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COAXIAL TUBE ARRAY SPACE TRANSMISSION LINE CHARACTERIZATION

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Abstract

The coaxial tube array tether/transmission line used to connect an SP-100 nuclear power system to the space station was characterized over the range of reactor-to-platform separation distances of 1 to 10 km. Characterization was done with respect to array performance, physical dimensions, and masses. Using a fixed design procedure, a family of designs were generated for the same power level (300 kWe), power loss (1.5 percent), and meteoroid survival probability (99.5 percent over 10 yr). To differentiate between vacuum insulated and gas insulated lines, two different maximum values of the E field were considered: 20 kV/cm (appropriate to vacuum insulation) and 50 kV/cm (compressed SF6). Core conductor, tube, bumper, standoff, spacer and bumper support dimensions, and masses were also calculated. The results of the characterization show mainly how transmission line size and mass scale with reactor-to-platform separation distance.

Discussion

The space power transmission line is the element used to connect SP-100 to a space station (Fig. 1) where the combined spacecraft (platform, transmission line, and remote power system) travels as a tether-connected constellation in gravity gradient stabilized orbit. The power system occupies the superorbital position 1 to 10 km above the platform. The transmission line mechanically connects SP-100 to the platform and retains it in its remote superorbital position, conveys electrical power, and provides a reactor-platform separation such that radiation levels in the platform vicinity are reduced from instrument-safe to man-safe levels.

This transmission line isolates the nuclear power source, but carries the electrical power it produces to users aboard the platform. Key requirements are the ability to convey power with minimal loss across the distance separating the space platform from the SP-100, and to perform reliably for 10 yr in the meteoroid environment of low earth orbit. Over the range of reactor-to-platform separation distances considered (1 to 10 km), voltages on the order of several kilovolts are required. Due to the space plasma and its interaction with the spacecraft, however, conventional transmission means such as cables are not viable. This transmission line must be much different in order to isolate the high voltage power transmission from spacecraft/plasma interactions. It is therefore important to consider its construction, the methodology and constraints governing its dimensions.

The coaxial tube array, shown in Fig. 2, consists of individual tube assemblies enclosed by a common cylindrical meteoroid bumper. Multiple tube assemblies provide redundancy which results in overall system mass reductions.[1] Each tube assembly is made up of a solid rod, or core, which is located concentrically inside a jacket tube. Each coaxial tube assembly in the array forms an independent transmission circuit (Fig. 3). Cores are energized at transmission voltage and carry power from the source to the spacecraft. The jacket tube serves as a ground return and provides gaussian isolation of the power system high voltage (inside the tethered spacecraft) from spacecraft/plasma interactions outside.

Array dimensions are governed primarily by transmission voltage (determined by allowable line losses) and by the level of meteoroid survival probability desired. Voltage isolation is accomplished by the coaxial gap between the core and jacket. Standoff capability of this gap depends on the maximum voltage gradient, or E field, which is related to the coaxial parameters by:

$$E = \frac{V}{r \ln\left(\frac{r_2}{r_1}\right)}$$

where

- r the radius from the assembly center to a specified point within the annular gap
- r_1 core radius
- r_2 jacket tube inner radius
- V potential between core and jacket

The maximum field that must be withstood obviously occurs at the surface of the core

$$E\Big|_{r=r_1} = \frac{V}{r_2} * \frac{1}{\left(\frac{r_1}{r_2}\right) \ln\left(\frac{r_2}{r_1}\right)}$$

This field then possesses a minimum value when $\ln(r_2/r_1) = 1$ which relates r_2 to r_1. The thickness of the tube is determined from the requirement (current continuity) that the core and jacket cross sections be equal. Cross section is a function of power, voltage, acceptable transmission loss, conductor materials properties, and meteoroid penetration resistance. If a jacket tube is punctured by meteoroids it is permanently disabled; therefore it must have sufficient wall thickness for penetration resistance as well as electrical conductivity.

The bumper is a sacrificial wall which reduces the possibility of tube penetration. This thin wall serves to break up and disperse the incoming meteoroid into a cloud of molten droplets and smaller fragments which then impact the tube wall over a wide area instead of a single point. Penetration resistance can be increased by either thickening the bumper wall or increasing the gap between the bumper and the tube. Redundant tubes are used to give the transmission line a larger chance of surviving a hit. If three tubes are used, two tubes could be hit over the 10 years and the transmission line can still deliver power.

