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N79-24028

SPACE ENVIRONMENTAL EFFECTS AND THE SOLAR POWER SATELLITE

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ABSTRACT

This report summarizes some preliminary findings regarding the interactions between the space plasma at GEO and the Marshall Space Flight Center January 1978 baseline SPS design. These include the following:

1. The parasitic load will be dominated by photoelectrons and will amount to about 34 MW.

2. Material of higher conductivity than kapton should be used for the solar reflector substrate and the solar cell blanket support material.

3. The satellite structure and solar reflector should be tied electrically to midpoint voltage of each solar cell array.

4. Tests should be run on the proposed solar cell cover glass material (synthetic sapphire) to determine if breakdown is expected.

INTRODUCTION

Figure 1 illustrates the basic concept of the solar power satellite. A large area solar cell array converts sunlight into D.C. electricity. This is in turn converted to microwaves via klystrons. The 1 km diameter microwave antenna directs the beam from the geosynchronous orbit satellite to a receiving antenna on the ground. The receiving antenna (called a rectenna) consists of a large array of dipoles, rectifying diodes and filters whose output is D.C. electricity suitable for conversion to A. C. distrbution to a power grid.

The area of the solar cell array is about 50 km^2 for a 5GW output satellite. If solar concentrating reflectors are used the solar cell surface area may be reduced.

The Rice University study is concerned with the NASA Marshall Space Flight Center SPS baseline design as of January

1978. The purpose of the study is to investigate and make design recommendations regarding satellite charging due to geostationary orbit ambient plasmas.

The study involves the following steps:

1. Define the "worst case" plasma environment.
2. Calculate probable voltages at critical points on the satellite.
3. Identify vulnerable areas.
4. Suggest design changes where necessary.
5. Calculate the probable new voltages after design changes.
6. Calculate the parasitic current loads.

Based on a search of the literature and data we have selected the following "worst case" conditions for the plasma sheet at geosynchronous orbit:

$$kT\ (\text{electrons}) = 5\ \text{kev}$$

$$kT\ (\text{protons}) = 10\ \text{kev}$$

$$n_e = n_p = 2\ \text{cm}^{-3}$$

These are not the absolute worst case conditions found but they are typical of a severe substorm and should be adequate to indicate out trouble spots in the spacecraft design.

Figure 2 illustrates the MSFC baseline design used in our study. This design employs solar reflectors to concentrate the sunlight on the solar cells. The concentration ratio is 2. The solar reflectors are the sides of the troughs shown in arrays of three at each end of the satellite. The solar cell blankets are suspended by cables at the floor of each of the troughs in a trampoline fashion. The solar cells are connected in parallel across the trough and in series along the trough so that each pair of blankets puts out about 6000 amps at 45.5KV. There are six such pairs on each of the six troughs.

CURRENTS

Our first task was to compute the plasma thermal currents and photoelectron currents to the solar cell array. In treating the plasma electron and ion currents we assumed a thin sheath approximation, ie. that the collecting area was the area of solar cell array (front and back) and that positive ions would be attracted to the negative portion of the array and electrons to the positive. We assumed that the photoelectron current from the negative array would be the expected photoelectron current density times the array area. The photoelectron current density was obtained by integrating the product of the photoelectron yield function for synthetic sapphire and the solar spectrum. The resulting photocurrent density is 3×10^{-9} amp/cm^2. For the positive array, we assumed that the solar reflectors would supply a bath of photoelectrons which would be attracted to the positive array. Since the subtended area of the solar reflector adjacent to the solar array is about the same as that of the array the photoelectron current is taken to be the current density times the array area. Figure 3 illustrates the photoelectron paths and gives the current densities. The photoelectron current is found to dominate the thermal ion and electron currents both of which are given by

$$J = \frac{ne}{4} \sqrt{\frac{8kT}{\pi m}}$$

where n, T and m are the number density, temperature and mass of the ions or electrons, and k and e are the Boltzman constant and electron charge, respectively. The resulting parasitic current, I_p, mostly photoelectrons, is about 3000 amps. Assuming the midpoint of the solar array is grounded to the solar reflector, the average voltage above and below ground $\bar{V}$ is 11,375 volts. The parasitic load is therefore

$$P_p = I_p \bar{V} = 34 \text{ MW}$$

This is about 0.7% of the 5 GW output.

