,-1.,VARST)
      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 750 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
      NC1=I
      IF(I.GT.3) NC1=I-4
      CALL COLOR(1,NC1,1,0,0,0,0)
```

Plotting Subroutine for all Configurations

(concluded)

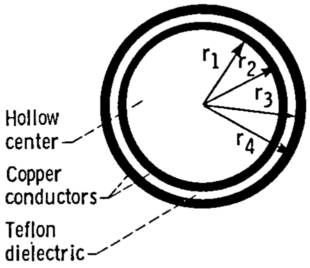
```
      CALL CHARS(12,SIDE(ISIDE),0.,7.,YSIDE,15)
  750 CALL GPLOT(X,Y(IY),IVARS1)
      CALL DISPLA(1)
      RETURN
C
C     PLOT INDUCTANCE OF PARALLEL LINES
C
  800 CALL TITLE (0,28,20,TCHAR1)
      CALL TITLE (4,17,15,XCHAR1)
      CALL TITLE (3,35,15,YCHARI)
      CALL XAXIS(-1.,-1.,VARSX)
      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

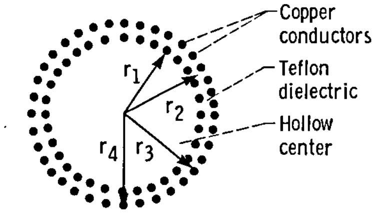
Inside radius, mm	5 to 30
Thickness, mm	
Copper conductor	0.2 and 0.5
Teflon dielectric	0.5
Geometries	Coaxial, stranded coaxial, and parallel lines
Frequencies, kHz	10, 20 and 30
Distance between parallel lines, mm	1, 4, 7, and 10
Power (1000 V at 100 A), kW	100
Line length, m	50

TABLE II. - EXAMPLE OF COMPUTER OUTPUT

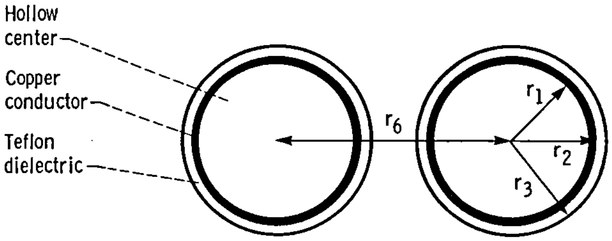
```
 INNER CONDUCTOR RADII          OUTER CONDUCTOR RADII          SHIELD RADII
INSIDE     15.00 MM             INSIDE     16.00 MM            INSIDE     17.00 MM
OUTSIDE    15.50 MM             OUTSIDE    16.50 MM            OUTSIDE    17.00 MM
VOLTAGE                 1000. VOLTS
CURRENT                 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 RESISTANCE0.0358 OHMS
AC FORMULA RESISTANCE0.0378 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
```



Hollow coaxial cable



Hollow stranded coaxial cable



Hollow parallel lines

Figure 1. - Configurations investigated.

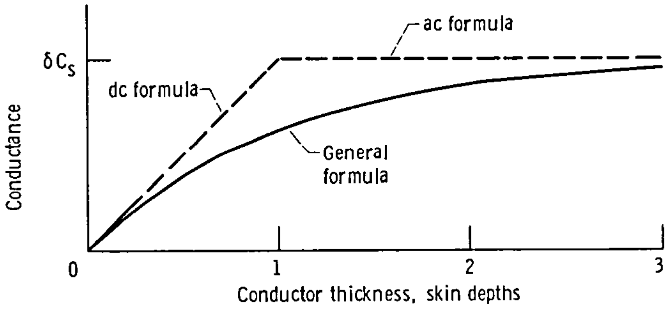
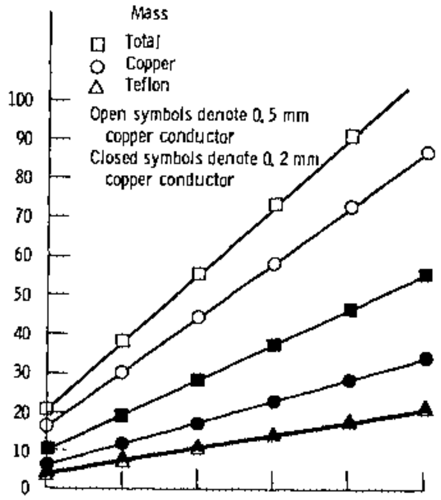
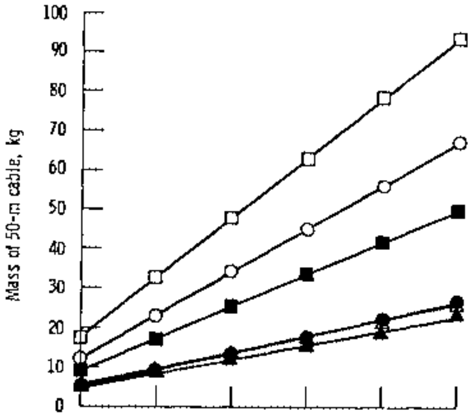


