N90-25544

# DISCHARGE TRANSIENT COUPLING IN LARGE SPACE POWER SYSTEMS

By

N. John Stevens and R. P. Stillwell

TRW Space and Technology Group
One Space Park
Redondo Beach, CA 90278

## ABSTRACT

Experiments have shown that plasma environments can induce discharges in solar arrays. These plasmas simulate the environments found in low earth orbits where current plans call for operation of very large power systems. The discharges could be large enough to couple into the power system and possibly disrupt operations. In this paper, the general concepts of the discharge mechanism and the techniques of coupling are discussed. Data from both ground and flight experiments are reviewed to obtain an expected basis for the interactions. These concepts were applied to the Space Station solar array and distribution system as an example of the large space power system. The effect of discharges was found to be a function of the discharge site. For most sites in the array discharges would not seriously impact performance. One location at the negative end of the array was identified as a position where discharges could couple to charge stored in system capacitors. This latter case could impact performance.

## INTRODUCTION

The space environment can induce discharges in space power systems either by surface charging via geomagnetic substorm environments in geosynchronous orbit or by interactions between biased surfaces and the space plasma environment in low earth orbits [1,2]. These discharges have been demonstrated in laboratories and there is sufficient space flight data to substantiate the laboratory results [3,4,5,6]. It is important, therefore, to know how large space power systems will respond to these transients. While the phenomenon in both orbits is interesting, this paper will address only the low orbit, large power systems.

The tests indicated two major results. The first was that, as the bias voltage increased above 100 volts, there was a dramatic increase in collected current (see Figure 4). This increase was plasma density dependent - larger currents were collected for higher plasma densities. This effect was explained by the fact that the interconnect electric field extended over the cover glass and accelerated plasma particles into the cover glass increasing secondary emission. These secondary particles were then collected by the interconnects increasing the total plasma collected current. This effect was called "snap-over' [13].

The second result was the discharges that occurred when the negative bias voltage, relative to the plasma potential, exceeded a density-dependent threshold (see Figure 5). These discharges could shut off laboratory power supplies [3].

Ground tests were run on a continuing basis with the available technology solar cells (2 X 2, 2 X 4, 6 X 6), using standard and wrap-around interconnects. The segments tested ranged from small 100 $cm^2$ arrays to substantial 2 $m^2$ arrays. Testing with both bias power supplies and self-generated voltage arrays was conducted. The results were similar: snap-over at positive voltages and discharges at negative voltages.

There were two flight experiments conducted to measure the interaction in actual space environments; Plasma Interaction Experiment (PIX) 1 and 2 [14,15]. The results here were the same as in the ground simulation tests. The discharge data for both ground and space results have been assembled and, while there is some uncertainty in the absolute threshold voltage values, there is no doubt that discharges do occur [2,16]. For plasma densities corresponding to the Space Station orbit, discharge threshold values range from -138 to -250 volts. The low value is from the self-generated voltage testing [17].

The largest space power system planned for low earth orbit operations is the Space Station, Freedom. This Station is to have an array that will generate 215 kw of power at a nominal voltage of 160 volts in order to provide the 70 kw required at the Station electrical loads [7]. The final operating Station is planned to have a solar array configured in eight separate

PRECEDING PAGE BLANK NOT FILMED

blankets in four wings. An artist's conception of one version of the final operating configuration of the Station is shown in Figure 1 and gives an idea of its physical size. If there were discharges in these arrays, then there could be system damage if the discharge could drain the array power.

The current plan for the Station is to have the power generated in the solar arrays and transmitted to the Station electrical loads via an AC transmission line. The option of using a DC system from the arrays to the loads is still being discussed. The array configuration consists of 16 solar cell sectors, connected in series (with a bypass diode), to form a 160 volt block. The blocks are then connected in parallel to form the 13.5 kw blanket. There are two blankets per wing (see Figure 2). The solar cell chosen for the Station is a new 8 X 8 cm silicon cell.

Before considering the interactions between the Space Station and the environment in more detail, it is necessary to review the background data on plasma induced discharges in solar cells.

## DISCHARGES IN SOLAR CELLS

The behavior of solar cells, biased to various voltages in plasma environments, has been studied since the late sixties [3-6, 8-12]. These experiments used small segments of arrays, biased by external power supplies, to measure the plasma-cell interaction. The test arrangement is similar to that shown in Figure 3. The initial concern was for possible power losses that could be induced in the array because of the parasitic parallel loop through the plasma. The tests soon showed that there were other concerns.

The missing piece of data that is required to assess the Station behavior is data on the 8 X 8 cm solar cell. At this time, there has been no plasma interaction testing of these cells. There are differences in the construction techniques for these new cells and these may cause the cell to respond differently to plasmas. Since this data is missing, it will be assumed, for the following discussion, that they will behave similarly to the other cells.