The designer's task is to meet the conflicting requirements with minimum mass. Due to the geometric relationship previously stated, tube assembly dimensions and characteristics can be expressed as functions of the jacket wall thickness only. This allows straightforward comparison to be made between electrical transmission requirements versus meteoroid survival probability. The design process typically begins by choosing the highest E field, or voltage gradient, that can be allowed within a tube assembly, then calculating the dimensional parameters (tube size, area at risk) and the electrical parameters (voltage, round trip resistance, dc line loss) as a function of wall thickness.

A computer program was developed to facilitate the design process and provide characterization. For a given allowable gradient, line length, and power per tube the program calculated line voltage, percent power loss, and area at risk for a range of wall thicknesses. From this array of choices a design could be selected that gave a reasonable round trip percent power loss, mass per tube, and small surface area at risk.

The design process continues with meteoroid survival considerations. A survival probability of 99.5 percent would be needed if the array used only one tube. But if three redundant tubes are used, there only needs to be an 85 percent survival probability on an individual tube for a 99.5 percent probability that at least one out of the three lines will survive.

The mass of the largest meteoroid which the tube must resist during the 10 yr of expected life needs to be found next. The mass of the meteoroid is found by finding N_t, the number of particles of mass m or greater per square meter per second. This is done using the following equation with P being the probability needed per tube.

$$P(\text{n or fewer strikes}) = \sum_{r=0}^{r=n} \frac{e^{-N_t AT}(N_t AT)^r}{r!}$$

where

A area at risk
T time in seconds
n is zero in this case since no strikes are allowed

Once N_t is found then the mass of the largest possible meteoroid can be found using

$$\text{Log } N_t = -14.37 - 1.213 \text{ Log } m$$
(does not account for space debris)

This is the largest meteoroid the array would be expected to encounter during its life, and the largest one it must resist. Penetration resistance is designed into the array by choosing bumper thickness and gap according to the following empirical method: the mass of the meteoroid is converted to an equivalent aluminum sphere of diameter D. A graph is entered next, which relates penetration resistance of a two sheet aluminum barrier to the bumper and tube wall construction of the array. The graph (Fig. 4) is an experimentally determined penetration relation for aluminum projectiles fired into aluminum sheets (Fig. 47)[2] and it is used to determine the thickness of the bumper wall and the minimum bumper to wall separation. The first sheet of aluminum, T1, is the bumper, the space, S1, between the two sheets is the bumper separtion gap, and the second sheet, T2, is equivalent to the tube wall. To minimize the weight of the tube array it is best to stay as close as possible to the diagonal line for minimum T1/D + T2/D. Once the bumper thickness and diameter have been established, the mass of the array itself can be calculated depending on how many redundant coaxial tubes are used.

Further characterization of the transmission line considers the dielectric spacers, sleeves, and bumper spacers (Fig. 5). The purpose of the dielectric spacers are two-fold. The first is to help prevent arcing between the core and the jacket wall and secondly to keep the core centered in the jacket. A spring steel sleeve is used between the two rows of beads to hold them tight against the wall and core. There is one spring steel sleeve for every six beads. The dielectric spacers are made of glass and their length is twice their diameter. The spring steel sleeve is twice the length of the dielectric spacers; for the 300 kWe design it is 0.254 mm thick. The bumper spacers keep the three coaxial tubes in proper position. The bumper spacers are 0.72 mm thick; they are made from aluminum 6061-T6.

Longitudinal spacing for dielectric spacer and bumper spacers is found by looking at a worst case bend for the tether (90°). The dielectric spacer interval is calculated by finding the radius of curvature, and spacing the dielectric spacers just far enough apart so that the core does not deflect more than one-third the minimum gap distance. The bumper spacers interval is found the same way except the coaxial tubes can deflect half the distance between the bumper and the tubes.

The mass added onto the tether from the spacers and sleeves is negligible compared to the mass of the tether itself. The computer program developed to perform these calculations outputs all needed dimensions, numbers of items, and masses of the spacers and sleeves.

