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**HIGH VOLTAGE SURFACE-CHARGED PARTICLE ENVIRONMENT  
TEST RESULTS FROM SPACE FLIGHT AND  
GROUND SIMULATION EXPERIMENTS**

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INTRODUCTION

The large power systems required for future satellites may utilize solar array panels that are operating in the kilovolt range. Solar arrays operating in the space environment at this voltage range can have adverse surface-charged particle interactions. These interactions have been investigated in ground facilities for many years. In 1968 TRW (ref. 1) experimentally showed that milliamperes of current could be drawn through a small pinhole ( $\sim 0.051$  cm in diameter) in Kapton films to an electrode beneath the Kapton when the electrode is biased positively. NASA Lewis (refs. 2 to 4), Boeing (ref. 5), and Hughes (ref. 6) verified these results and extended the experimental investigations to other plasma conditions, materials, configurations, and sample types. These early investigations provided the background for the Space Plasma High Voltage Interaction Experiment (Sphinx) satellite program. Sphinx would have provided the first flight data concerning the high voltage surface-charge particle interaction phenomena. The satellite consisted of 16 different experiments and was designed to operate in the varying plasma environment of its elliptic orbit for 1 year. It was launched in 1974 but failed to reach orbit due to malfunctions in the Titan-Centaur proof flight vehicle. Investigations in ground facilities continued, however.

In 1978 another opportunity arose for flight data with the launching of the Landsat-C satellite. Space was available on this launch only for an auxiliary payload that could be attached to the second stage of the Delta vehicle. PIX, an acronym for plasma interaction experiment, was designed for this launch. In contrast to Sphinx's 16 experiments, PIX consisted of only three experiments. These three experiments were designed to evaluate interaction phenomena in the space environment and specifically, to see whether an insulator enhances the electron current for positively biased samples and whether conventionally constructed solar arrays arc when negatively biased. Both of these phenomena had been observed in ground tests. PIX was launched on March 5, 1978 from NASA Western Test Range. It remained with the second stage of the Delta and used the Delta's telemetry system.

Before PIX was launched, tests were conducted in ground simulation facilities under various plasma conditions and using many different types of samples. These investigations were directed at understanding the interaction phenomena that occur on solar array panels operating in a plasma environment. This paper presents the pre-flight and the flight results for solar array panels. The flight array was limited to biases between  $\pm 1000$  volts. Therefore, most of the pre-flight data was obtained for this same voltage range. Additional ground tests were performed at higher voltages and these results are also presented.

### EXPERIMENTAL SAMPLES

The flight solar array panel consisted of (24)  $2 \times 2$  cm solar cells connected in series. The panel's total area was  $\sim 100 \text{ cm}^2$  and the interconnect area was  $\sim 5 \text{ cm}^2$ . A 6-mil fused silica glass covered each individual solar cell. The interconnects were conventional bar interconnects and were left uncovered. The interconnects served as the electrodes for collecting charges from the plasma. A picture of the array is shown in figure 1. This array was also used for the pre-flight ground test data. In addition to this small array, limited ground tests were performed using a  $38 \times 38$  cm array consisting of (370)  $2 \times 2$  cm solar cells.

### GROUND TEST RESULTS

The results for three different plasma densities for electron collection when the array was biased positive up to 1000 volts are shown in figure 2. As can be seen the current increases sharply when the voltage is between 100 and 500 volts. In this region the array makes a transition from collecting electrons that fall only on the interconnects to those that strike the whole array surface including the cell's cover glasses. This phenomenon of an insulator surrounding a positive bias electrode enhancing the electron collection from a plasma has been observed and reported previously in references 2 to 4. As will be shown in a later figure, when this transition occurs the voltage over the cover glass is only a few volts below the applied voltage. Therefore, the full area of the array panel appears to be attracting the electrons from the plasma. From figure 2 it is also seen that after the transition occurs the current varies approximately linearly with voltage and plasma density.

The results for the same array when the voltage is increased to 10 000 volts in a plasma density of approximately  $4 \times 10^4$  electrons/cm<sup>3</sup> is shown in figure 3. As can be seen, the current continues to vary approximately linearly with voltage up to 10 kV. This is the same voltage dependence that a sphere would have. This is as expected since the sheath becomes large and spherical in shape at these voltage levels for this size array.