## APPLICATION TO SPACE STATION POWER SYSTEM

A space power system, operating at a given voltage, will interact with the space plasma environment such that the net current collected from the plasma is zero. This means that the structure potential will vary, relative to the space plasma potential, until this current balance is reached. Since electrons are more mobile than ions, this usually means that the system will float negative to repel electrons and attractions.

The Space Station design currently calls for the positive side of the array to be grounded to the structure. The structure will then be at or near plasma potential and the array voltage will be negative. There will be velocity effects as the Station moves around its orbit and plasma conditions change [7]. These effects are illustrated in Figure 6. Previous studies of system behavior has indicated that the voltages will not be high enough for snap-over to occur unless active charge control techniques are used. This means that discharges would be the dominant concern for the Station power system performance. As shown in Figure 6, all blocks in the eight blankets have areas that are at sufficiently negative potential where discharges can occur. The discharge threshold used is based on the minimum values found in the PIX-2 data extrapolated to Space Station altitudes.

The actual discharge transient is not well characterized. Measurements have been attempted that appear to show pulses of several microsecond duration, but this is more probable the test sample response than a actual discharge [18]. Other experiments have shown that the discharge is really a multiple process involving the initial discharge transient stretched by decharging of other capacitors in the array [19]. It is this latter type of discharge process that will be considered here.

The Station power system is still being designed so that only the conceptual elements of that system can be included in this discussion. The DC generation - DC transmission and the DC generation - AC transmission power distribution systems are shown conceptually in Figures 7 A and B. An initial study of this system was concerned primarily with the effect of discharges on the Station electrical loads [7]. It used a model in which the structure ground was firmly tied to space potential. The batteries, required to provide power during eclipse, were mounted on the wings. A solar array switching unit (SASU) was also included to maintain array power at the maximum power point by switching units in and out of the circuits as required. The SASU was simulated as a capacitor and resistor in this model. A diode characteristic was used to simulate the solar array performance.

In that study, discharges were simulated simply by turning off various levels of power for periods of up to 60 microseconds. Small discharges were shown to have little effect on the electrical load. This is because the batteries would come on line to maintain power. Any ripple due to the transient would be damped out by the transmission line inductance. For the DC-DC system appreciable power losses occurred only when the whole array was involved in a discharge or when the array diodes failed. This was due to the back-biased array being an additional load for the battery to supply. The DC-AC system didn't seem to respond to complete array shut down of up to 60 microseconds.

Based upon the assumptions used, it became apparent that discharge effects in the array should be evaluated in more detail. Therefore, this study was undertaken to evaluate the effect in the DC-DC system. Since the interest was now in the array, the circuit model was simplified as shown in Figure 8. In this model, the Station is now coupled to space with a typical value of 400 picofarads. The battery system is also diode protected from reverse current flows. This eliminates any possibility of having the battery being drained by the dark array during eclipse.

The characteristics of the discharge itself are not really important. The discharge is assumed to trigger a process resulting in the decharging of other capacitors. The process assumed is that a discharge occurs in the negative portions of the array locally reducing the voltage. This causes the array material capacitors (cover glass and substrate) to decharge by ejecting electrons to space to correspond to the change in voltage. This stretches out the duration of the pulse. For a small discharge involving two sectors, the cover glass and substrate capacitance would be on the order of 0.35 microfarads. The resistance to space has been set at 50 ohms and the discharge inductance computed at a value to give an underdamped pulse ($1X10^{-4}$ H).

This discharge must occur in the array in or between sectors where the voltage is sufficiently negative with respect to the space plasma potential. Since an absolute discharge threshold has not yet been established, two separate discharge locations will be considered in the following sections.

### Discharge Occurring Between Sectors

A discharge is assumed to occur between the 25th and 26th sector where the voltage, relative to the space plasma potential, is -154 volts (switch position marked A in Figure 8). The discharge is triggered by a breakdown in the cell circuit. This drives the voltage at this point towards zero based on the relationship that the discharge current equals the discharge capacitance times the time dependent change in voltage. This change in voltage causes the charged cover glass and substrate capacitors to decharge stretching the discharge pulse. This type of discharge also will cause the sector voltages to change since the current flow in the cells has been modified. When the discharge current was less than the plasma current collected by the block, then the plasma currents drove the voltage distribution back initial value. The capacitor controlling this rate of change of voltage was assumed to be the system capacitance to space. Hence, the return to normal conditions is more rapid. This effect has been modeled with a circuit analyzer code and the results shown in Figure 9. A single discharge, at this location, could effectively shut down the block or reduce the power generated by 1/36 of the total blanket power for about 60 sec (assuming 36 parallel blocks). The sector cell reverse current resistances and the sector diodes would prevent other blocks from being affected by the discharge. The battery would come on-line and maintain power to the load and the battery diodes would isolate both the battery and the Station loads from the discharge. The problem that could occur here would be stressing the diodes; although they should be capable of withstanding such stresses. Hence, this type of discharge should not cause any serious disruption of power service in the station. If multiple discharges do occur, then it is possible for several blocks in all the blankets to go down simultaneously. If the battery is charged, then these losses again would not affect the Station loads. There would still be a concern if the discharge rate were high, but such rates for large arrays have not yet been determined.