Results and Summary

The design procedure was exercised over a range of distances from 1 to 10 km, for a 99.5 percent probability of one out of the three tubes surviving 10 yr. All designs have a 300 kW power level and a nominal 1.5 percent power loss. Two values of the voltage gradient were considered; 20 kV/cm, appropriate for the vacuum insulation, and 50 kV/cm, comparable to pressurized SF6. Table I compares the mass, tube diameters, area at risk, and the amount of spacers needed for the coaxial array at these gradients over a variety of separation distances from 1 to 10 km. Figure 6 compares the cross section of two 10 km tether/transmission lines, notice the difference in tube size as the gradient is changed. Figure 7 compares a 1 km and 10 km tether at 50 kV/cm. Of most interest to the system designer is a summarization of mass versus separation distance which is presented in Fig. 8.

A definite difference can be seen between the 20 and the 50 kV/cm line. The bumper diameter does not change very much between the two gradients, but the tube diameter size of the 50 kV/cm line is reduced to about two-thirds the diameter of the 20 kV/cm line. Using the higher voltage gradient the mass of the line was roughly cut in half. Longer lines are heavier per unit length; using the higher voltage gradient allows for lighter lines.

References

1. D.J. Bents: "Tethered Nuclear Power for the Space Station." NASA TM-87023, 1985 IECEC, Miami.

2. J.F. Lundeberg, P.H. Stern, and R.J. Bristow: "Meteoroid Protection for Spacecraft Structures." Boeing Co., Seattle, WA, D2-24056, Oct. 1985. (NASA CR-54201.)

TABLE I. - COAXIAL TUBE ARRAY CHARACTERISTICS AT SELECTED SEPARATION DISTANCES

	20 kV/cm					50 kV/cm				
Length, km	1	3	5	8	10	1	3	5	8	10
Assembly mass, kg	364	1937	4257	8751	12 783	182	969	2187	4743	6530
Tube od, mm	13.7	17.7	20.1	22.5	24.1	8.9	11.3	12.9	14.5	15.3
Wall thickness, mm	0.84	1.1	1.24	1.4	1.5	0.54	0.7	0.8	0.9	0.94
Bumper diameter, mm	80	117	144.5	176.5	200	83.5	123	151	192.6	218.6
Bumper thickness, mm	0.118	0.16	0.19	0.204	0.22	.09	0.12	0.14	0.163	0.16
Area at risk, m^2	43	167	316	566	758	28	106	202	364	480
Volts, kV	4.7	6.1	7	7.8	8.4	7.7	9.8	11.2	12.6	13.3
Number of beads	1619	2491	3051	3647	3939	2012	3131	3785	4549	5158
Number of sleeves	269	415	508	607	656	335	521	630	758	859
Number of bumper spacers	151	201	225	248	255	120	166	190	208	216
Distance between beads, m	3.7	7.2	9.8	13.2	15.2	3.0	5.75	7.93	10.6	11.6
Distance between bumper spacers, m	6.6	14.9	22.2	32.2	39.1	8.3	18.0	26.2	38.4	46.1