The results obtained using the larger size array in a plasma density of approximately  $2.9 \times 10^4$  electrons/cm<sup>3</sup> is shown in figure 4. The total area of this array is approximately 2000 cm<sup>2</sup> with total interconnect area of approximately 93 cm<sup>2</sup>. This is about 20 times the small array areas. As can be seen the maximum current is about 20 times higher than the small array current also. Also, as can be seen, the jump in current is quite pronounced for this array. Also shown in figure 4 is the ion current for negative bias on the large array. As can be seen no jump in current occurred for negative bias. However, this panel did arc at the high negatively biased levels.

The results for negative bias on the small array at three different plasma densities is shown in figure 5. The current increases almost linearly with voltage. However, at the plasma density of  $1.7 \times 10^4$  electrons/cm<sup>3</sup> arcing occurred and tripped off the power supply. These arcs have been observed in all the tests with negative bias on the array. For this array at the lower densities, arcs occurred at voltages higher than -1000 volts. The inception of arcs seemed to vary with each array for a given plasma density. Usually, the lower the density the higher the arc's inception voltage.

To see how the voltage is distributed across the solar array, a surface voltage probe was swept across the array to measure the voltage on each cell beneath the trace. Figure 6 shows the voltage profiles for positive bias voltages of 100 and 1000 volts. Notice that at the 100 volt level the applied voltage is confined only to the interconnects. While at the 1000 volt level the whole array including the cells' cover glasses is at the applied voltage. This latter type of voltage profile is always observed after the current has made its steep rise with voltage. This implies that at the higher voltages the whole array serves to attract the electrons. These electrons are funneled to and collected by the cells' interconnects causing the jump in the electron current.

The voltage profile for negative biases of -100 and -1000 volts on the array is shown in figure 7. As can be seen even at the -1000 volt level the voltage is essentially confined to the interconnects. This explains why there is no jump in current for negative biases.

In order to determine if the plasma electrons were actually striking the solar cell cover glasses when the array was biased at different voltages another small array was coated with phosphor P4 and tested in a plasma density of approximately  $1 \times 10^4$  electrons/cm<sup>3</sup>. Pictures of the array at several bias voltages during this test are shown in figure 8. In figure 8 the solar array is located in the upper right hand side of the pictures. The bright areas in the upper center section of the pictures is from the light given off by the hot filament of the plasma source. As the array bias

voltage increases from +900 to +2000 volts, the whole array glows brighter and brighter. This indicates that more and more of the electrons are actually striking the solar cells cover glasses and generating secondary electrons which could be collected by the interconnects. The phosphor is activated only by electrons. So the light areas as seen for negative bias must be from electrons emitted from the cells. For the negative biases, most of the light area is near the bottom row of the solar cells that are within 2 cm of a grounded metal bar that supports the panel. This metal bar creates large field gradients between the bar and the solar cell which enhances the electron emission from the bottom row of cells. These electrons may travel along the surface activating the phosphor.

### FLIGHT RESULTS

Figure 9 shows an overview of the PIX auxiliary payload package. PIX consisted of two experimental packages, an electronic enclosure box and an experimental plate. Two of the three experiments were mounted on the experimental plate and the other on the electronic enclosure box. The two experimental plate experiments were the solar array segment and a 3.5 cm diameter metal disk resting on a 20 cm diameter Kapton film. This Kapton/disk arrangement was designed to investigate the effect of an insulator surrounding an electrode. The third experiment which was mounted on the electronic enclosure box, consisted of a 3.5 cm diameter metal disk with a grounded plane surrounding it. This third experiment was called the plain disk experiment and was to act as a control. PIX remained with the second stage of the Delta and used the Delta's telemetry system in real time. Due to the life of the telemetry battery, PIX data was received for only about 4 hours. Of this time only 2 hours of data was recovered.

PIX operational sequence is shown in figure 10. The voltage was cycled between  $\pm 1000$  volts. The voltage was varied first positively on the disk on Kapton experiment, then positively on the solar array, then negatively on the solar array, and finally negative on the disk-on-Kapton experiment. This cycle lasted 20 minutes and was continuously repeated. Each voltage level was held for 1 minute. The plain disk was hard-wired to the high voltage power supply so it was active during all of the sequence. Only about half of the data cycles were received due to limited ground coverage. More details of the PIX satellite is given in reference 7.

Figure 11 shows the flight results for positive bias during the 7th cycle. Cycle 7 was one of the cycles where data was received for the full positive half of the voltage cycles. As can be seen the agreement with ground base results is relatively good. Both the disk-on-Kapton and the solar array showed the transition in electron current. The plasma density was estimated to be approximately  $2 \times 10^4$  electrons/cm<sup>3</sup>

from using the plane disk data.

