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LDEF SPACE PLASMA-HIGH VOLTAGE DRAINAGE EXPERIMENT POST-FLIGHT RESULTS

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INTRODUCTION

The Space Plasma-High Voltage Drainage Experiment (SP-HVDE) was comprised of two identical experimental trays. With one tray located on the leading (ram facing, B10) edge and the other located on the trailing (wake facing, D4) edge of the LDEF, it was possible to directly compare the effects of ram and wake spacecraft environments on charged dielectric materials. Six arrays of Kapton dielectric samples of 2 mil, 3 mil, and 5 mil thicknesses maintained at +/- 300 +/- 500, and +/- 1000 voltage bias formed the experimental matrix of each tray. In addition, each tray carried two solar cell strings, one biased at +300 volts and the other at -300 volts, to study current leakage from High Voltage Solar Arrays (HVSA).

The SP-HVDE provides the first direct, long-term, in-flight measurements of average leakage current through dielectric materials under electric stress. The experiment also yields information on the long term stability of the bulk dielectric properties of such materials. Data and findings of the SP-HVDE are an extension of those from shorter term flight experiments such as the PIX-I (Plasma Interaction Experiment) and PIX-II [1,2,3] and are therefore valuable in the design and evaluation of long-lived space systems with high voltage systems exposed to the low earth orbital environment.

This paper is a summary the SP-HVDE post flight analysis final report delivered to the LDEF Project Office under contract to the National Aeronautics and Space Administration.

MISSION PROFILE

The LDEF was placed in a 482 km, near circular, orbit of 28.4 degree inclination on April 7, 1984 by the Space Shuttle Challenger. The LDEF was to have been retrieved from space after a two-year mission, but due to a catastrophic Shuttle launch incident and subsequent two-year hiatus from Shuttle launches, the LDEF was not retrieved until January 12, 1990 by the Columbia orbiter at an altitude of 340 km. The SP-HVDE gathered data over the first 233 days of the LDEF mission.*

Even though the objective of the SP-HVDE was not to characterize the space environment, knowledge about that environment is helpful in understanding the experimental results, therefore a summary of the LDEF environment experienced by SP-HVDE is included in Table 1. The ram-facing tray of the SP-HVDE saw micro meteoroids and space debris (M/D) as well as energetic atomic oxygen. On the wake-facing side of the LDEF, the trailing-edge tray saw a substantially lower flux of atomic oxygen and space debris. Both trays incurred essentially the same natural radiation dose.

* Harry Dursch, LDEF Systems Special Investigation Group, private communication, 1991.

Table 1. SP-HVDE Space Environmental Exposure Summary

	Leading Edge (D-10)†	Trailing Edge (B-4)†
Atomic Oxygen	$7.88 \times 10^{21}/cm^2$	$1.15 \times 10^5/cm^2$
UV	10698 Eqv. sun hrs.	10458 Eqv. sun hrs.
M/D	187 Impact sites (1.3×10^{-5}) (Frational Area Coverage)	23 Impact sites (2.0×10^{-6}) (Frational Area Coverage)

† Tray location designation

SP-HVDE CONFIGURATION

A schematic of the SP-HVDE is shown in Figure 1. Separate coulombmeters were employed to obtain time integrals for the leakage current and bias voltages for each set of samples. These devices can record currents flowing in either direction by either deplating or plating the electrodes. The Plessey coulombmeters used in the experiment had been plated to 10,000 mA-seconds by the manufacturer. The duty cycle of the storage capacitor was 0.5%, with the power processing unit, consisting of DC-DC power converters controlled by a switching circuit, satisfying the duty cycle requirement.

Each tray contained six sets of four dielectric samples, with each set maintained at a different bias voltage (i.e., ±300, ±500 or ±1000 volts). The sets were comprised of various combinations of Kapton/VDA film in one of three thicknesses (i.e., 2 mils, 3 mils, and 5 mils) bonded to the fiberglass/epoxy substrate with a 60 wt% silver loaded epoxy. Thus, the long-term average leakage current and resistivity were determined by using a matrix of dielectric samples of different thicknesses and biases comprising 22 dielectric samples per tray. The adhesive and the VDA (Vapor Deposited Aluminum) served as conducting layers of the dielectric stack for collecting leakage current. The layered construction of the dielectric stacks is shown in Figure 2. Both trays also contained two solar cell modules, one maintained at +300 and the other at -300 volts bias. Each cell module consisted of three solar cells in a closed loop circuit with a load resistor.