### Discharge At End Of Block

This type of discharge is assumed to occur at switch position marked B in Figure 8 at breakdown voltage of -160 volts. The process involved in the discharge is the same as in the preceding case: a discharge triggers the decharging of the cover glass and substrate capacitors. The effect here, however, is far more serious. The discharge is triggered at the most negative voltage area of the block and again, the voltage is driven towards zero. The block current is available to add to the discharge as before. Now, the other blocks can add their current to the discharge since there are no blocking diodes nor high resistance cell paths to hinder current flow. This means that the SASU capacitor can also decharge. This unit has a 2000 microfarad capacitor charged to 160 volts or a stored charge of 0.32 coulombs. The behavior during this type of discharge was also modelled and the results are shown in Figure 10. As shown the current in the pulse can rise 75 to amperes in 70 sec. This could be sufficient to cause significant damage to wires and components. While this is going on, power for the station electrical loads will be provided by the battery until this supply is exhausted.

If this type of discharge is so serious, why hasn't it been observed in the laboratory tests of array segments? The answer is that it has been. The early test results mentioned that the discharge would drain the full capability of the power supply. As the tests became more sophisticated, current limiting resistors were added in the test lines to isolate the power supply during the discharge so that the discharge process could be studied. This prevented current flow from the supply and since the array samples were small, the discharge pulse was small.

There are possible mitigation techniques that can be used here to prevent serious consequences from this type of discharge. This is to provide additional diode protection to prevent capacitor decharging current flows.

## CONCLUDING REMARKS

Large solar array power systems must function in the space plasma environment for long periods of time. Possible interactions in such arrays have been studied for the past twenty years by biasing small segments of the array to various voltages while exposed to a simulated space plasma environment. Two major effects were found: the "snap-over" current collection when the bias voltages were greater than 100 volts and discharges that occurred in negative biased regions of the array. Snap-over phenomenon resulted in high plasma current collection which implied additional power losses. Discharges generated transients that could conceivably damage systems. Previous system evaluations have indicated that the proposed operating voltages would preclude operating at greater than 100 volts relative to the plasma potential, so this is not considered to be a serious problem. That leaves only the question of discharges.

The Space Station power system represents the largest power generating array to be flown on low earth orbit. This array would generate 215 kw of power while operating at 160 volts. Solar cells for this array are to be the new 8 X 8 cm cells for which there is no data on plasma interactions. Under the assumption that these cells would behave similar to all other types of cells, system evaluations have been conducted. An initial study concluded that there would be minor disruption in the power flow unless either the entire array shut down temporarily or that the back-bias diodes failed. Then there could be a 10% power loss for the duration of the discharge (up to 60 microseconds durations were considered).

In a recent study of solar array discharges, the results indicated that a discharge could couple into other capacitors in the system, stretching out and amplifying the pulse. This concept was applied to the Space Station system. The Station power distribution system designed used in the initial study was modified to incorporate space capacitance and discharges occurring in two different locations on the array were evaluated. If the discharge occurred at the end of a block, then the results were more serious. Such a discharge would shut down all of the blocks in a blanket. The SASU capacitance could also dissipate its charge appreciably increasing the current flow. A mitigation technique to minimize this effect is to use blocking diodes in the array lines between the blocks. A major unknown in these studies is the discharge repetition rate. If discharges are frequent, then they could prevent or reduce battery charging capability.

The basic assumption in this study is that the 8 X 8 cm cells behave the same as the other, older cells. If these new cells have the same discharge characteristics, then the effects described here will happen. If the cells behave in a different manner, then the whole question would have to be revisited.

## REFERENCES

1. Archer, J. S., Rauschenbach, H. S. and Stevens, N. J.; "Investigation of ESD Hazard for Large Space Solar Arrays Configured with GFRP/Kapton Substrates," AIAA Paper 89-0617, January 1989.

2. Stevens, N. John; "Interactions Between Large Space Power Systems and Low-Earth Orbit Plasmas," Spacecraft Environmental Interactions Technology - 1983, NASA CP-2359/AFGL-TR-85-0018, 1985, pp. 253-276.

3. Kennerud, K. L.; "High Voltage Solar Array Experiments," NASA CR-121280, 1974.

4. Herron, B. G., Bayless, J. R. and Warden, J. D.; "High Voltage Solar Array Technology," AIAA Paper 72-443, April 1972.

5. Domitz, S. and Kolecki, J.; "Effect of Plasma Currents on Solar Array Power Output," Spacecraft Charging Technology - 1978 - NASA CP-2071/AFGL-TR-79-0082, 1979, pp. 358-375.