Figure 12 shows the flight results for negative bias during the 6th cycle. Cycle 6 was one of the cycles where all the negative bias data was received. Again the agreement is relatively good. The solar-array began to arc above the 500 volt level in agreement with ground test results. Both the positive and negative bias data substantiate ground test results.

#### CONCLUDING REMARKS

The following conclusions are reached from the data obtained using both the ground and the flight tests results:

1. Insulators enhance the electron but not the ion current collected from a plasma.
2. At high positive bias voltages on solar cell panels, the cover glass over each cell is essentially at the applied bias voltage. Therefore, the whole array rather than only the interconnects attracts the electrons.
3. At high negative bias voltages, large transient currents due to arcing occurs.
4. For small samples, ground facilities can be used to simulate space conditions for the surface-charge particle interactions.

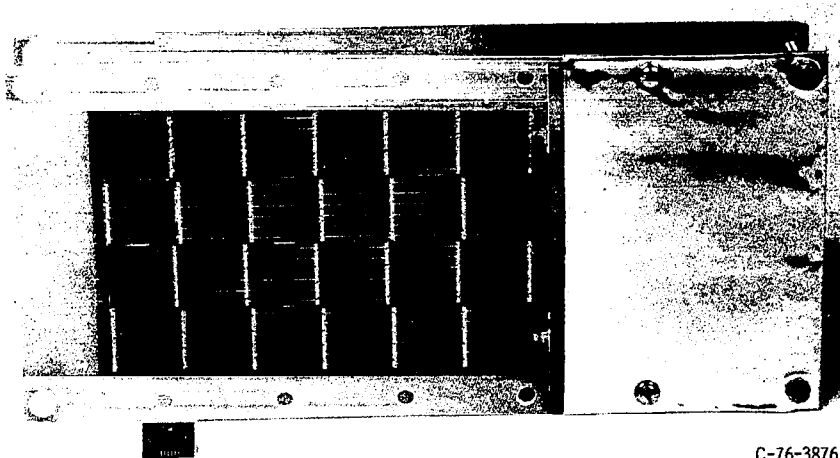
The above conclusions are based on extensive testing of a small 24-cell solar array, samples with insulators surrounding the electrodes, and limited testing of a 370-cell solar array panel. For the sizes anticipated for future spacecraft, much larger arrays must be tested and the scaling laws formulated. Extrapolations from the small array data is not logical.

For negative bias, arcing is a serious problem. In both the ground and the flight tests, arcing created large transient currents which caused the power supplies to trip off. It is theorized that these arcs originate from sharp minute asperities on the array. If this is true, one would expect the asperities to be burned off as the testing time is increased. The testing time for the samples reported herein was too short to substantiate this hypothesis, however.

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Figure 1. - 24-Cell solar array used in ground and flight tests.

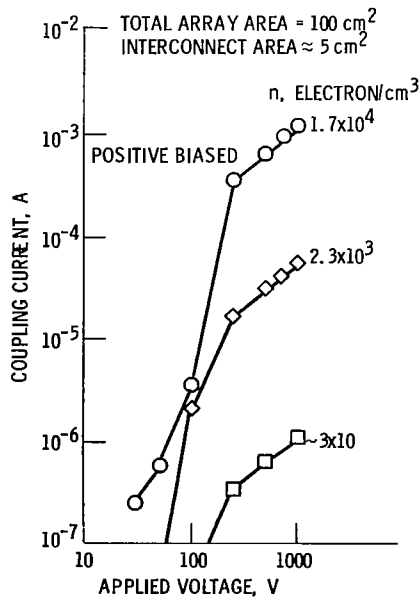


Figure 2. - Coupling current as a function of positive applied bias voltage to the 24-cell solar array panel at three plasma densities.

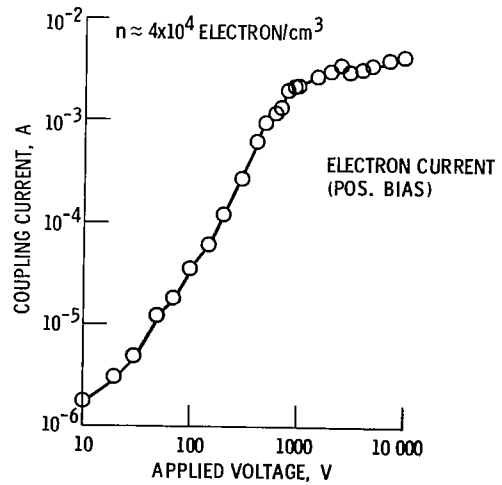


Figure 3. - Coupling current as a function of positive bias voltage to the 24-cell solar array up to 10 kV.



