ELECTRICAL POWER LOSS FROM HIGH-VOLTAGE POWER CIRCUITS THROUGH PLASMA LEAKAGE

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SOLAR POWER SATELLITE (Figure 1)

The phenomenon of power leaking through plasma can best be explained by considering a solar power satellite which would have a large high-voltage solar-cell array.

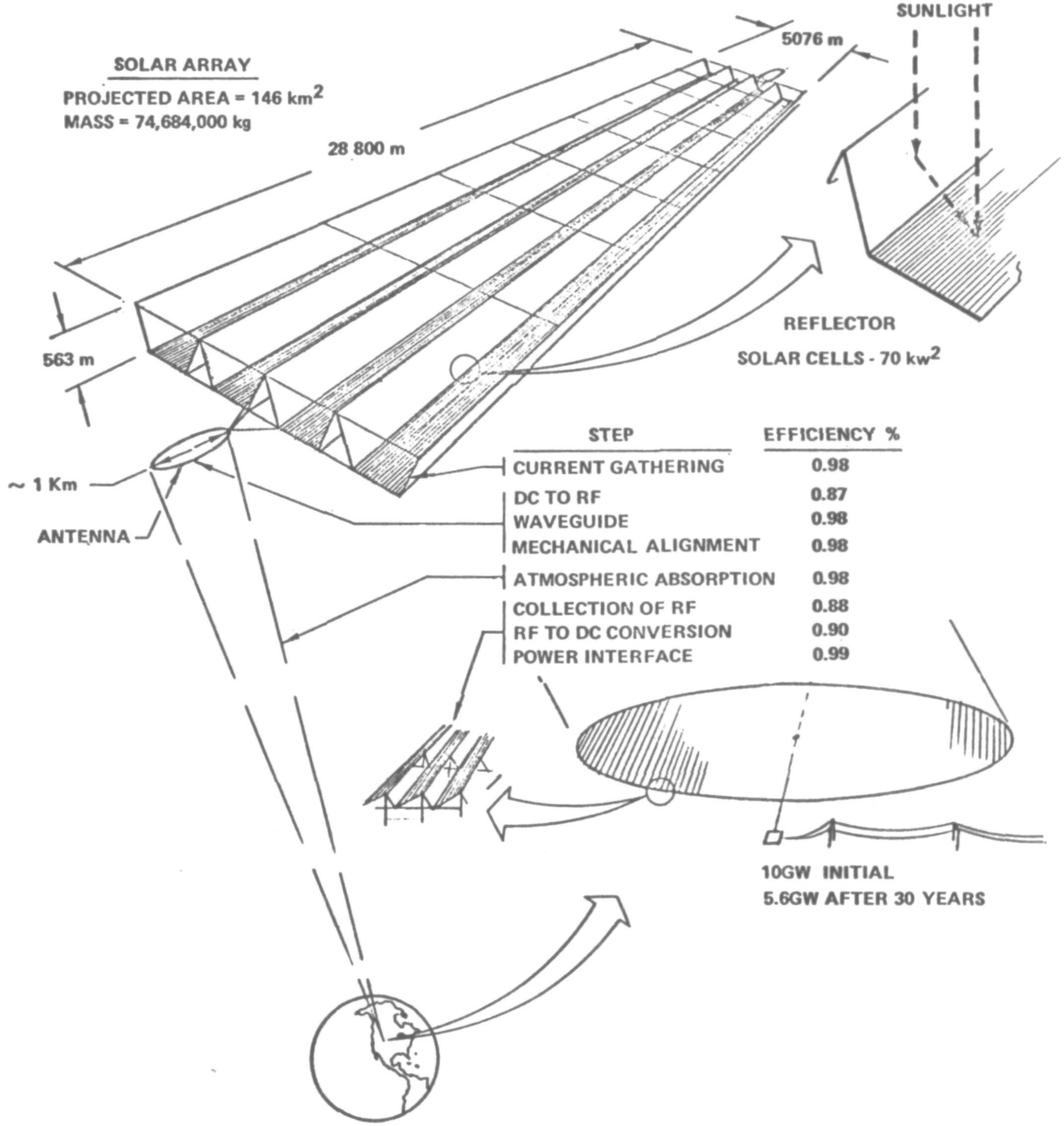
A solar power satellite is the energy-converting portion of a system which injects into Earth-surface public utilities power generated from sunlight in a geosynchronous orbit, 35,693 km altitude. Other elements of the system are the microwave beam that transmits the power to Earth, and the receiving station with its array of antenna elements, rectifiers, and equipment for converting the collected power to high-voltage 60-Hz alternating current that is delivered to distributing utilities. A solar power satellite having solar cells in simple trough-type concentrators is shown in Figure 1, along with the other major system elements and their power losses.