POST-FLIGHT RESULTS

The striking contrast in the post-flight condition of the leading and trailing edge trays is evident in Figures 3 and 4. The trailing edge tray appears essentially the same as it did when the LDEF was deployed, but the leading edge tray shows the result of exposure to an atomic oxygen fluence of $7.88 \times 10^{21}/cm^2$. Of course the complete erosion of the Kapton material radically changes the dielectric properties of the experiment, but over the intended functional period of the experiment, approximately 1.5 mils of Kapton were eroded by the action of energetic atomic oxygen. Leakage current data, taken during the 233 day design life of the SP-HVDE, are presented below.

Leakage Current Measurements

Average leakage currents versus sample thickness and bias voltage for both trays are shown in Table 2. The average leakage current was obtained by measuring the current required to deplate the coulombmeters back to the pre-flight condition of 10,000 mA-seconds. The deplating process serves to integrate leakage current over time and yields an average over the operational life of the experiment. During the course of post-flight measurement, 6 of the 152 coulombmeters exhibited anomalous behavior, *i.e.*, 3 showed "open circuit" such that the readout equipment could not deplate the coulombmeter and 3 coulombmeters showed "short circuit" such that deplating during readout did not terminate at the pre-flight endpoint.

Table 2. Average Leakage Current (micro amperes)

Trailing-edge Thickness (mil)	Bias Voltage(V) +300	+500	+1000	-300	-500	-1000
5	N/D	0.53	0.11	N/D	0.17	0.196
3	0.196	0.43	1.9	0.194	N/D	0.184
2	0.36	0.16	N/D	0.27	0.2	N/D

Leading-edge Thickness (mil)	Bias Voltage(V) +300	+500	+1000	-300	-500	-1000
5	N/D	1.3	0.61	N/D	0.496	0.48
3	0.598	1.0	1.2	0.497	0.38	0.487
2	0.58	-0.65	N/D	N/D	N/D	N/D

N/D=No Data

Ground simulations predicted leakage current to increase with positive bias voltage and decrease with greater dielectric sample thickness. Figure 5 shows the leakage current data for positively biased samples on the leading and trailing edge trays. The data show that only the 3 mil samples followed the predicted trend and that the 5 mil samples showed an unexpected decrease in leakage current over the 500 to 1000 +volt range. The limited data obtained for the 2 mil samples also seems to follow the atypical trend, although the 2 mil sample did demonstrate an expectedly larger leakage current compared to the thicker samples at the 300 +volt bias.

Leakage current data shown in Figure 6, for negatively biased samples, are distinctly different compared to those for positively biased samples. For the negatively biased condition, the leakage currents obtained are lower than those measured for the positive bias condition by a factor of three. Also of significance is the smaller change in leakage current across the voltage range. It is speculated that for the negatively biased surfaces even the lowest voltage (i.e., -300 volts) is beyond the threshold at which interaction with the space plasma results in localized but intense electrodischarge events. The occurrence of such discharges is consistent with the lower post-flight average leakage currents measured and also consistent with work performed by Thiemann, et al. (ref. 4) which reported greater numbers of discharges for negatively biased surfaces during ground simulations. The reason for the dip in the leakage current at -500 volts for the 3 mil sample on the leading edge tray is unclear at this time, but it should be noted that a similar phenomenon was seen in the data from the PIX-I experiment (see ref. 1).

Dielectric Property Measurements

The leakage current time integrals and bias voltages permit the calculation of an average resistivity across the dielectric sample stack. Tables 3 and 4 show the average voltages and resistivities derived from post-flight measurements.

Table 3. Average Voltage (V)

Bias Voltage (V)	+300	+500	-300
Trailing-edge Tray	123.4	N/D	57.1
Leading-edge Tray	16.2	N/D	326.2

N/D=No Data

Table 4. Derived Resistivity (ohm-cm)

Trailing-edge Tray Thickness (mil)	Bias Voltage(V) +300	-300
5	N/D	N/D
3	2.3×10^{13}	1.1×10^{13}
2	2.0×10^{13}	1.2×10^{13}
Average:	2.2×10^{13} ohm-cm	1.2×10^{13} ohm-cm

Leading-edge Tray Thickness (mil)	Bias Voltage(V) +300	-300
5	6.8×10^{11}	N/D
3	1.4×10^{12}	6.2×10^{13}
2	5.5×10^{12}	6.6×10^{13}
Average:	3.8×10^{12} ohm-cm	6.4×10^{13} ohm-cm

Unflown reference Kapton: $\rho = 3 \times 10^{15}$ ohm-cm at +300 V bias.