6. Stevens, N. John; "Solar Array Experiments on the SPHINX Satellite," NASA TMX-71458, 1973.

7. Stevens, N. J. et.al.; "High Voltage System Performance in Low Earth Orbit Plasma Environment Vol. 1 - Space Station Environmental Interactions," TRW 46870-6005-UT-00, NASA CR-179640, October 1986.

8. Inouye, G. T. and Sellen, J. M., Jr.; "TDRSS Solar Array Arc Discharge Tests," Spacecraft Charging Technology - 1978 - op. cit, pp. 834-852.

9. Brady, G. F., Jr., Vance, D. A. & Greenberg, S. A.; "Charging & Discharging Characteristic of a Rigid Solar Array," Spacecraft Charging Technology - 1980, NASA CP-2182/AFGL-TR-81-0270, 1981, pp. 228-236.

10. Beaver, Renate & Staskus, J.; "Tank Testing of a 2500 $cm^2$ Solar Panel," idid. pp. 211-227.

11. Grier, N. T.; "Experimental Results on Plasma Interactions with Large Surfaces at High Voltage," NASA TM-81423, January 1980.

12. McCoy, J. E. and Konradi, A.; "Sheath Effects Observed on a 10-Meter High Voltage Panel in Simulated Low Earth Orbit Plasmas," Spacecraft Charging Technology - 1978, op. cit., pp. 315-340.

13. Purvis C. K., Stevens, N. J. and Berkopec, F. D.; Interactions of Large, High-Power Systems with Operational Orbit Charged-Particle Environments," NASA TMX-73867, 1977.

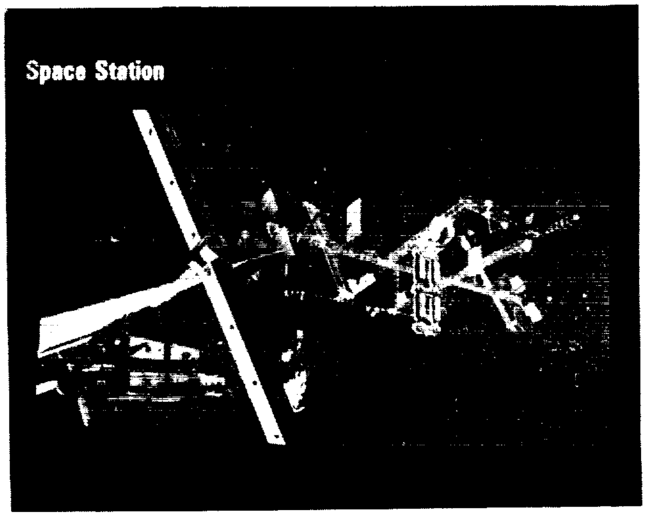
14. Grier, N. T. and Stevens, N. J.; "Plasma Interactions Experiment (PIX) Satellite Results," Spacecraft Charging Technology - 1978, op. cit, pp. 295-314.

15. Purvis, C. k.; "The PIX-II Experiment: An Overview," Spacecrft Environmental Interactions Technology - 1983, op. cit., pp. 321-332.

16. Ferguson, D. C.; "The Voltage Threshold for Arcing for Solar Cells in LEO - Flight and Ground Test Results," NASA TM-87259, March 1986.

17. Snyder, D. B.; "Discharges on a Negatively Biased Solar Cell Array in a Charged-Particle Environment," Spacecraft Environmental Interactions Technology - 1983, op. cit., pp. 379-388.

18. Stevens, N. J. and Stillwell, R. P.; "Environmentally Induced Discharges in Solar Array," paper presented at this conference.