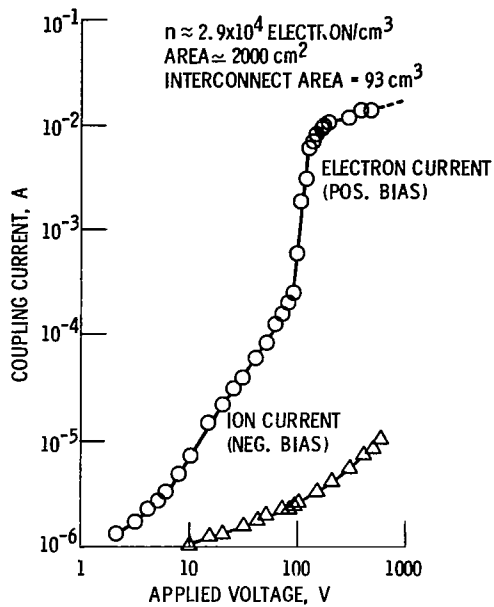


Figure 4. - Coupling current as a function of positive applied voltages to the large 370-cell solar panel.

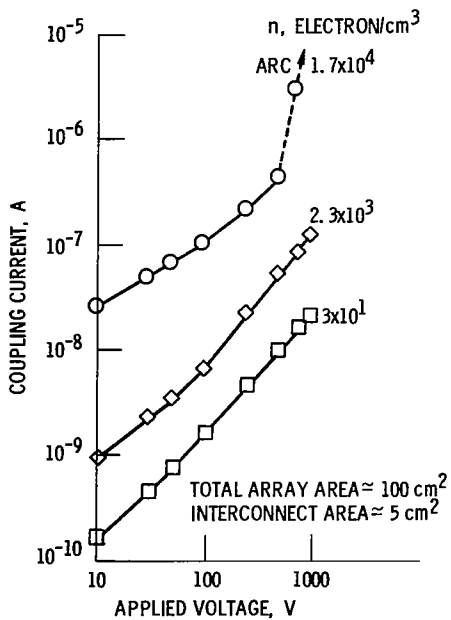


Figure 5. - Coupling current as a function of negative applied voltages to the 24-cell solar array for three plasma densities.

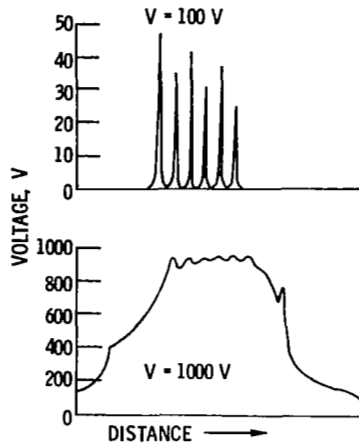


Figure 6. - Voltage profile across the 24-cell solar array. Positive bias.

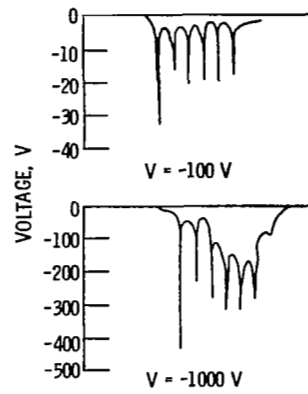


Figure 7. - Voltage profile across the small 24-cell array. Negative bias.

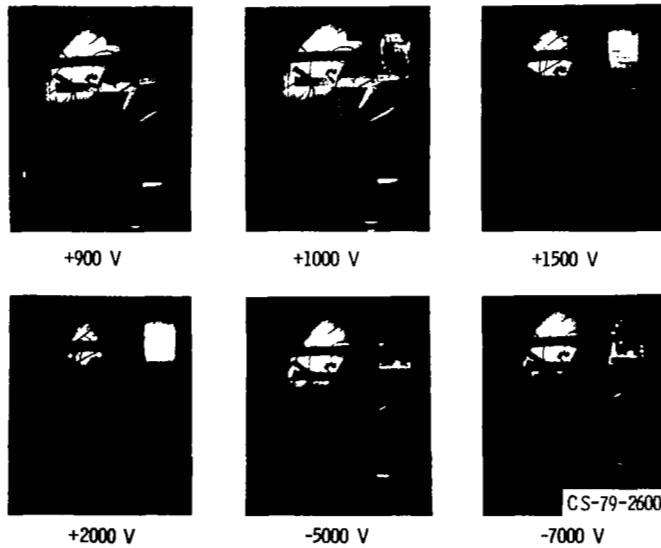


Figure 8. - Small 24-cell solar array (upper right hand quadrant) with phosphor covering the array, various bias voltages.