SOLAR CELL SURFACE VOLTAGES

Turning to the voltages developed on the satellite, we decided at the outset that the solar cells were probably the single most vulnerable item on the satellite because they are exposed solid state devices. Figure 4 shows the design of the GaAlAs Solar Cell being considered for the MSFC Baseline design. This cell is an inverted design with synthetic sapphire forming both the cover glass and substrate. The sapphire is 20 micrometers thick. The cell is supported by a 25 micrometer kapton blanket.

For our purposes the cell is idealized as a sapphire, active region, Kapton sandwich (see Figure 5). The voltages across the sapphire and Kapton dielectrics are then the IR drops resulting from the photoelectron and plasma thermal currents times the resistance of the dielectrics. These voltages are shown in Figure 5. The assumed resistivities of sapphire and kapton are 10^{12} ohm-cm and 10^{16} ohm-cm respectively. The largest voltage is that across the kapton blanket on the positive array. This may exceed the breakdown voltage for kapton, 2×10^6 V/cm.

THE OPTIMUM GROUNDING POINT

To calculate the floating potential for the solar cell array (defined as the point on the series voltage string closest to the plasma potential) we require that, at equilbrium, the sum of all currents between the satellite and the plasma be zero. We calculate this sum by adding the currents to the positive and negative areas of the array, A^+ and A^-

$$A^-(J_{phe} + 2J_i) = A^+(J_{phe} + 2J_e)$$

ignoring the metallic solar reflectors. Here J_{phe}, J_i and J_e are the photoelectron, ion and electron current densities. This yields

$$\frac{A^-}{A^+} = 1.17$$

Ideally, the negative area (and hence voltage string) should be 17% larger than the positive surface. We do not consider the calulation to have 17% precision, however. We recommend grounding the midpoint of each voltage string to the satellite structure and the solar reflectors.

It might be argued that the photoelectrons, J_{phe}, are not part of the spacecraft-magnetospheric plasma current loop and therefore should not be included in the current balance equation. We believe that a substantial fraction of the photoelectrons will escape to space and that their inclusion is therefore appropriate. In calculating the electric potentials of bodies in space it is accepted practice to include the photoelectron currents (eg. Whipple, 1965; Manka, 1973). Moreover, estimates of the electric potential of the lunar surface can only be made to agree with the experimental values when photoelectron emission is included (Freeman and Ibrahim, 1975; Freeman, Fenner and Hills, 1975).

The floating potential will change with time but will probably tend to equilibrate about the midpoint on the voltage string so this is probably a good choice as a practical matter (L.W. Parker, private communication).

VOLTAGES ON PASSIVE SURFACES

We estimate the voltage, ϕ, on the darkside passive (unbiased) surfaces of the satellite using Chopra's equation (Chopra, 1961)

$$\phi \equiv - \frac{kT_e}{2e} \ln \left[\frac{M_i T_e}{M_e T_i} \right]$$

For the sunlit surfaces, the potential is several times the mean photoelectron energy. Thus, we expect +10 to +100 volts for the sunlit surfaces and -10,000 to -20,000 volts for the darkside surfaces. The backside of the solar reflectors are 1/2 mil kapton whose breakdown voltage should be less than 2500 volts. Thus, arcing is to be expected on the backside of the solar reflectors. Figure 6 summarizes these voltages at various points on the satellite.

THE SHEATH THICKNESS

Because of the high voltage biases produced by the solar cells the appropriate sheath is a Child-Langmuir sheath given by (Langmuir, 1914)

$$J = \frac{1}{9\pi} \left(\frac{2e}{m_e} \right)^{1/2} \frac{V^{3/2}}{d^2}$$

If we take J to be the plasma electron thermal current given by

$$J = \frac{en}{4} \left(\frac{8kT}{\pi m} \right)^{1/2}$$

we have for the sheath thickness

$$d = 933\ n^{-1/2}\ (kt)^{-1/4}\ V^{3/4}$$

d is in cm; n, electrons cm^{-3}; kt in eV and V in volts. This is the expression given by Parker (this volume) except for the deletion of his term which corrects for a significant ram current. The ram current due to satellite motion through the medium is negligible because the thermal plasma and the satellite both co-rotate at the same velocity. Plasma flows from the geomagnetic tail are ignored here.