To be practical, a solar power satellite must be large, in the order of 100 km^2. This is because the microwave beam should be sharp enough to focus its energy on a reasonable size receiving station, say 60 km^2 in area. An antenna generating such a beam would have to be about a kilometer in diameter. It can then transmit enough power to support on Earth a receiving station that delivers about 10 gigawatts (GW) of power. For reference, the larger nuclear power plants in operation in 1977 deliver about one GW.

Constructing a solar power satellite in low-Earth orbit, followed by self-powered electrically-thrusted transfer to its geosynchronous operating station seems to be the best approach. However, self-powered orbit transfer requires the generation of high voltage directly from the solar-cell array. About 1800 volts is the limit because at higher voltages current leaking through the plasma in low Earth orbit would steal too much power from the solar array.

In geosynchronous orbit, where there are only about 100 electrons per cm^3. the leakage current through the plasma will be insignificant, even when voltages up to 100 kV are generated in the solar array. However, ion engines used to control attitude and station location will generate charge-exchange plasma which can provide a path for leakage-current flow out of the solar cell array.

SOLAR POWER SATELLITE CAN DELIVER 10 GW ON EARTH



STEP	EFFICIENCY %
CURRENT GATHERING	0.98
DC TO RF	0.87
WAVEGUIDE	0.98
MECHANICAL ALIGNMENT	0.98
ATMOSPHERIC ABSORPTION	0.98
COLLECTION OF RF	0.88
RF TO DC CONVERSION	0.90
POWER INTERFACE	0.99

Figure 1

SPACE ENVIRONMENT (Figure 2)

The environment for the solar power satellite is summarized here, with altitude plotted in Earth radii, nautical miles, and kilometers horizontally on a logarithmic scale, but with the center of the Earth brought from minus infinity to the edge of the illustration.

The Earth's magnetic field does not directly affect the high voltage solar array of a solar power satellite, but it controls other phenomena that do affect the array. These phenomena vary by orders of magnitude in intensity as a result of solar activity induced changes in the Earth's magnetic field and particle arrival rates. For example, the ionospheric layers, of which the F_1 and F_2 are in the 100 nautical mile (NM) to synchronous-altitude operating regime, are affected not only by the magnetic fields, but also by the time of day and season of the year. During the day the ultraviolet in the sunlight ionizes the oxygen and nitrogen neutral atoms of the air, and produces over 10^6 electrons per cm^3. At night the recombination of electrons with ionized oxygen produces the air-glow. At synchronous altitude the normal electron count falls to 100 per cm^3, and 60 cubic kilometers must be swept to find a coulomb of charge.