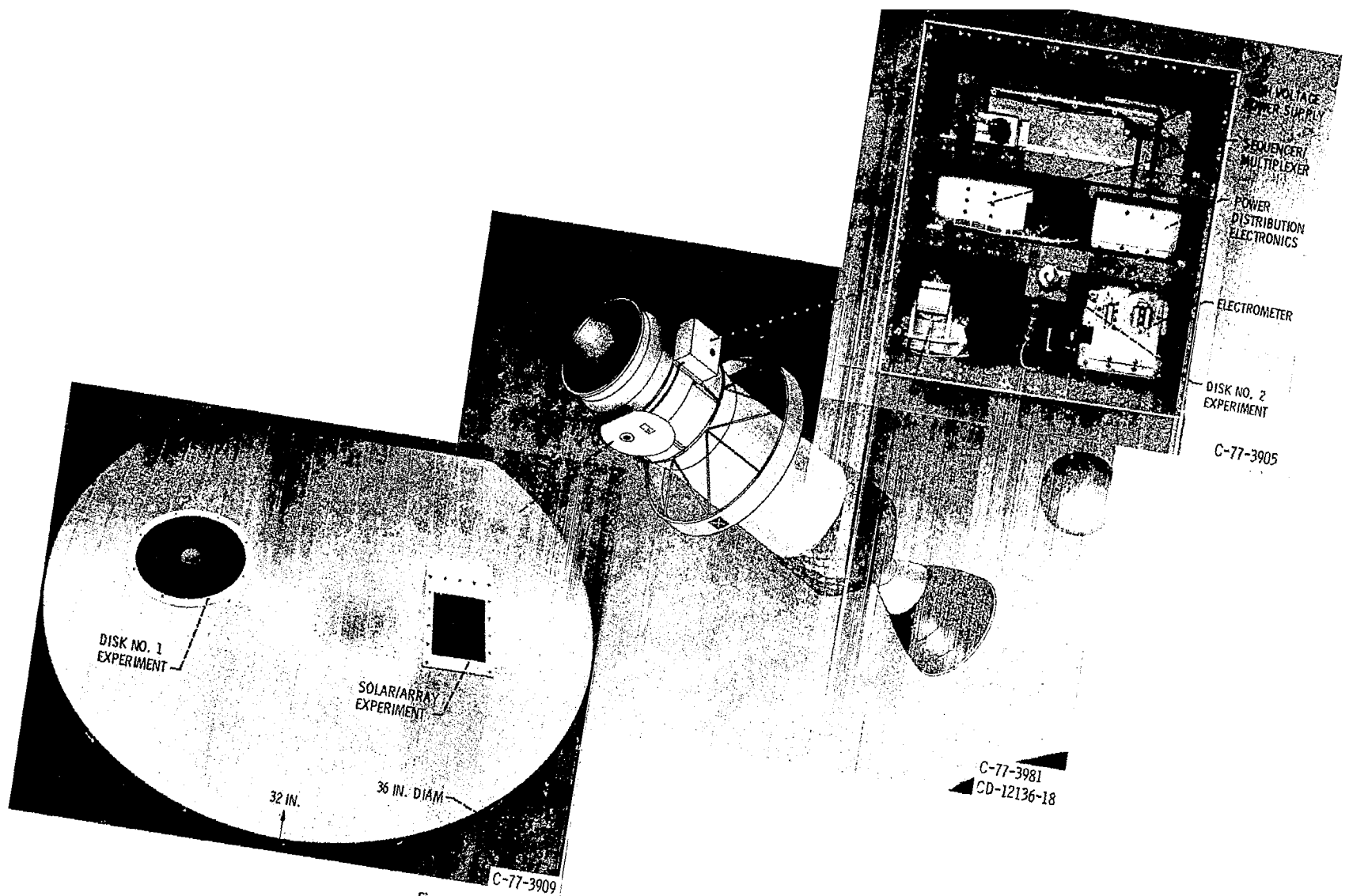


Figure 9. - Overview of Plasma Interaction experiment.