Figure 7 is a sketch showing the dimensions of the Child-Langmuir sheath. Note that it is of the order of the width but not length dimensions of the satellite. Our earlier thin sheath approximation is valid only to within factors of unity.

CONCLUSIONS

At this point in the study, our conclusions are as follows:

1. Voltage breakdown will occur on the solar reflector backsides and probably on the solar cell kapton support blanket.
2. The parasitic load will be dominated by photoelectrons and will amount to about 34 MW (for GEO only).
3. The optimum ground point to the structure and solar reflectors is the middle of each solar cell voltage string ie. we want +22.75KV to -22.75KV.
4. Tests should be run on the solar cell front face in a substorm test facility to see if conductive cover glasses should be used.

ACKNOWLEDGEMENTS

We would like to acknowledge helpful discussions with Dr. L.W. Parker. This research was supported by the Marshall Space Flight Center and The Brown Foundation.

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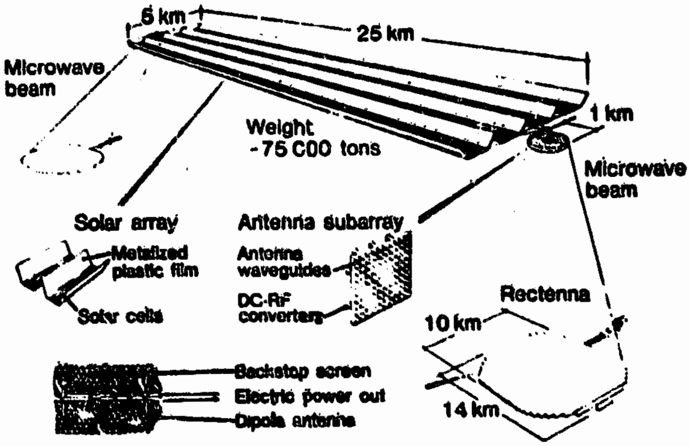

Figure 1. - Typical SPS configuration (2x5000 MW output).

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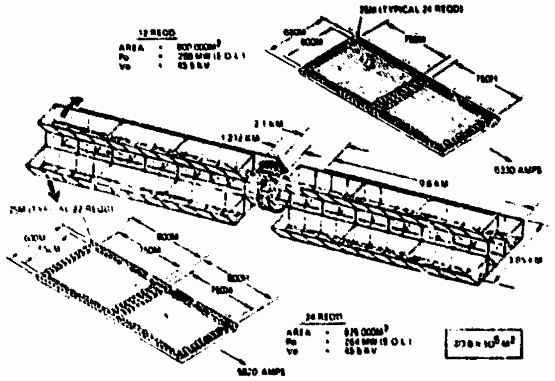


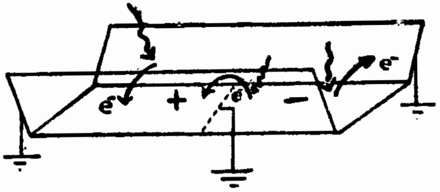
Figure 2. - Marshall Space Flight Center baseline design.

THE VARIOUS CURRENT DENSITIES ARE:

$J_{PHE} = 5 \times 10^{-9}$ AMP/CM^2 (FOR SAPPHIRE)

J_i (PLASMA) $= 3 \times 10^{-10}$ AMP/CM^2

J_i (PLASMA) 1×10^{-11} AMP/CM^2



PHOTOELECTRON FLOW DIRECTIONS

TOTAL PARASITIC CURRENT:

$I_p \cong 3000$ AMPS

$\bar{V} = 11,375$ V

THE PARASITIC POWER IS:

$P_p \cong 34$ MW

(0.7% OF OUTPUT POWER)

Figure 3. - Photoelectron paths and current densities.