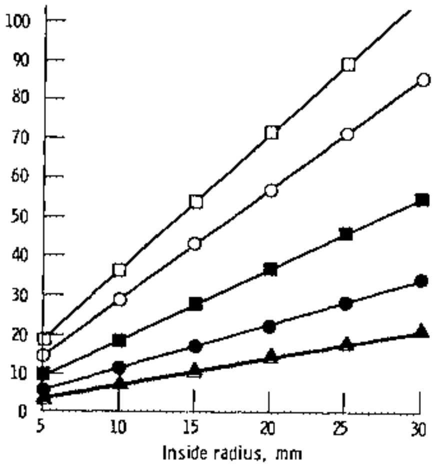
Figure 2. - Conductance versus conductor thickness.



(a) Mass of copper coaxial cable.

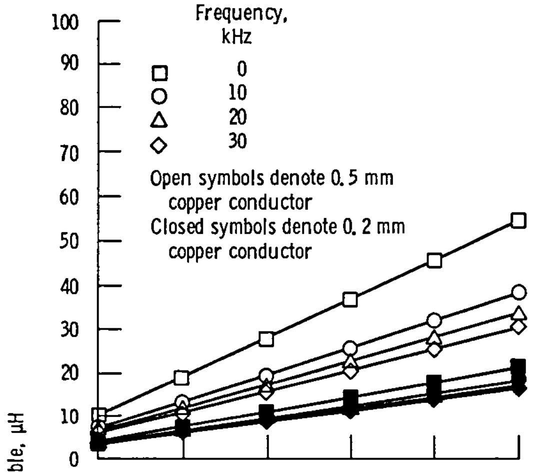


(b) Mass of stranded coaxial cable.

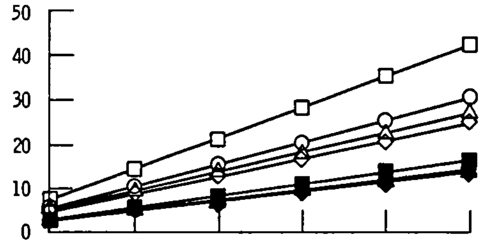


(c) Mass of parallel lines.

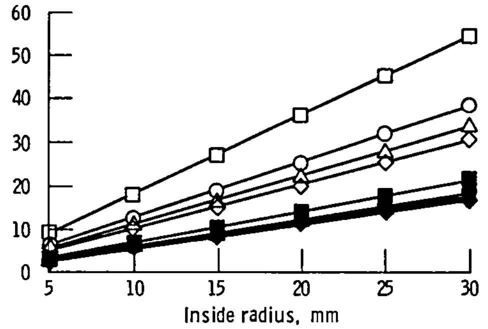
Figure 3. - Mass of copper conductor, mass of Teflon dielectric and total mass of transmission lines. Diameter of Teflon dielectric, 0.5 mm.



(a) Conductance of copper coaxial cable.



(b) Conductance of stranded coaxial cable.



(c) Conductance of parallel lines.