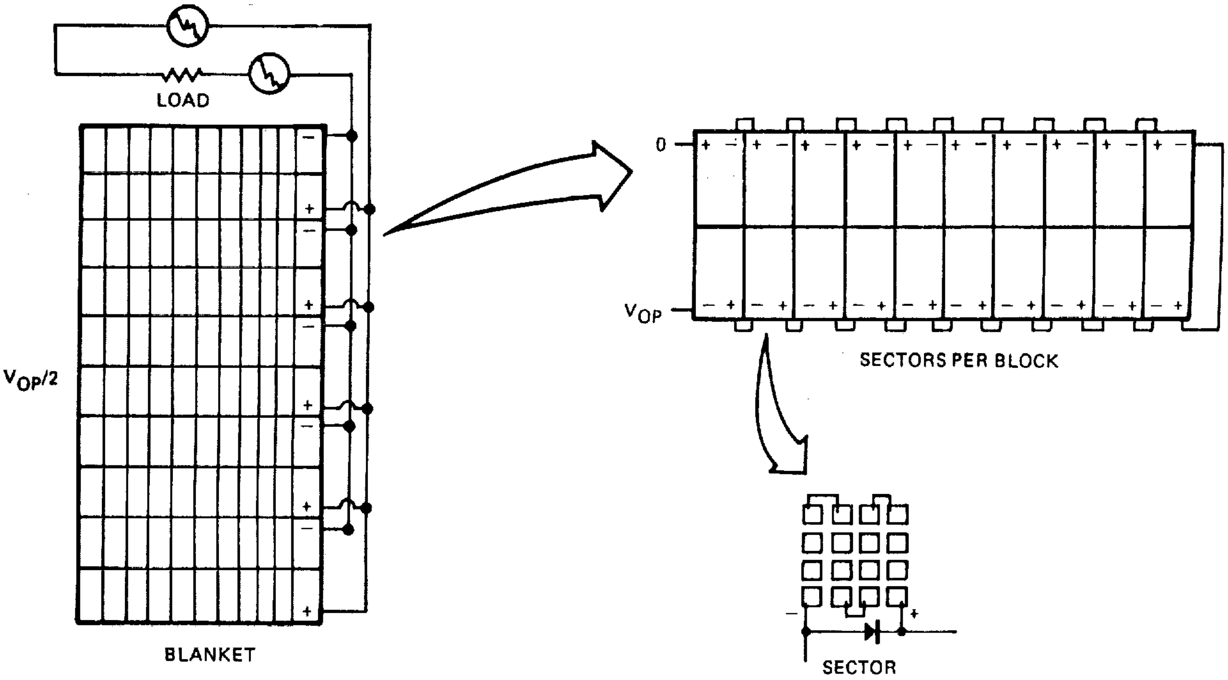


FIGURE 2. SOLAR ARRAY BLANKET CONFIGURATION

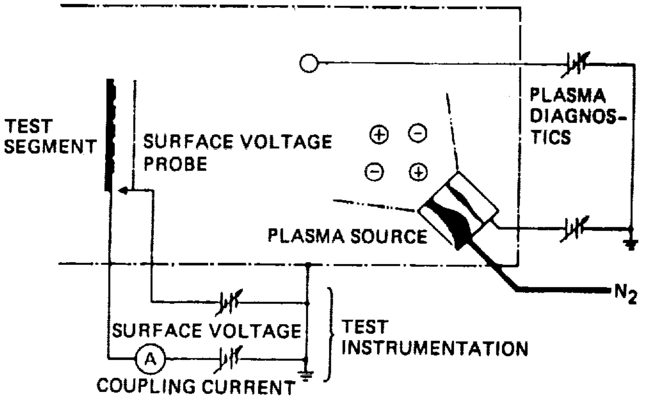