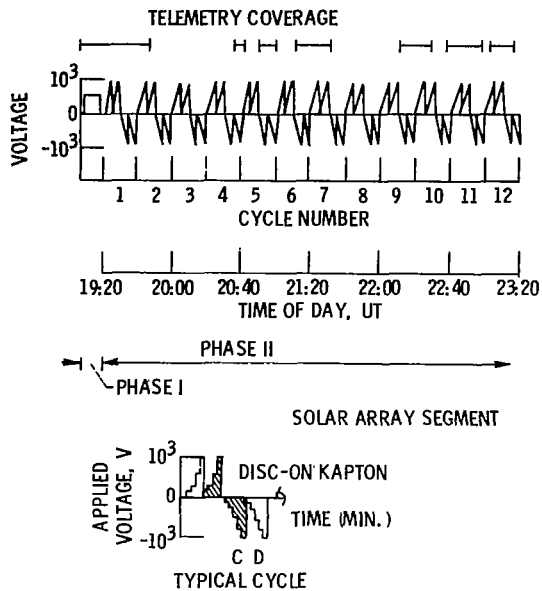


Figure 10. - PIX operational sequence.

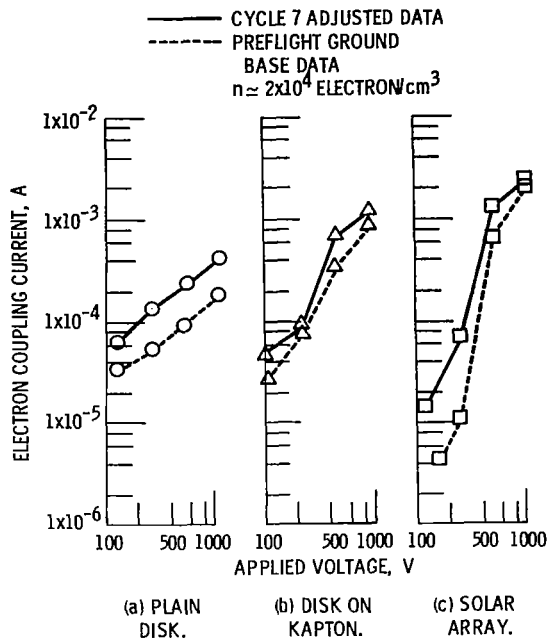


Figure 11. - Adjusted flight current for cycle 7 compared with preflight ground current as a function of applied voltage.

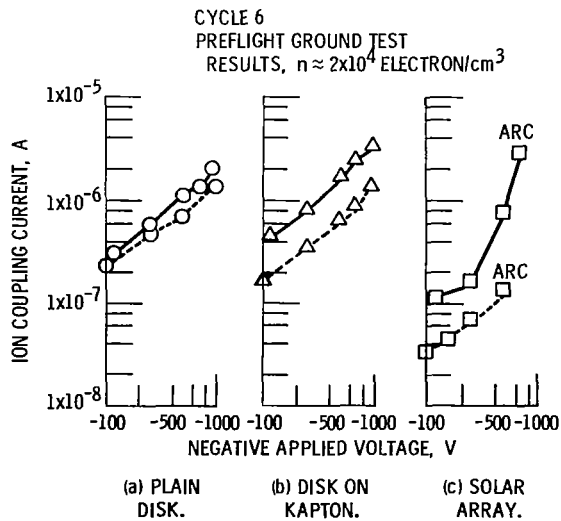


Figure 12. - Flight ion current for cycle 6 compared with preflight ground current as a function of applied voltage.

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16. Abstract <p>The large power systems required for future satellites may be more efficient if the solar array panels operate in the kilovolt range. Solar arrays operating in this voltage range in the space environment can exhibit adverse surface-charged particle interactions. These interactions were studied in this investigation for a small 100 sq cm conventionally-constructed solar cell panel in ground facilities and in a flight experiment. This array was biased with an external power supply between <math>\pm 1000</math> volts in a plasma with densities of <math>\sim 10^4</math> electron/cm<sup>3</sup>. The flight experiment, PIX (Plasma Interaction Experiment), was an auxiliary payload on the Landsat-C launch. The flight data substantiated preflight ground test results showing that at high positive biases the cover glass over each solar cell enhances the coupling current and that, at high negative biases, arcs create large transients in the coupling current.</p>			
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