PLASMA ENVIRONMENT VARIES WIDELY BETWEEN 500 AND 35693 KM

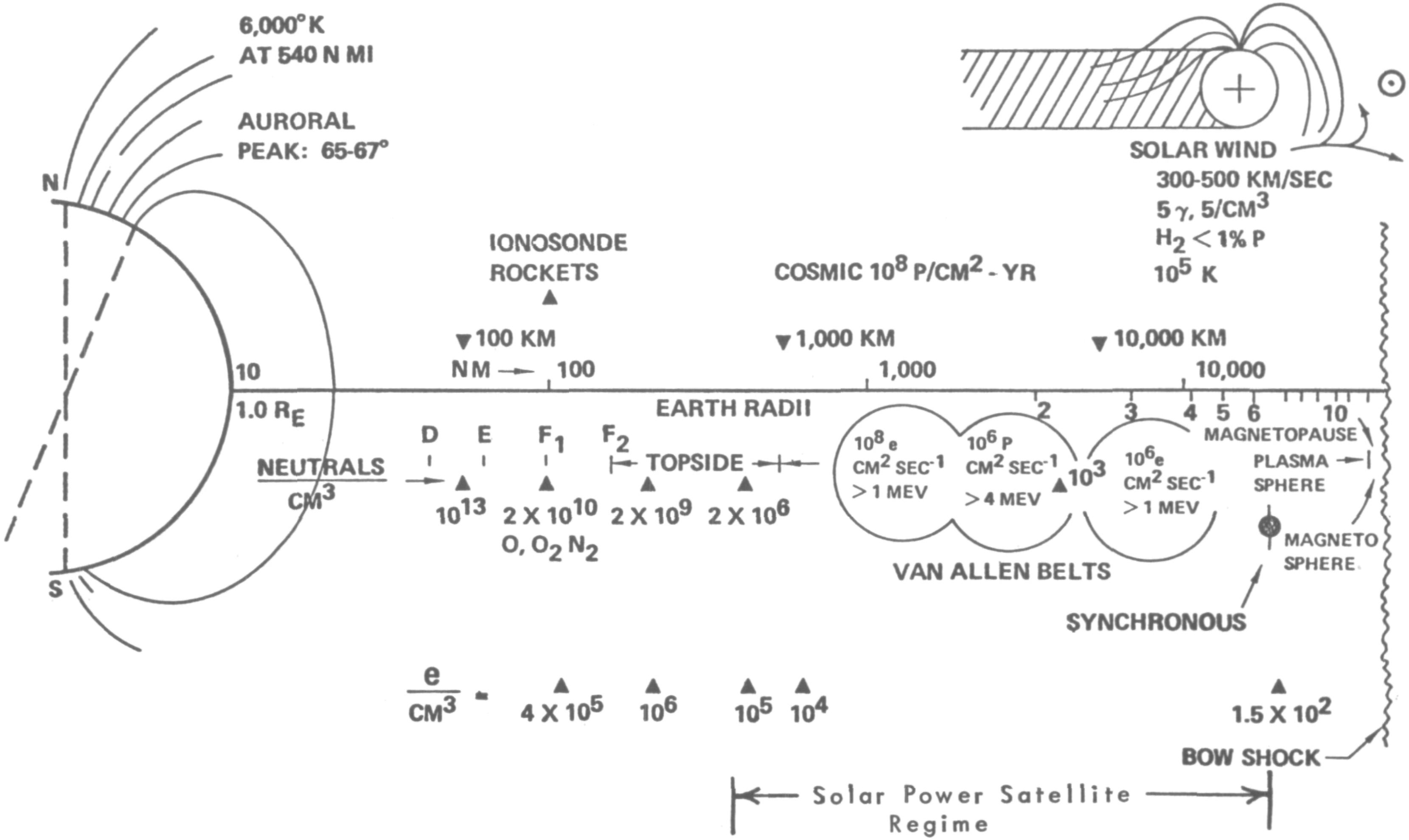


Figure 2

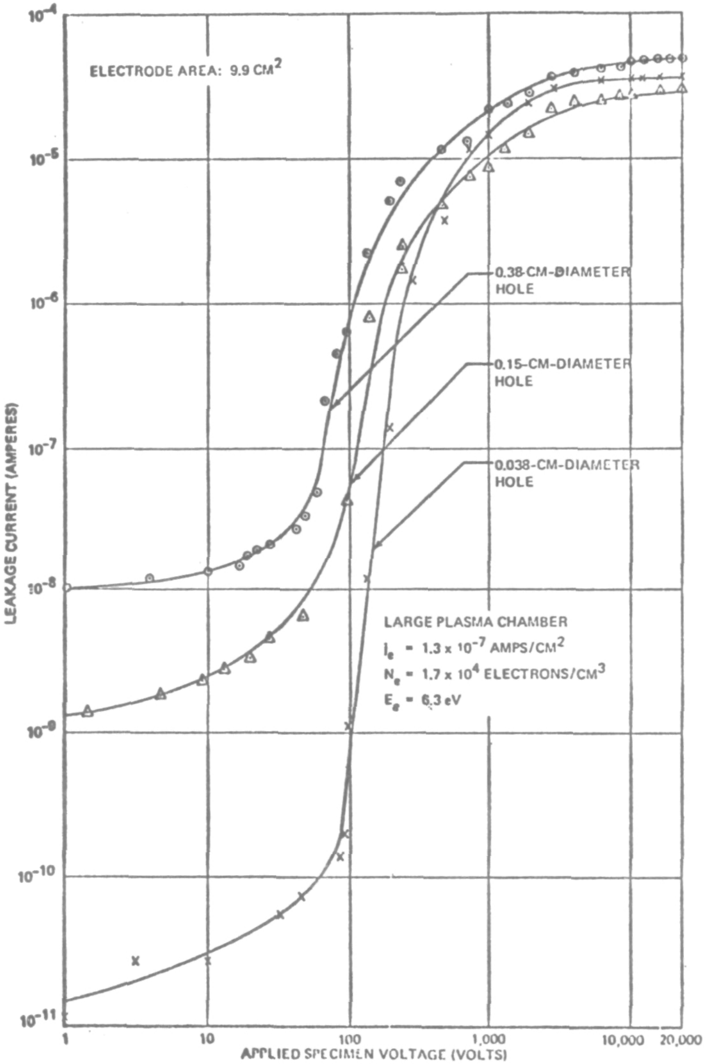
PINHOLE CURRENT COLLECTION (Figure 3)

Current flow through pinholes in insulation is an important mechanism in the escape of power from high-voltage solar arrays through a plasma path. Kennerud measured the current flowing from plasma through pinholes while varying pinhole size, insulation type, area of electrode and surrounding insulation, shape of pinhole, and type of insulation adhesive. Environmental and electrical parameters that were varied are plasma density, voltage level and polarity, length of plasma exposure, and background pressure.

In one of his tests he used 0.0127 cm Kapton insulation and measured current flow through the pinholes having hole diameters of 0.038 cm, 0.152 cm, and 0.381 cm. The Kapton was bonded to a stainless steel disc with conductive epoxy and mounted in a Teflon holder.

The measured leakage current with the electrode positive is shown here. At low voltages (<40 volts) the collected plasma current strongly depends upon hole size and is nearly independent of voltage. In this voltage range the collected plasma current density of the largest two holes is of the same order of magnitude as the random electron current density calculated from Langmuir probe data. The relatively low plasma current density collected by the 0.015-inch-diameter hole may be an insulation shielding effect; the hole diameter and depth, being nearly equal, make it a relatively "deep" hole whose walls limit the ability of the applied voltage to collect plasma electrons.

At intermediate voltages (+60 volts to +100 volts),the collected plasma currents start rising rapidly with increasing voltage. At high voltages (+1,000 volts to 20,000 volts) the currents for all three hole sizes are roughly equal and do not increase appreciably as voltage is increased.



At Above 200 Volts the Hole Size in 1.25 μm Kapton Ceases to Significantly Affect Leakage Current.

Figure 3

POWER LOSS BY LEAKAGE THROUGH PLASMA (Figure 4)

The space between 400 km altitude and the orbits of geosynchronous satellites contains neutral atoms, free electrons, positive ions, and high-energy charged particles. The high-energy particles, although damaging to solar cells and optical surfaces, are not numerous enough to carry a significant current. The free electrons, generated each morning when ultraviolet photons ionize neutral atoms, have energies of around one to two electron volts. This energy is dissipated in reactions with neutral atoms and ions increasing the temperature of the medium to the region of 500K to 2000K.