Solar Cell Module Characterization

We were very pleased to be able to locate the original set of control samples for the SP-HVDE solar cell modules after some ten years since the experiment was first conceived. These control samples gave us the opportunity to compare not only the relative performance of leading and trailing edge flight specimens but also to compare the flight data to a baseline reference. Having found the control cells, there was however some question as to exactly what type of cells they were and the type of coverglass used. Based on the age and configuration of the cells it is reasonably certain that the cells are of a low efficiency, 10 ohm-cm, single crystal silicon type with fused silica coverglass and conventional bar interconnects.

One of the cells on a leading edge module experienced an impact by a micro meteoroid or debris particle which, from the data shown in Tables 5 and 6, resulted in a significant reduction in performance. Scanning electron micrographs of the impact site are presented in Figure 7. The particle penetrated the coverglass and the silicone coverglass adhesive and produced a raised and melted spall zone on the silicon solar cell. The damage to the cell extends well beyond the immediate impact site with radial cracks in the coverglass extending 0.25 inches from the impact center. Elemental analysis of the impact site did not reveal any material that could be conclusively identified as extraterrestial or as anthropogenic debris.

Environmental Interaction

The metal interconnect strips between the cells of each module were exposed to the ambient space plasma, providing a path for current leakage. The area ratio of interconnect to coverglass is 2.8%. As with the other charged surfaces of the experiment, average current integrals were obtained through coulombmeters. The average current integrals for each cell flight module are presented in Table 6.

Table 5. Electrical Characteristics of
LDEF SP-HVDE Solar Cell Modules

Cell Module Number/Type	V_{oc}(V)	I_{sc}(A)	V_{mp}(V)	I_{mp}(A)	P_{mp}(W)	Comment
# 1, Trailing	1.63	0.285	1.36	0.271	0.369	
# 2, Trailing	1.63	0.286	1.36	0.272	0.370	
# 3, Leading	1.63	0.290	1.36	0.272	0.369	
# 4, Leading	1.64	0.223	1.51	0.222	0.336	Particle Impact
# 5, Control	1.64	0.287	1.37	0.275	0.377	
# 6, Control	1.64	0.287	1.37	0.273	0.374	

Table 6. Derived Current Integrals & Average Currents

Trailing-edge Tray:

Bias Voltage:+300 V		Bias Voltage: -300 V	
Current Integral (mA-second)	I_{av} (micro ampere)	Current Integral (mA-second)	I_{av} (micro ampere)
-469.74	-2.3×10^{-2}	1509.85	7.5×10^{-2}

Leading-edge Tray:

Bias Voltage:+300 V		Bias Voltage: -300 V	
Current Integral (mA-second)	I_{av} (micro ampere)	Current Integral (mA-second)	I_{av} (micro ampere)
5411.92	2.7×10^{-1}	355.30	1.8×10^{-2} (one cell damaged by M/D impact)

CONCLUSIONS

The concept of the High Voltage Solar Array (HVSA) was created around 1973. The goal of this power-efficient concept was to allow power conversion directly from the modular solar array to high voltage systems. In the early 1980s, the solar array community envisioned that SDIO would require many large solar power systems employing HVSA technology. Instead, the interest in the HVSA concept has materialized in the form of the proposed Space Station Freedom. The Space Plasma-High Voltage Drainage Experiment has extended the existing data base on spacecraft charging and current leakage phenomena first studied by the PIX-I and PIX-II experiments. The SP-HVDE also makes a substantive contribution to the overall LDEF solar cell data package which has confirmed the robustness of design practices and materials selection. The information obtained from the retrieved the LDEF has made an incalculable contribution to the database of space environmental effects on materials and spacecraft aging.

REFERENCES

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2. N.T. Grier, "Plasma Interaction Experiment II(PIX-II): Laboratory and Flight Results", in Spacecraft Environmental Interactions Technology - 1983, NASA CP-2359/AFGL-TR-85-0018, 1985, pp. 333-348.

3. N.J. Stevens, "Summary of PIX-2 Flight Results Over the First Orbit", AIAA-86-360, AIAA 24th Aerospace Sciences Meeting, Jan. 6-9, 1986, Reno, Nevada.

4. I. Thiemann and K. Bogus, "Anomalous Current Collection and Arcing of Solar-Cell Modules in a Simulated High-Density Low-Earth-Orbit Plasma", ESA J., 10, 43, (1986).