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

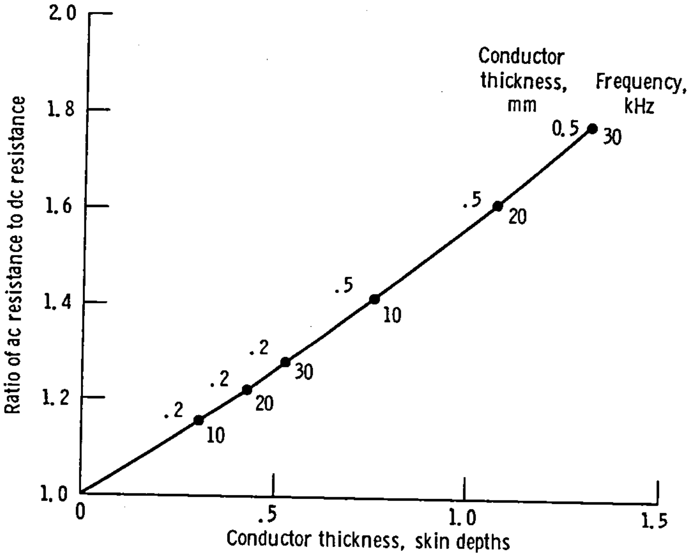
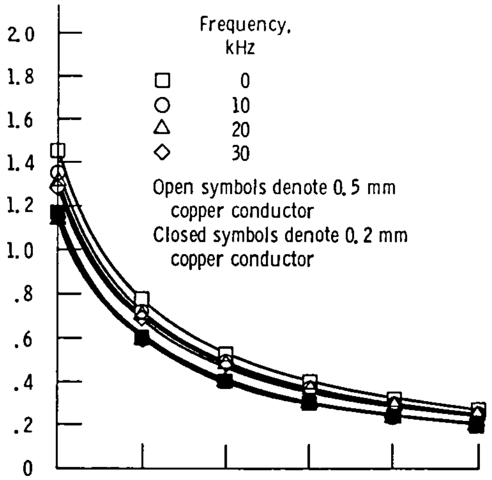
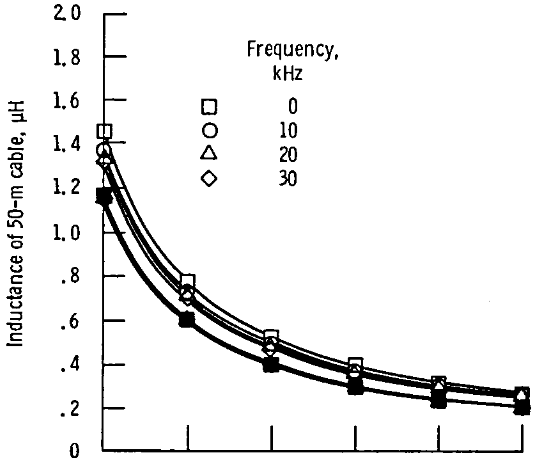


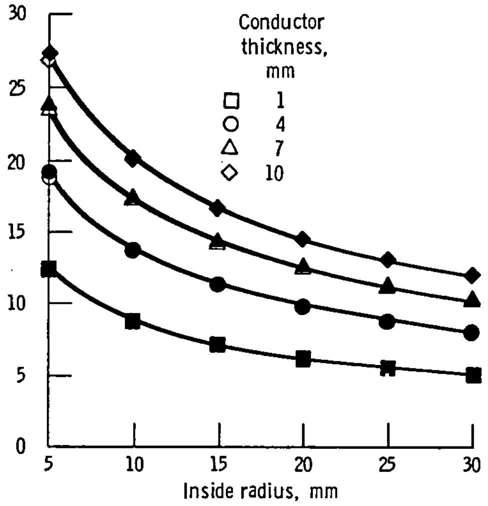
Figure 5. - Increases of ac/dc resistance ratio due to increasing conductor thickness and increasing frequency.



(a) Inductance of copper coaxial cable.