A positively charged spherical electrode, say one cm in diameter, will collect electrons when inserted into a plasma. The volume in which electrons are influenced by the electrode, called a sheath, is much larger than the sphere. Some of the electrons will orbit around the electrode and escape back out of the sheath. Current collection is then said to be orbit-limited and is affected in a complex manner by the radius of the electrode, the voltage of the electrode, and the temperature and density of the free electrons.

The high-voltage solar-cell array for a solar power satellite looks more like a sheet electrode than like a spherical probe. For example, let us assume that 10 km^2 of a solar power satellite array is deployed to supply 1500-volt power for electric propulsion thrusters for raising the satellite from low-Earth orbit, say 500 km, to geosynchronous orbit. We determined that at 500 km the electron-sheath extends to a few meters above the plane of the solar cells, in the range of electron concentrations, electron temperatures, and array voltages of interest. The calculation of leakage current then simplifies into analyzing the rate at which electrons drift into an electron sheath having essentially the same area as the solar array.

The calculated leakage currents from a 1500-volt array for several altitudes are shown in the table.

LEAKAGE CURRENT FROM POSITIVELY CHARGED SOLAR ARRAY

Array Altitude, Km	Electron Density, N_e Electrons/cm^3	Electron Temperature °K	Leakage Current		Power Loss, Percent of Generated
			nA/cm^2	Amperes per 1500 V String*	
500	6×10^5	3,000	824.5	0.8494	7.72
700	2×10^5	3,000	274.8	0.2831	2.57
1,000	7×10^4	3,000	96.19	0.0990	0.90
2,000	2×10^4	3,200	28.38	0.0292	0.265
5,000	1×10^4	4,400	16.64	0.0171	0.156
10,000	8×10^3	5,400	14.75	0.0152	0.138
20,000	2×10^3	9,000	4.76	0.0049	0.044
30,000	1×10^2	13,600	0.29	0.0003	0

* The string is 0.404 m by 255 m, with an area of 133.02 m^2

Figure 4

SOLAR ARRAY POWER LOSS THROUGH CHARGE-EXCHANGE PLASMA (Figure 5)

Charge-exchange plasma is generated in the downstream of an electric thruster when the beam ions interact with neutral atoms escaping from the thruster. The charge exchange plasma was first discovered to be a conducting medium in the path of electrons going from the thruster to the solar array during tests of the ATS-6 spacecraft in a large vacuum chamber. The spacecraft was biased at +15 volts relative to the thruster neutralizer, and substantial electron currents were observed flowing to the spacecraft.

The ions in the charge exchange plasma will be propelled by electric fields away from the ion beam and toward the back of the thruster. The positive ions in this plasma, not being readily absorbed by the solar array, constitute a minor part of the leakage current. The electrons, on the other hand, can funnel through holes in any solar array insulating surface and can rob significant power from the solar array.