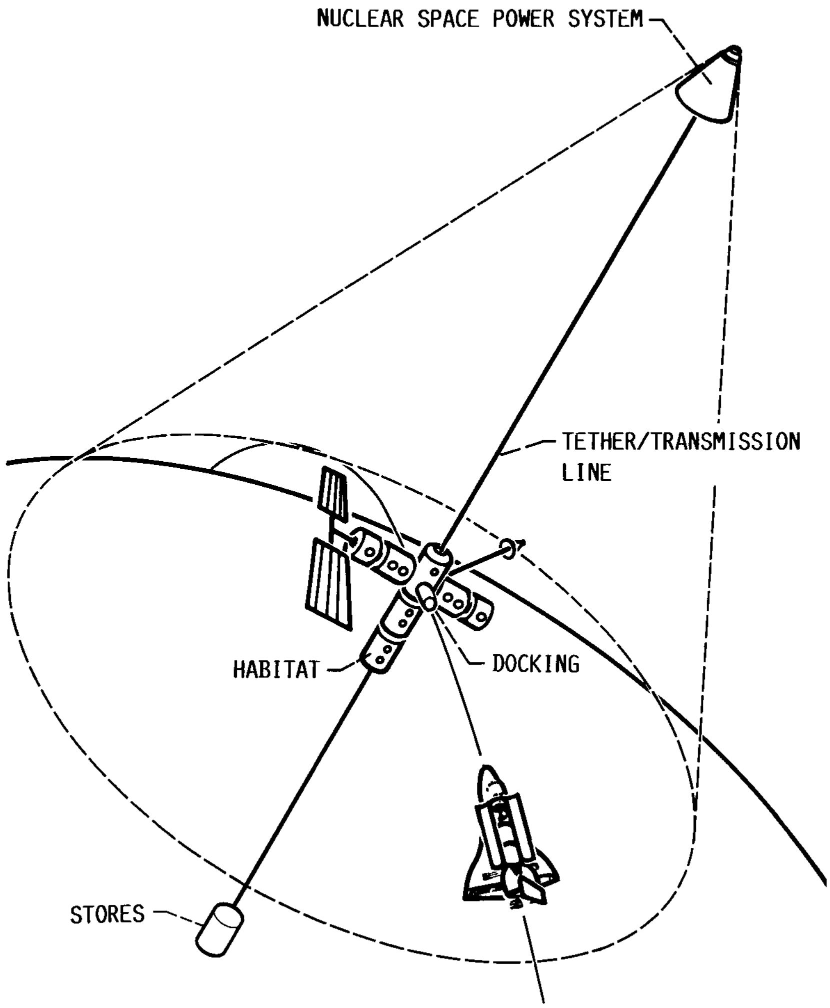


FIGURE 1. - SPACE STATION POWERED BY TETHERED NUCLEAR SYSTEM.

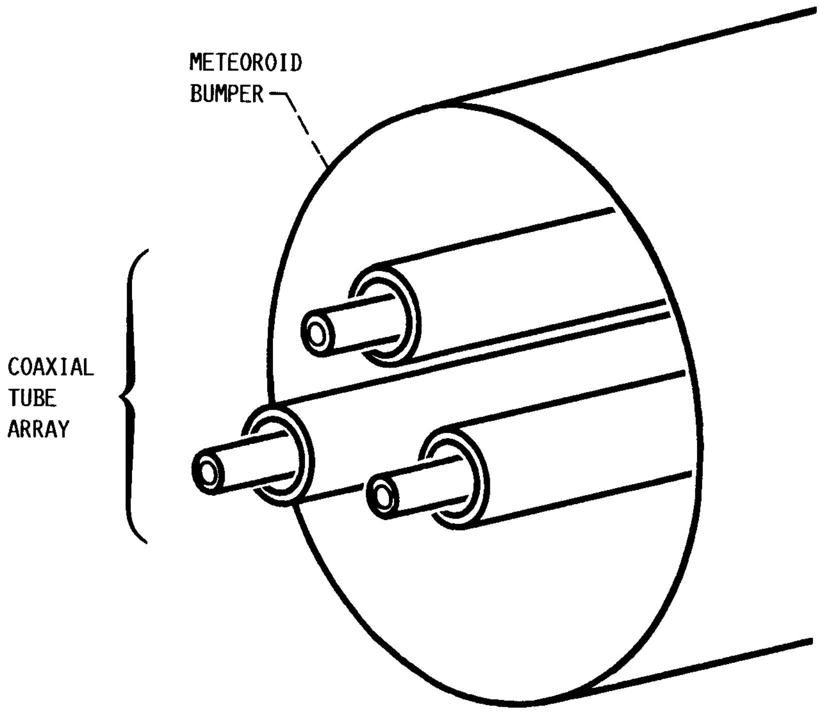


FIGURE 2. - SPACE TRANSMISSION LINE.

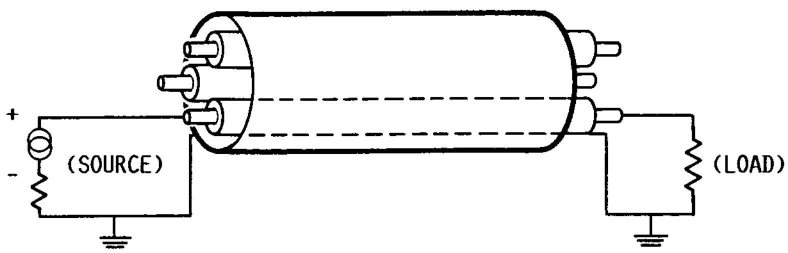


FIGURE 3. - SOURCE TO LOAD CONNECTION WITH COAXIAL TUBES. (3 TUBE ARRAY, 1 OUT OF 3 CIRCUITS SHOWN.)