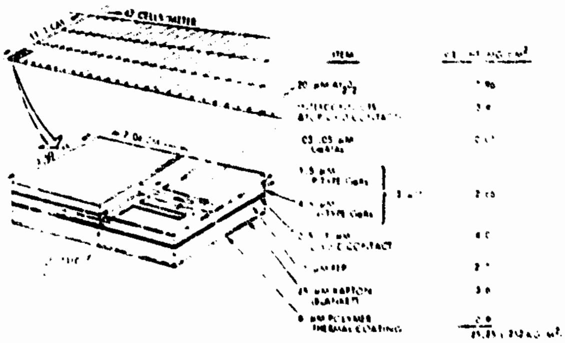
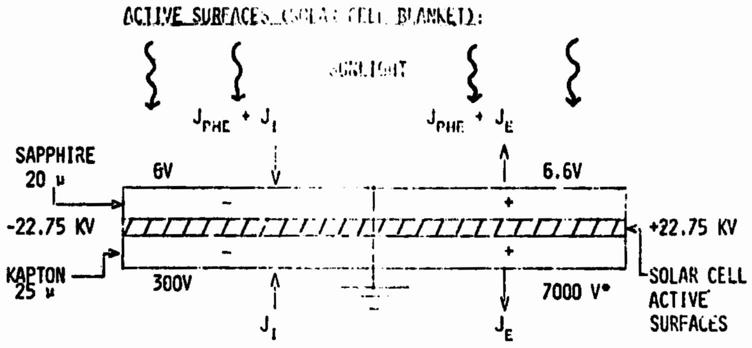


Figure 4. - Cross section of GaAlAs solar cell blanket.



VOLTAGES SHOWN ARE RELATIVE TO THE LOCAL SOLAR CELL VOLTAGE. THEY REPRESENT THE IR DROP ACROSS THE COVER GLASS OR KAPTON BLANKET.

- THE KAPTON BREAKDOWN VOLTAGE IS ~ 5000 V

Figure 5. - Schematic of solar cell.

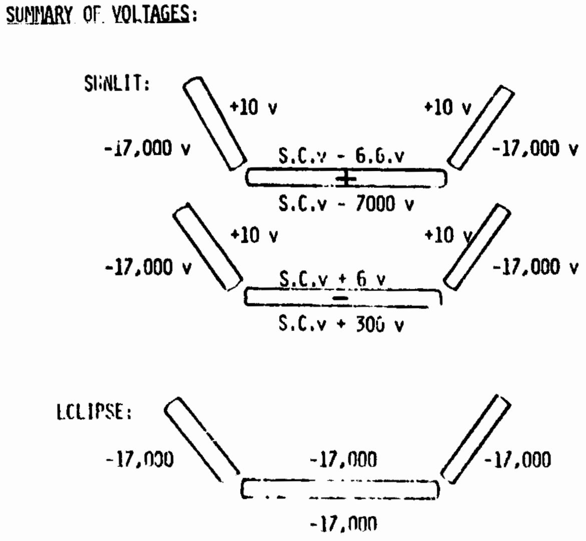


Figure 6. - Summary of voltages on satellite passive surfaces.

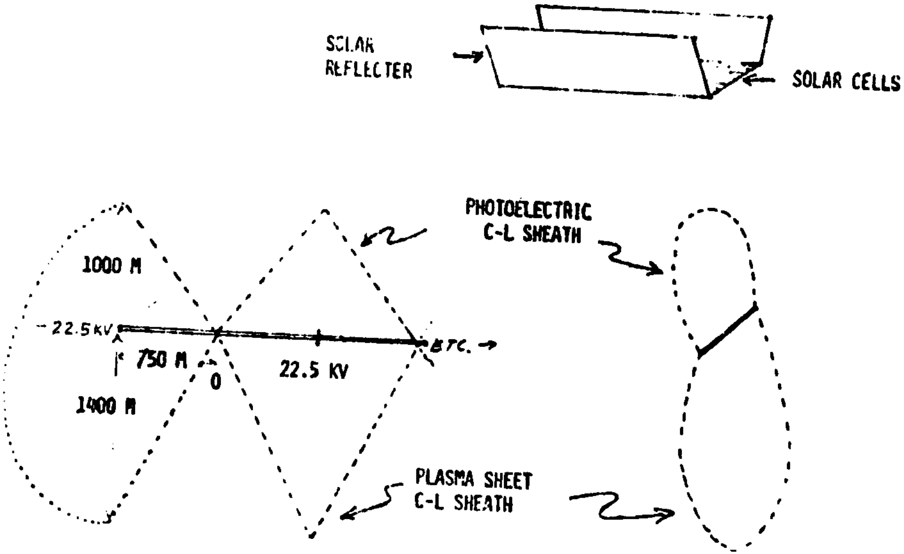


Figure 7. - One-dimmensional Child-Langmuir sheath shape for one trough in MSFC SPC design.