CHARGE EXCHANGE PLASMA IS GENERATED WHEN BEAM IONS IONIZE NEUTRAL PROPELLANT ATOMS DRIFTING OUT OF THRUSTER

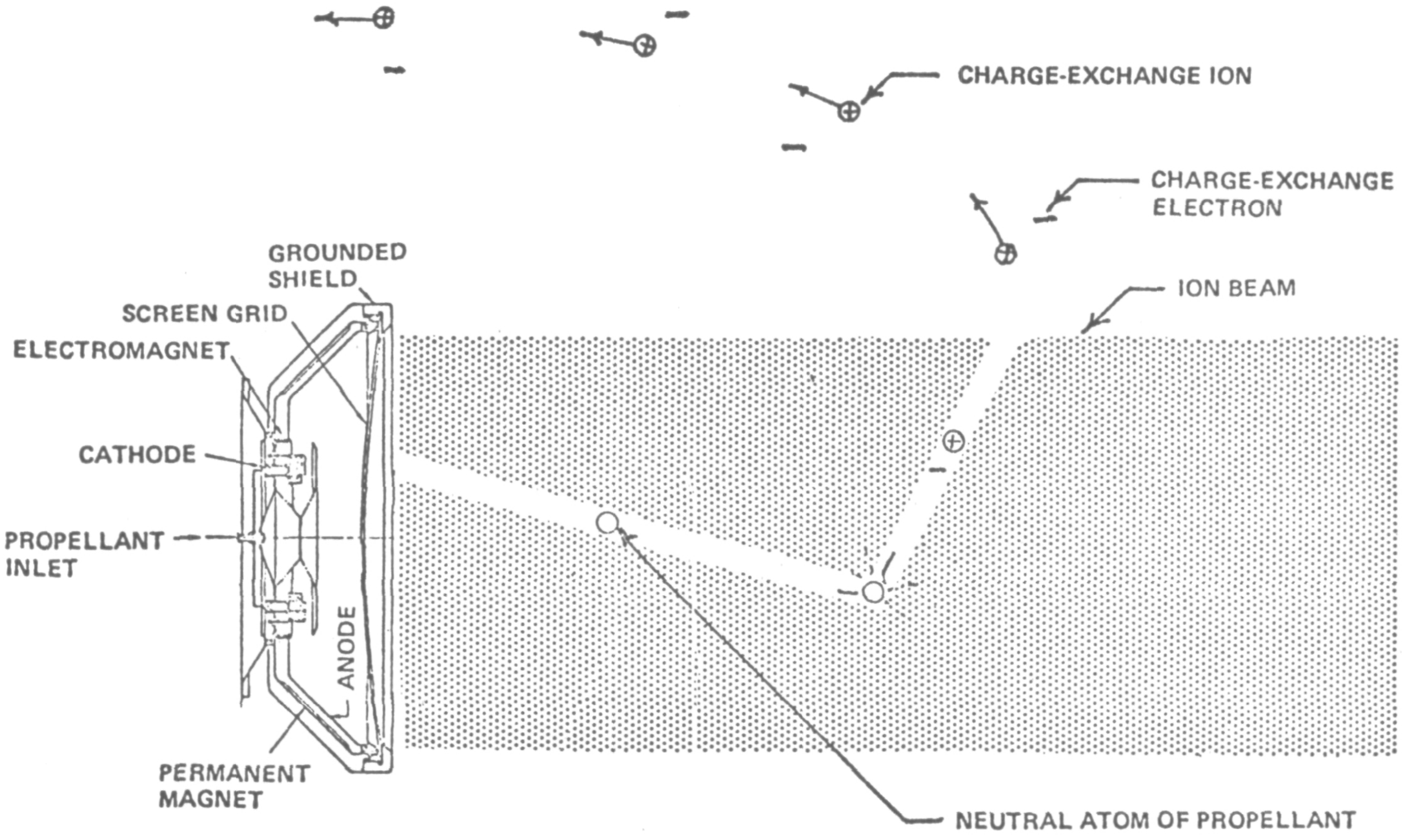


Figure 5

LIMITING POWER LOSS THROUGH CHARGE-EXCHANGE PLASMA (Figure 6)

Methods of avoiding the solar array loss in output caused by charge-exchange plasma conduction are shown. Using the cone shield does not reduce losses. The cone does move the apparent source of plasma generation downstream and further from the solar array. However, it also increases the density of the neutral atoms, and the net result is an increase in the leakage current from the solar array.

Insulating the solar array would eliminate the leakage-current loss were it not for the pinholes. Kennerud showed that within the plasma sheath surrounding the solar array, electrons will funnel into a pinhole from a large volume of the plasma. If the electron current is great enough, the pinholes will enlarge as the surrounding insulation sublimates away.