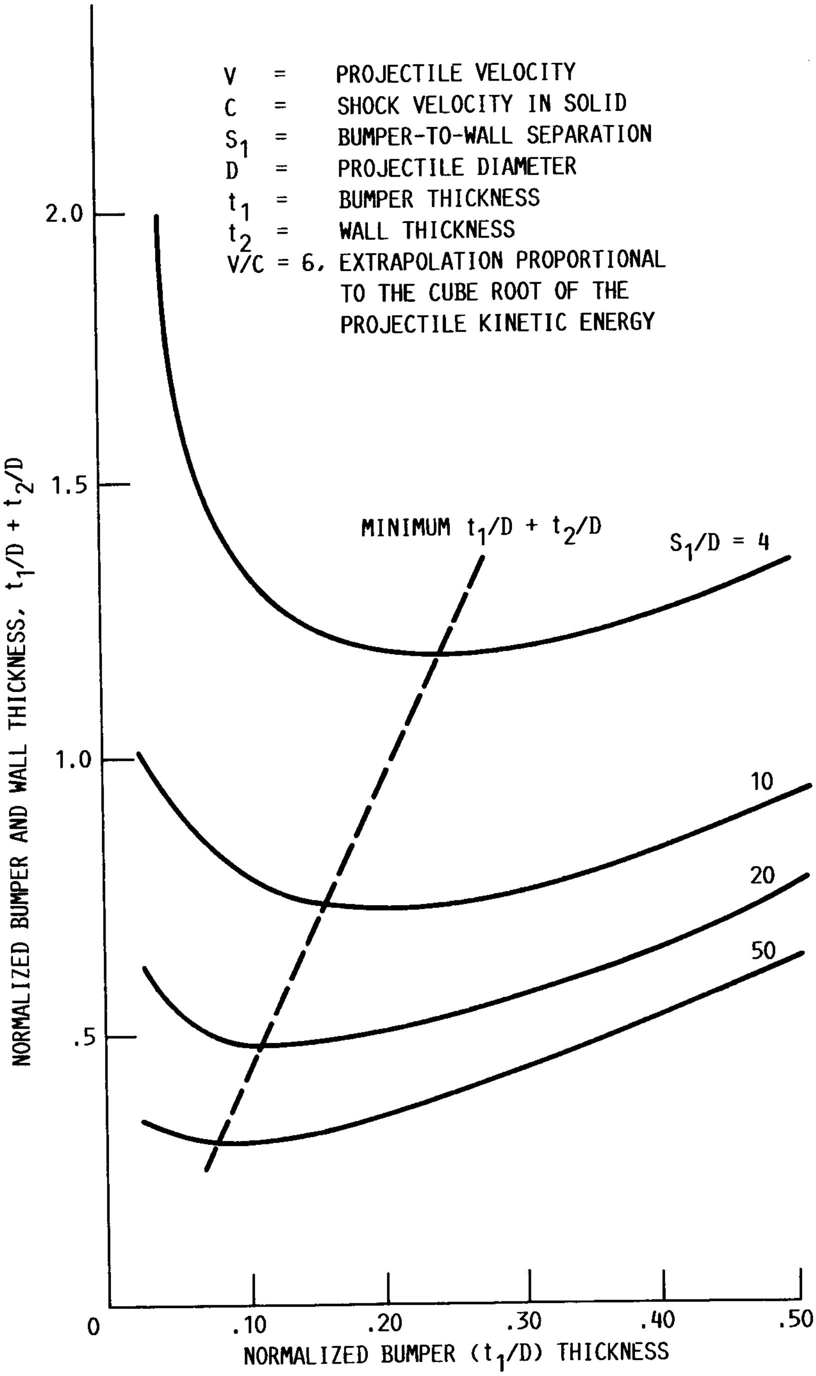


FIGURE 4. - MINIMUM WEIGHT TWO-SHEET BARRIER TO PREVENT PENETRATION.