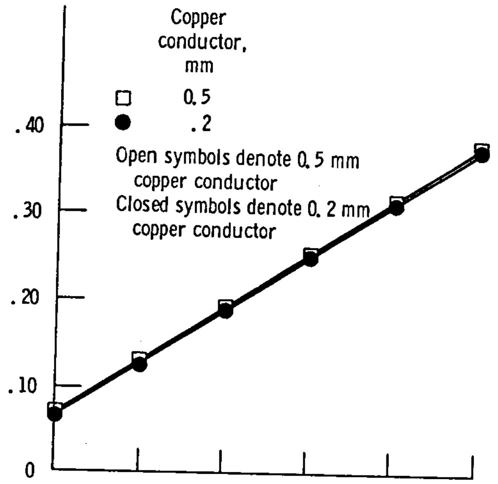


(b) Inductance of stranded coaxial cable.

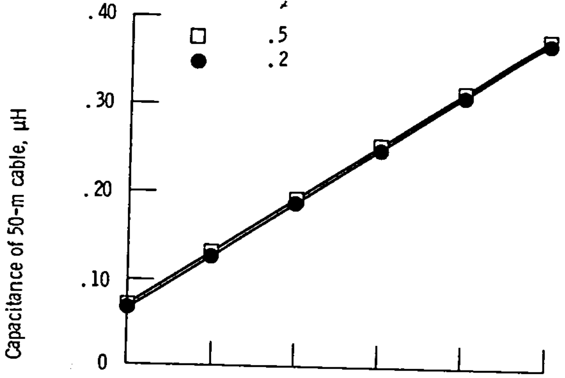


(c) Inductance of parallel lines.

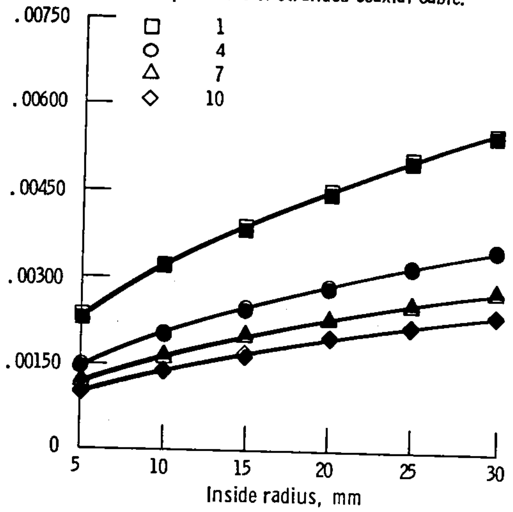
Figure 6. - Inductance of transmission lines. Diameter of Teflon dielectric, 0.5 mm.



(a) Capacitance of copper coaxial cable.

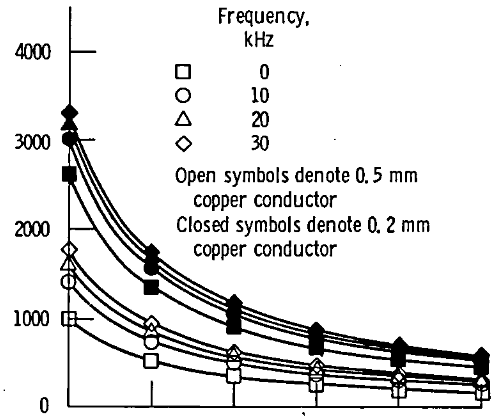


(b) Capacitance of stranded coaxial cable.

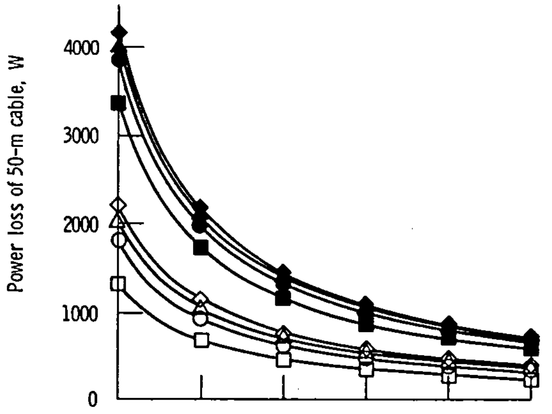


(c) Capacitance of parallel lines.