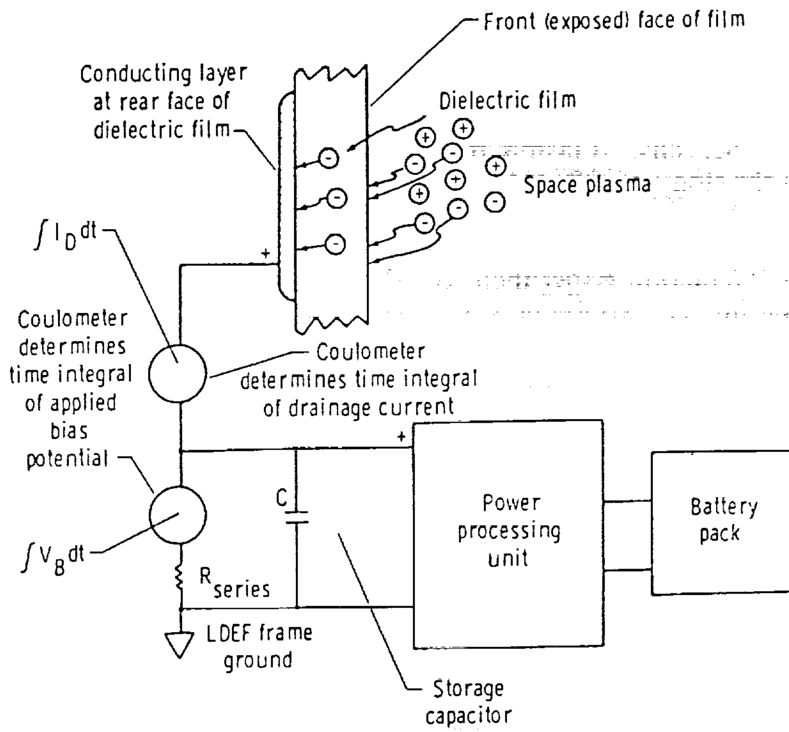


Figure 1. Schematic of SP-HVDE

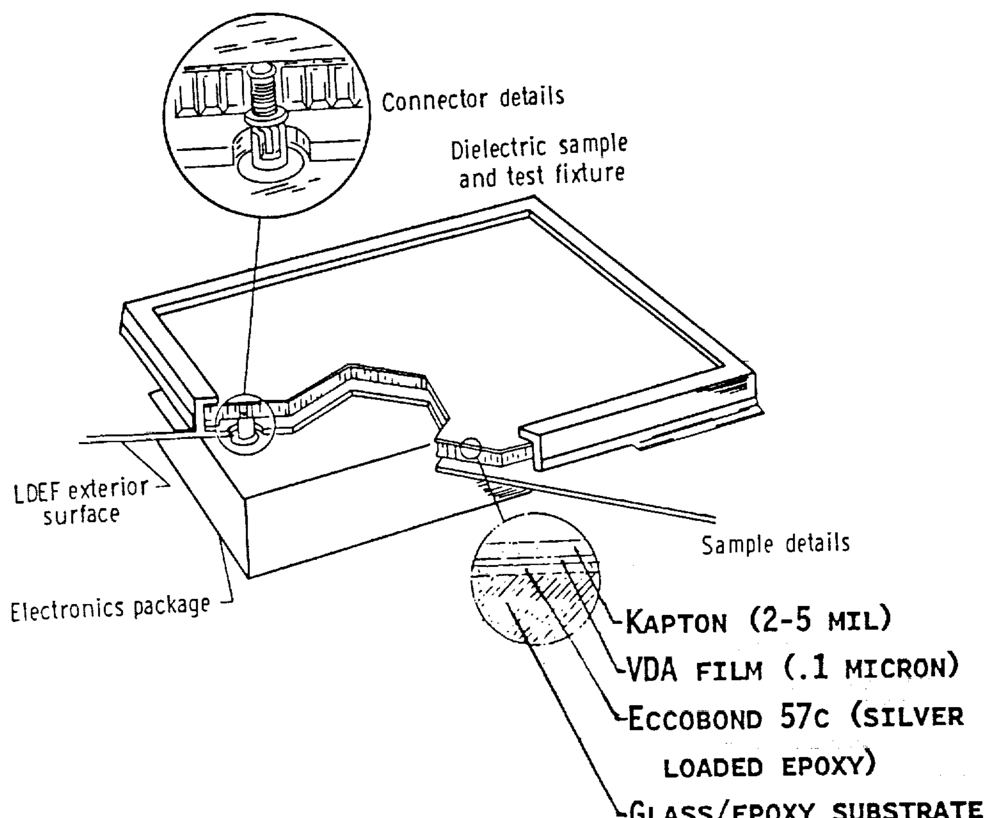