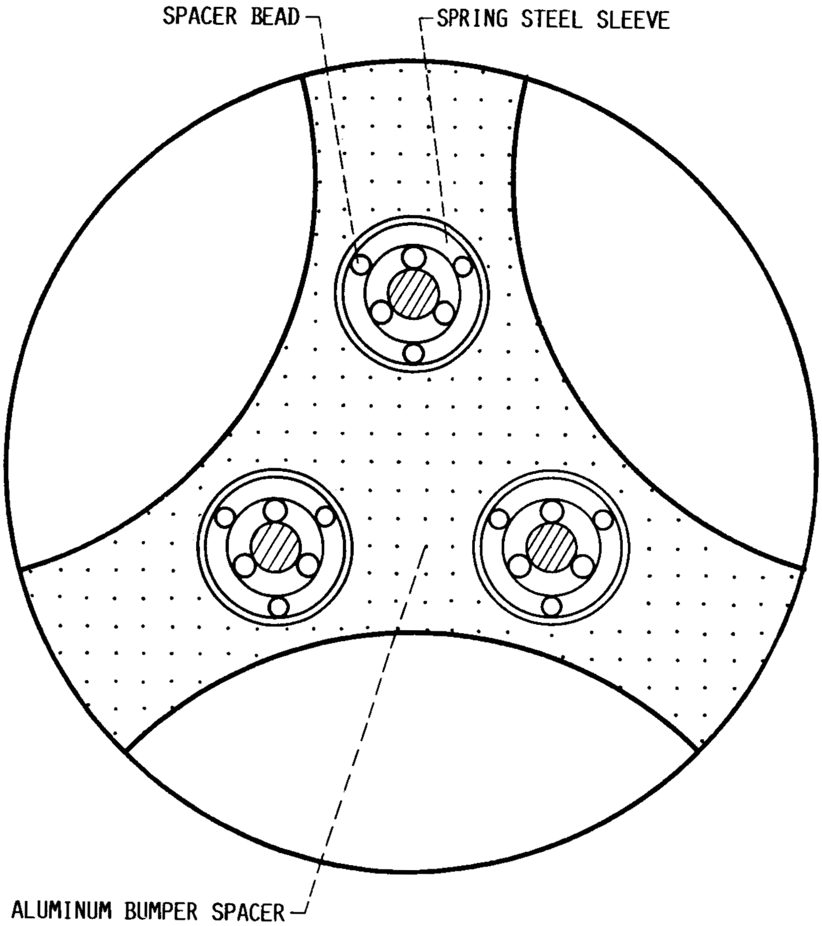
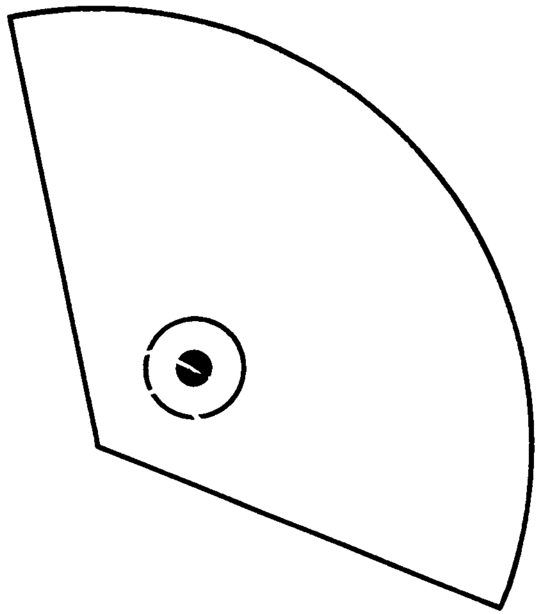


FIGURE 5. - TRANSMISSION LINE/TETHER CROSS SECTION.