FIGURE 3. SCHEMATIC DIAGRAM OF TEST ARRANGEMENT

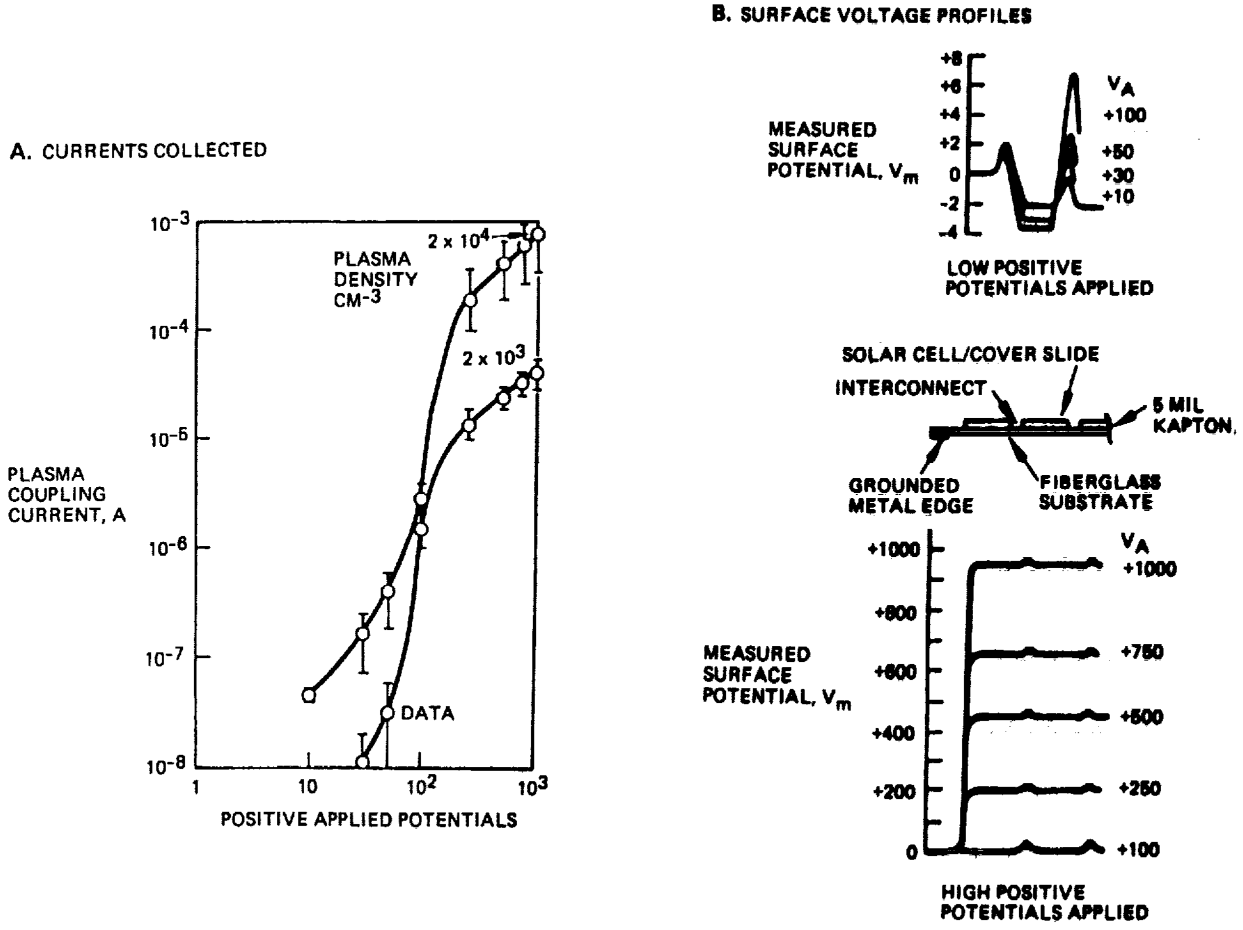
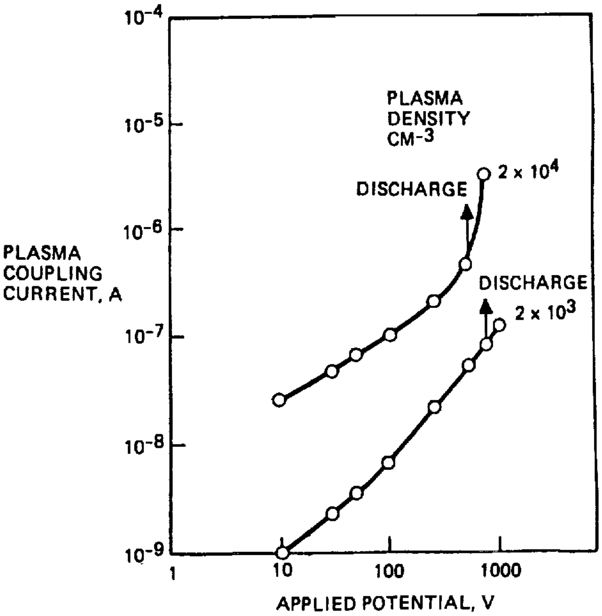