Figure 2. Dielectric Sample Construction

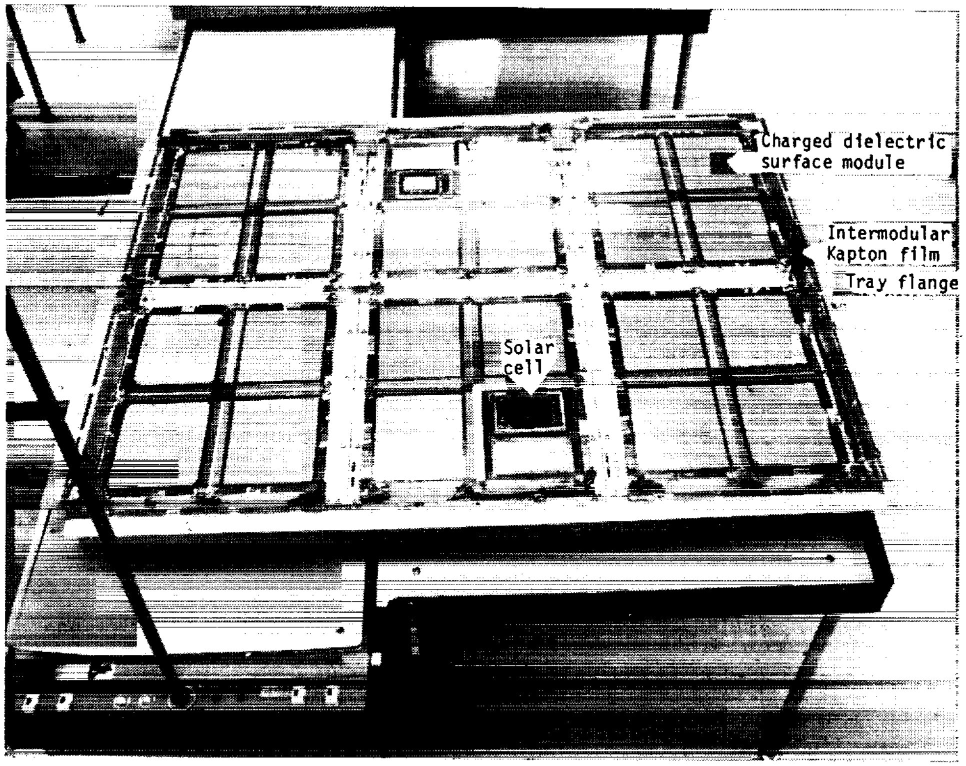


Figure 3. Leading Edge SP-HVDE Tray (Post Flight)