TRANSMISSION LINE LENGTH:	10 KM
POWER LEVEL (ALL TUBES OPERATING)	0.3 MWE
PERCENT POWER LOSS ALLOWED:	1.5%
VOLTAGE GRADIENT ALLOWED:	20 KV/CM
RELIABILITY	
METEROID SURVIVAL PROBABILITY	99.5%
NUMBER OF YEARS	10 YR

VOLTS = 8.4 KV

DIMENSIONS, MM	
OD	24.1
TUBE	
ID	22.6
OD	8.31
CORE	
ID	SOLID
THICKNESS	0.22
BUMPER	
DIAMETER	200
MIN. GAP	60

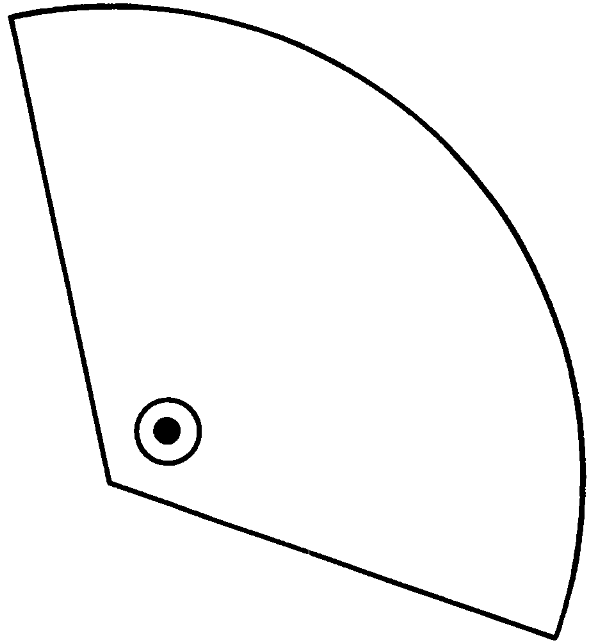


AREA AT RISK (EACH TUBE)	758 M^2
METEROID MASS (ARMORED AGAINST)	15.3 MG
TRANSMISSION LINE MASS (TUBES AND BUMPER)	12 774 KG

TRANSMISSION LINE LENGTH:	10 KM
POWER LEVEL (ALL TUBES OPERATING)	0.3 MWE
PERCENT POWER LOSS ALLOWED:	1.5%
VOLTAGE GRADIENT ALLOWED:	50 KV/CM
RELIABILITY	
METEROID SURVIVAL PROBABILITY	99.5%
NUMBER OF YEARS	10 YR

VOLTS = 13.3 KV

DIMENSIONS, MM	
OD	15.3
TUBE	
ID	14.36
OD	5.28
CORE	
ID	SOLID
THICKNESS	0.16
BUMPER	
DIAMETER	218.6
MIN. GAP	84



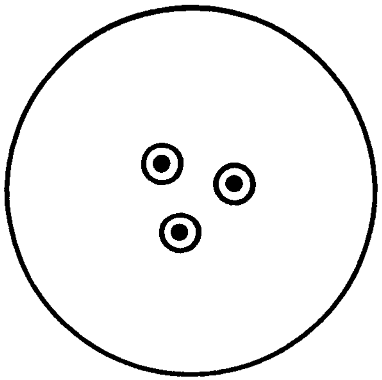
AREA AT RISK (EACH TUBE)	480 M^2
METEROID MASS (ARMORED AGAINST)	10.5 MG
TRANSMISSION LINE MASS (TUBES AND BUMPER)	6523 KG

FIGURE 6. - COAXIAL TUBE ARRAY CROSS SECTIONS, 10 KM SEPARATION DISTANCE, V = 20 KV/CM AND 50 KV/CM.

TRANSMISSION LINE LENGTH:	1 KM
POWER LEVEL (ALL TUBES OPERATING)	0.3 MWE
PERCENT POWER LOSS ALLOWED:	1.3%
VOLTAGE GRADIENT ALLOWED:	50 KV/CM
RELIABILITY	
METEROID SURVIVAL PROBABILITY	99.5%
NUMBER OF YEARS	10 YR