FIGURE 4. GROUND TEST RESULTS - POSITIVE BIAS

A. CURRENT COLLECTION



B. SURFACE VOLTAGE PROFILES

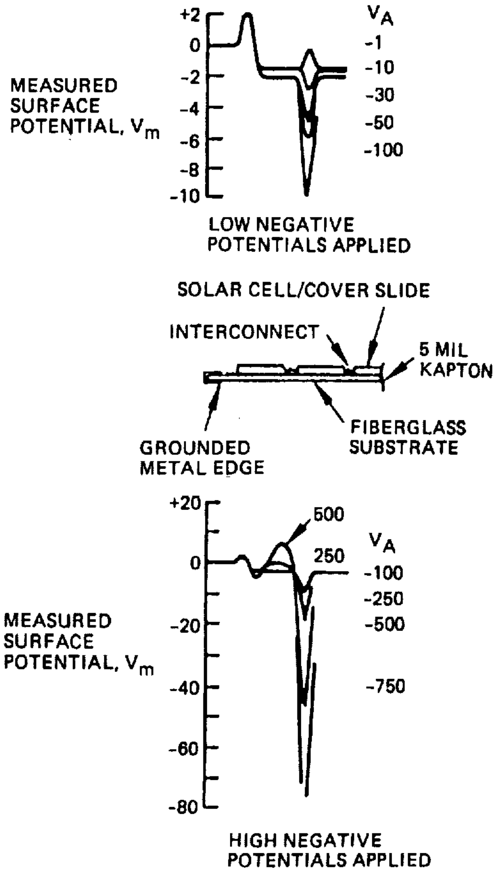


FIGURE 5. GROUND TEST RESULTS - NEGATIVE BIAS

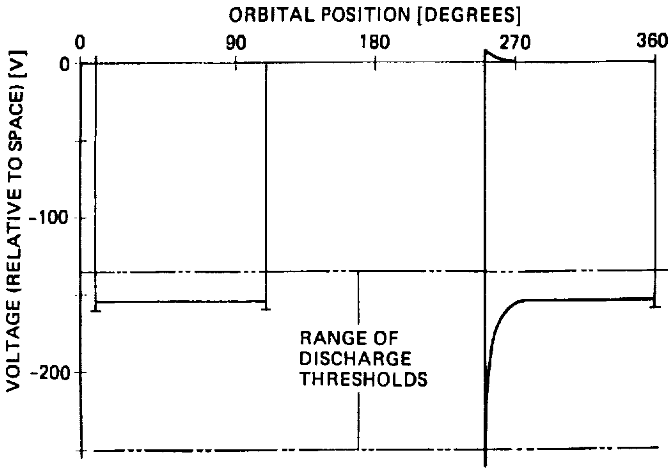


FIGURE 6. PREDICTED PERFORMANCE OF SPACE STATION ARRAY

A. DC GENERATION/DC TRANSMISSION

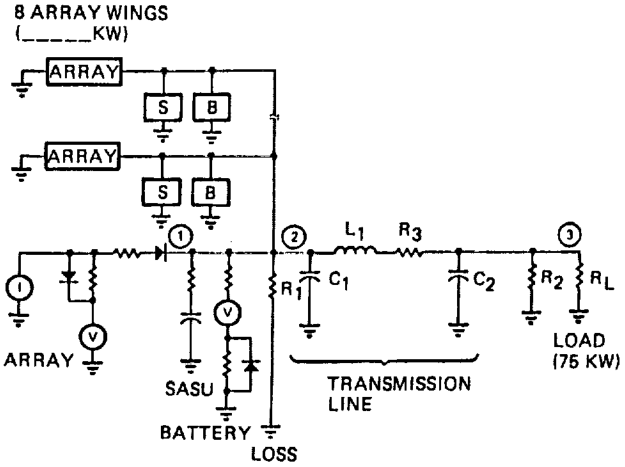


FIGURE 7. TRANSIENT RESPONSE CIRCUIT

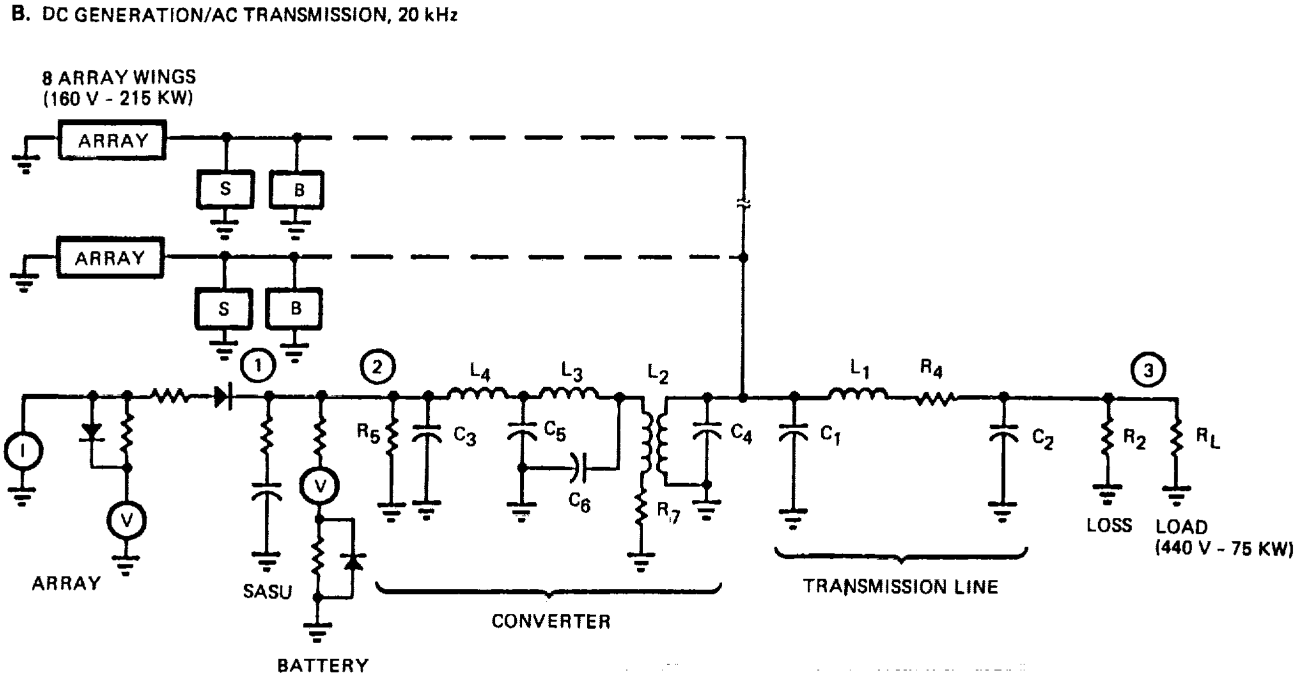


FIGURE 7. TRANSIENT RESPONSE CIRCUIT
(CONTINUED)