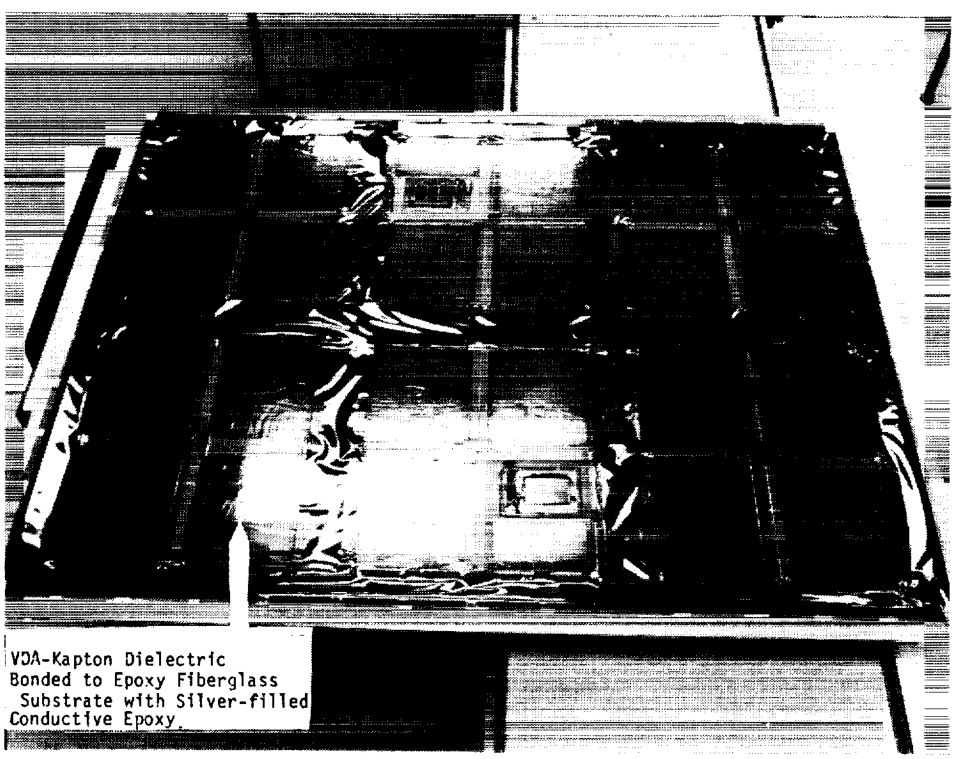
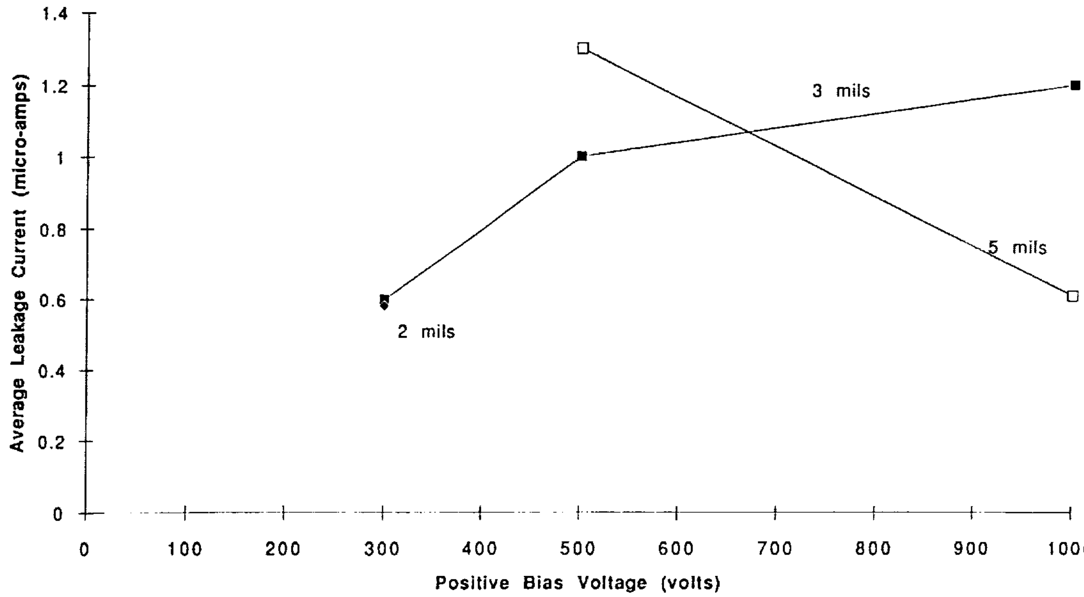


Figure 4. Trailing Edge SP-HVDE Tray (Post Flight)