VOLTS = 7.7 KV

DIMENSIONS, MM	
OD	8.9
TUBE	
ID	8.36
OD	3.08
CORE	
ID	SOLID



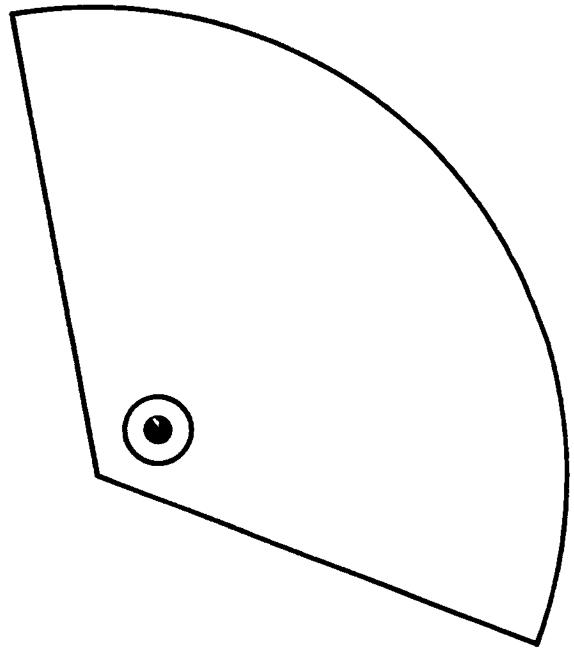
THICKNESS	0.09
BUMPER	
DIAMETER	83.5
MIN. GAP	27

AREA AT RISK (EACH TUBE)	28 M^2
METEROID MASS (ARMORED AGAINST)	1.008 MG
TRANSMISSION LINE MASS (TUBES AND BUMPER)	181 KG

TRANSMISSION LINE LENGTH:	10 KM
POWER LEVEL (ALL TUBES OPERATING)	0.3 MWE
PERCENT POWER LOSS ALLOWED:	1.5%
VOLTAGE GRADIENT ALLOWED:	50 KV/CM
RELIABILITY	
METEROID SURVIVAL PROBABILITY	99.5%
NUMBER OF YEARS	10 YR

VOLTS = 13.3 KV

DIMENSIONS, MM	
OD	15.3
TUBE	
ID	14.36
OD	5.28
CORE	
ID	SOLID



THICKNESS	0.16
BUMPER	
DIAMETER	218.6
MIN. GAP	84

AREA AT RISK (EACH TUBE)	480 M^2
METEROID MASS (ARMORED AGAINST)	10.5 KG
TRANSMISSION LINE MASS (TUBES AND BUMPER)	6523 KG

FIGURE 7. - COAXIAL TUBE ARRAY CROSS SECTIONS, V = 50 KV/CM, SEPARATION DISTANCE = 1 KM AND 10 KM.

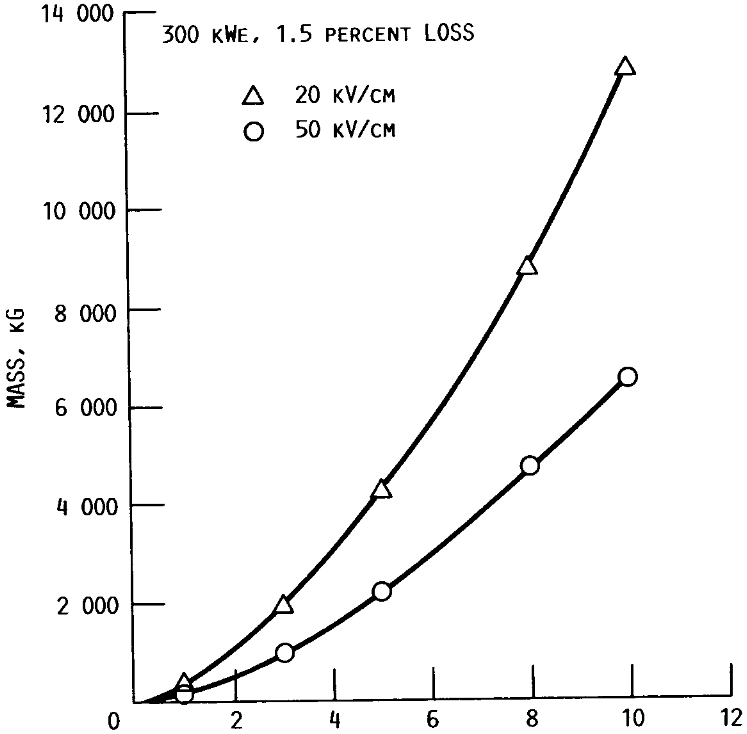


FIGURE 8. - MASS VERSUS LENGTH TRADEOFF FOR COAXIAL TUBE ARRAY.

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