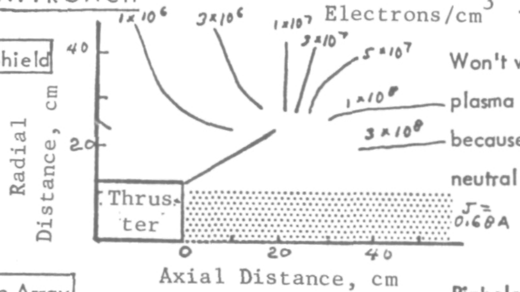
A third method of controlling leakage current going through the charge-exchange plasma is to collect the electrons with an anode before they can get into the solar array. Kaufman dismisses this approach with the note that it consumes too much power. However, most of the electrons can be collected on a 20-volt anode. Using Kaufman's generation rate of charge-exchange plasma gives a current of 56.4 kA, which at 20 volts represents 1.13 MW or 2.2 percent of the 52 MW consumed by the 800 thrusters.

If the charge-exchange plasma generation is limited by the supply of neutral argon atoms released by the thrusters, then the collecting plate will carry only 7.75 kA, which at 20 volts represents 155 kW or 0.3 percent of the power supplied to the thrusters. The anode could be a thin sheet of metal connected to the thruster structure through a 20-volt power supply.

If nothing else works, then the ion thrusters could be spaced away from the solar array.

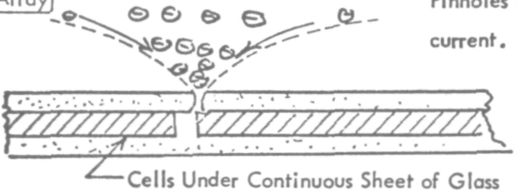
APPROACH — CONCERN

- Cone Shield



Won't work. Generates more plasma downstream of shield because of increased density of neutral atoms.

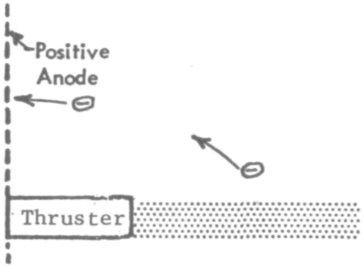
- Insulate Array



Pinholes in insulation funnel current.

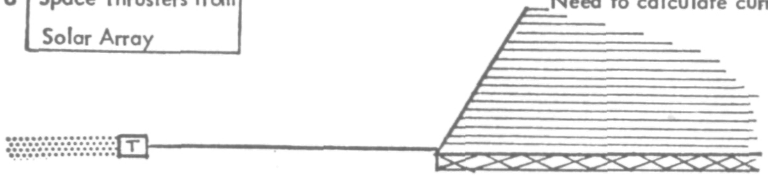
- Collect Charge-Exchange Electrons at Low Voltage

Not yet investigated.



- Space Thrusters from Solar Array

Need to calculate current loss.



Ways of Reducing Power Loss Through Charge-Exchange Plasma.

Figure 6

CONCLUSIONS

Generation of power at high voltage, around 40 kV, is advantageous on a solar power satellite. For example, power for the rf amplifiers would be carried by buses from solar cells as far as 10 km away, and even at 40 kV the current at the rotary joint between the array and antenna will be around 200 kA. Bus weight is reduced as voltage is raised. Also, generating power at 40 kV, a good input voltage for high-power klystron rf power amplifiers, avoids the need for heavy power conversion equipment.

Leakage of current through plasma can constitute a significant power loss from a high-voltage solar array. For example, at 300 km altitude a 2 kV array can barely generate enough power to feed the plasma losses. We believe that 477 km is a good altitude for assembling the solar power satellites, and that supplying power at 1.8 kV to the thrusters for orbit transfer is appropriate. Even at this voltage the I^2R losses in the power buses will be significant, but we need only about one-fourth of the satellite solar array for powering the thrusters.

In geosynchronous orbit where the satellite generates power and delivers it to Earth with a microwave beam, and the electron density is only around 100 per cm^3, plasma leakage current will be trivial if ion thrusters are not operating.

Leakage current through charge-exchange plasma, which is generated whenever ion engines are operated for orbit transfer or station keeping, is a phenomenon that is real but not yet fully understood. Leakage current through charge-exchange plasma might be reduced by shields, spacing, or ion collection at low voltage, but much more work needs to be done before we can be sure.

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