Ram-Facing Tray



Wake-Facing Tray

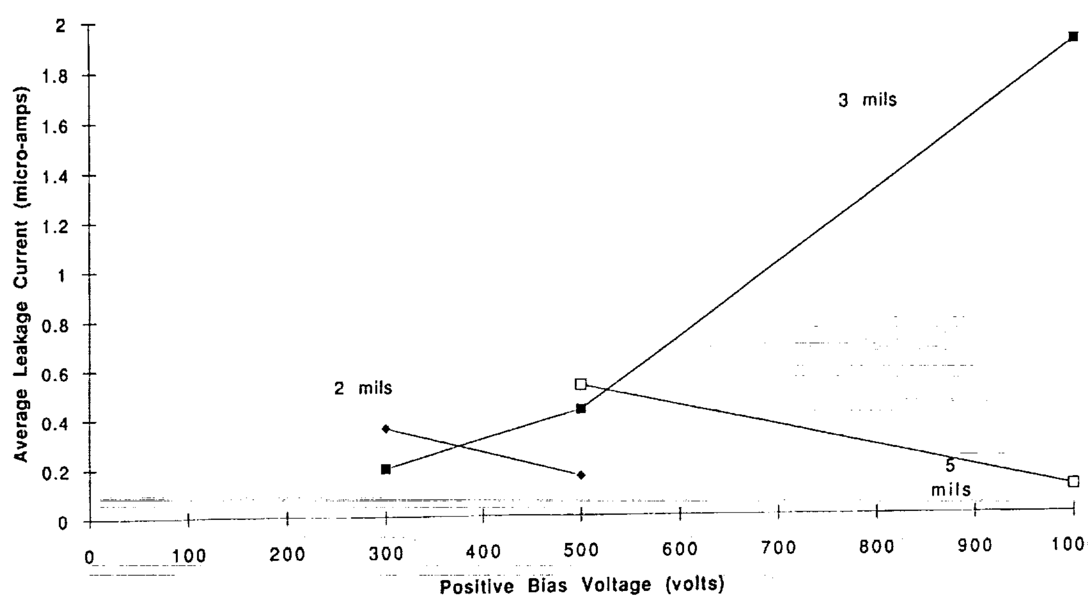
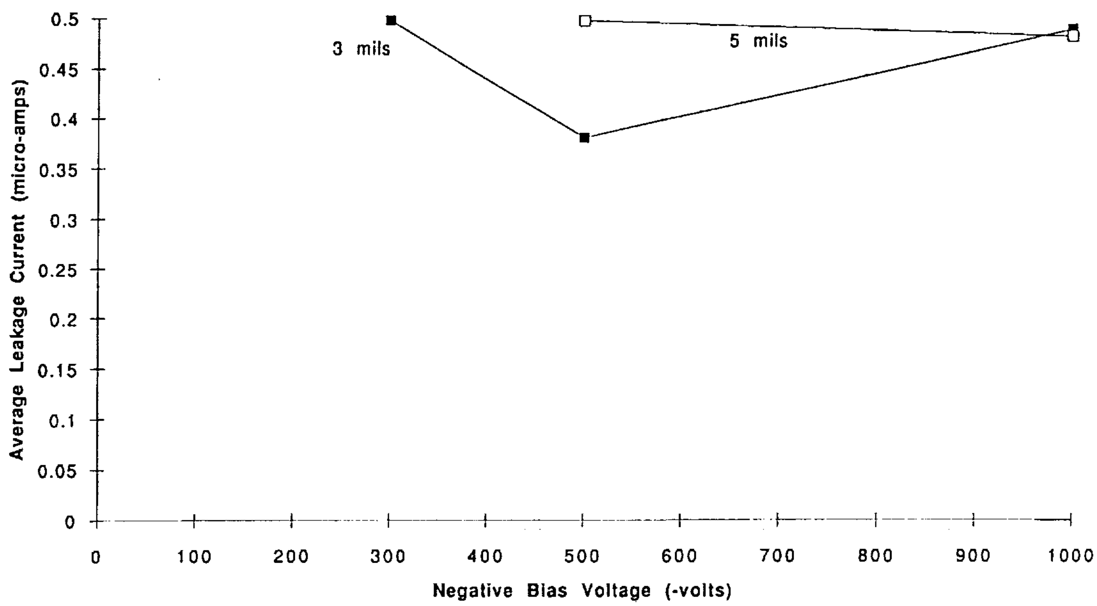