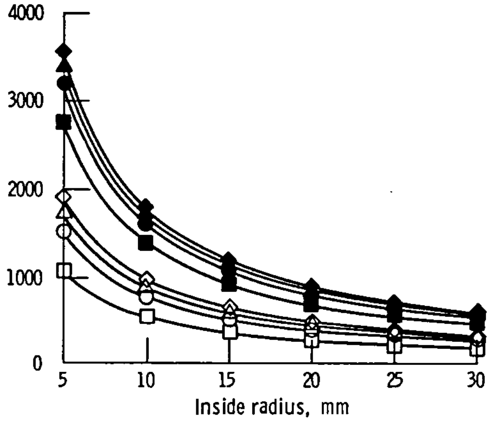
Figure 7. - Capacitance of transmission lines. Diameter of Teflon dielectric, 0.5 mm.



(a) Power loss of copper coaxial cable.

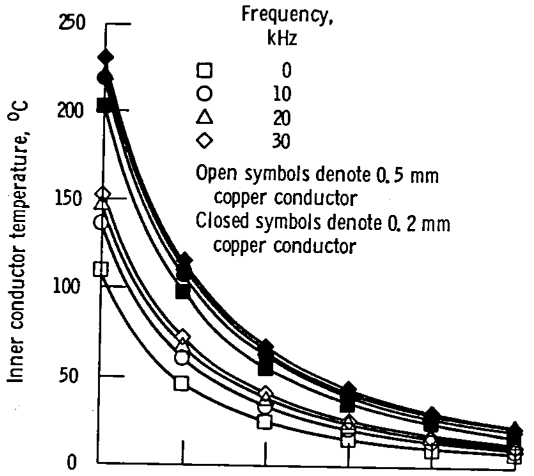


(b) Power loss of stranded coaxial cable.

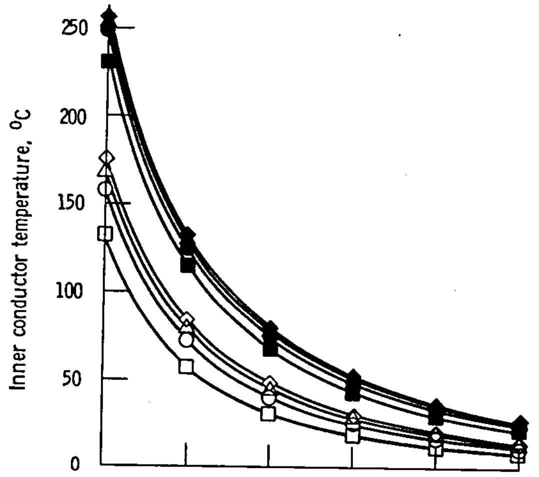


(c) Power loss of parallel lines.

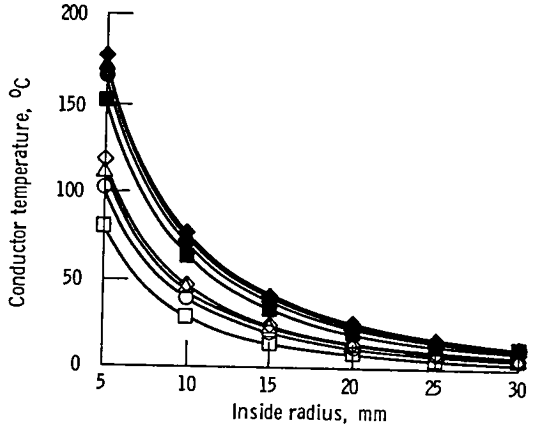
Figure 8. - Power loss of transmission lines. Diameter of Teflon dielectric, 0.5 mm.



(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.

1. Report No. NASA TM-83601	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

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

5. Report Date

March 1984

6. Performing Organization Code

506-55-72

7. Author(s)

Kent S. Jefferies and David D. Renz

8. Performing Organization Report No.

E-2013

10. Work Unit No.

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

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.

17. Key Words (Suggested by Author(s)) Electrical power; Transmission lines; High voltage; High frequency; Distribution; Analysis; Inductance; Capacitance	18. Distribution Statement Unclassified - unlimited STAR Category 20

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

SPECIAL FOURTH CLASS MAIL
BOOK

U.S. MAIL

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

NASA

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return