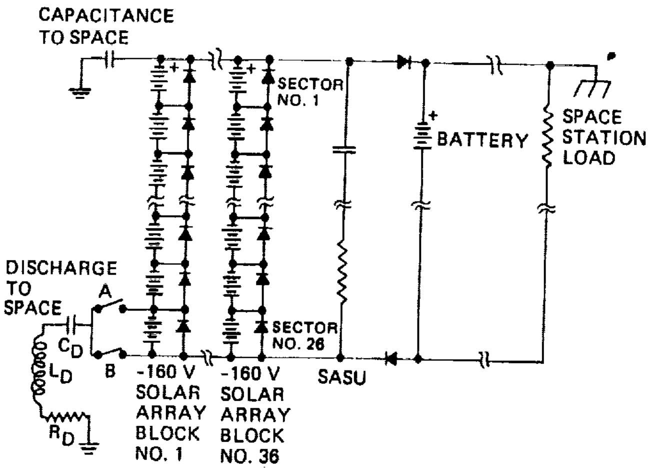


FIGURE 8. SIMPLIFIED SPACE STATION SOLAR ARRAY POWER SYSTEM SCHEMATIC

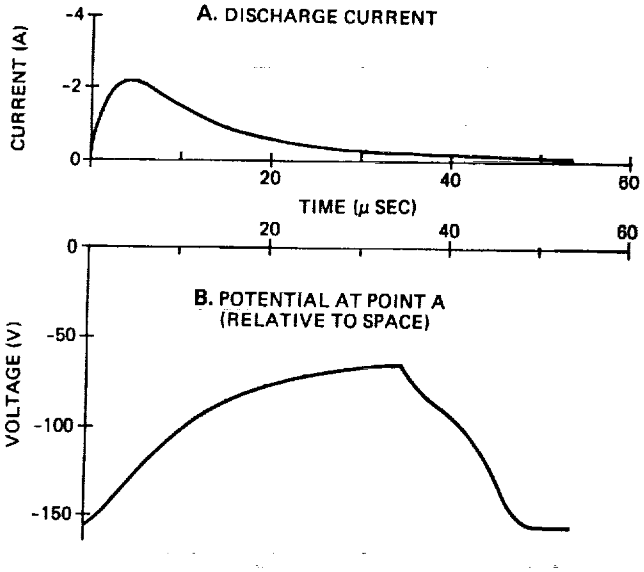
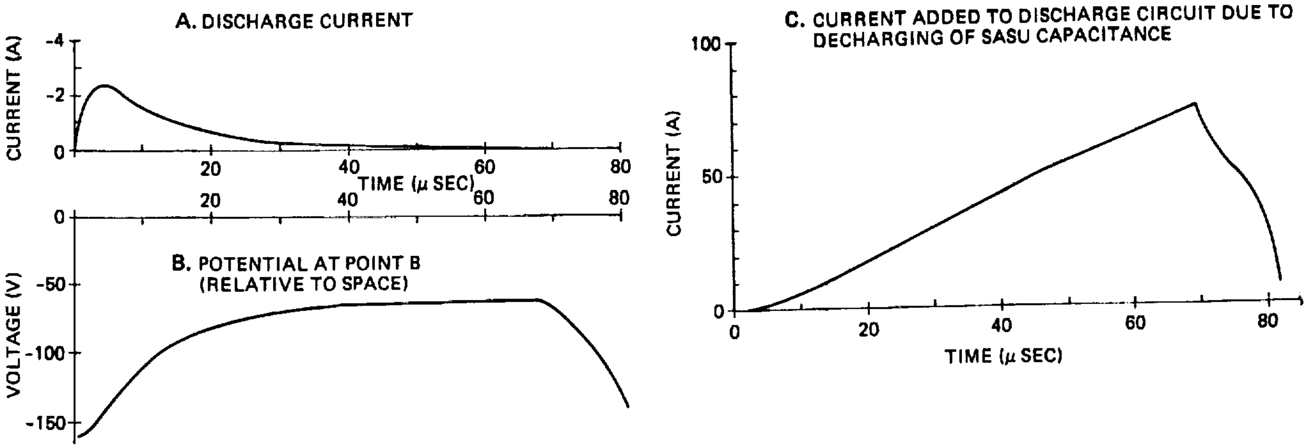


FIGURE 9. PREDICTED PERFORMANCE FOR DISCHARGE AT POINT A

 A. DISCHARGE CURRENT

B. POTENTIAL AT POINT B (RELATIVE TO SPACE)

C. CURRENT ADDED TO DISCHARGE CIRCUIT DUE TO DECHARGING OF SASU CAPACITANCE

FIGURE 10. PREDICTED PERFORMANCE FOR DISCHARGE AT POINT B