Figure 5. Average Leakage Current Data for Positive Bias Voltage Samples

Ram-Facing Tray



Wake-Facing Tray

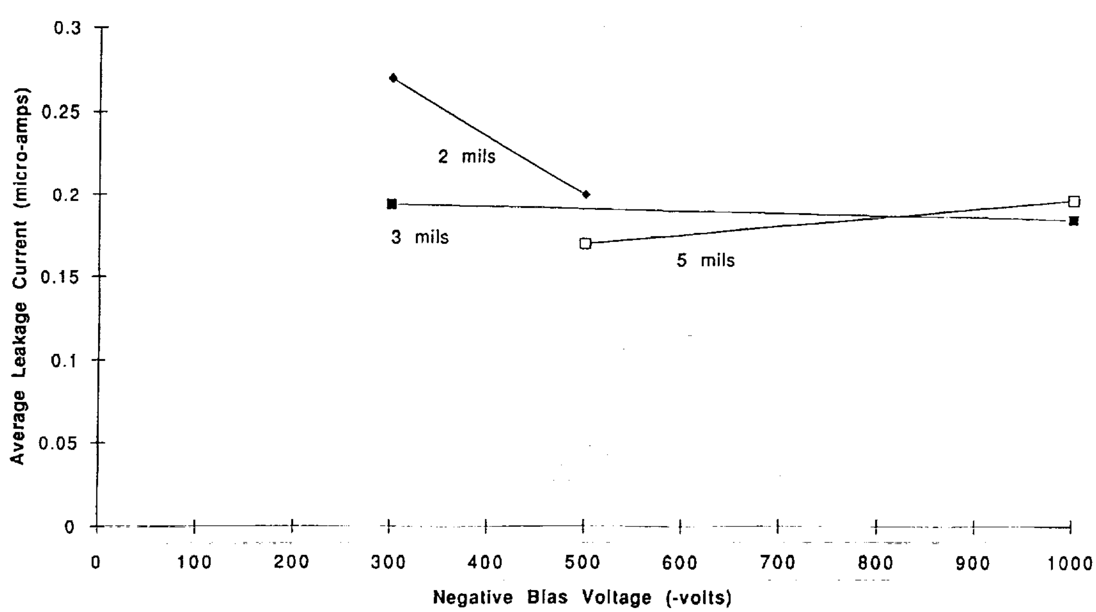


Figure 6. Average Leakage Current Data for Negative Bias Voltage Samples

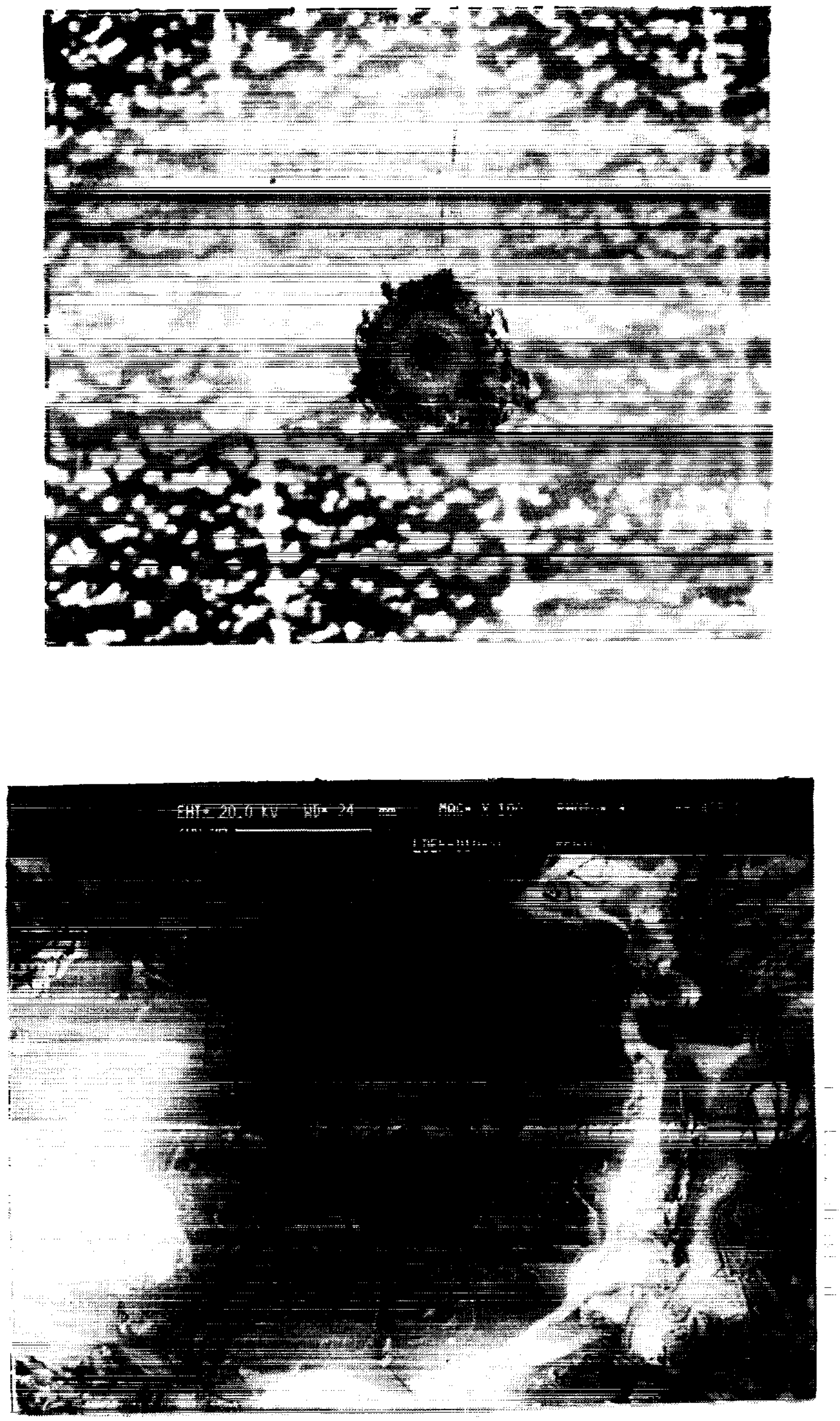


Figure 7. Impact Site on Photovoltaic Cell Stack