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# Laboratory Study of the Charging of Spacecraft Materials

M.S. Leung* and H.K.A. Kan†
*The Aerospace Corporation, El Segundo, Calif.*

**Charging profiles of typical spacecraft materials received from the Satellite Surface Potential Monitor experiment aboard the P78-2 satellite show a number of interesting as well as unexpected features. During the natural charging event on April 24, 1979, the Kapton sample was charged to a voltage significantly lower than that of the Teflon sample, whereas earlier test results showed they should be comparable. At the same time, also contrary to previous ground measurements, the quartz fabric sample acquired a surface potential up to several kilovolts instead of a few hundred volts normally observed in the laboratory. In order to resolve the differences observed between flight and ground measurements, a laboratory study has been carried out. Based on this study, these unexpected flight measurements can now be explained.**

## Introduction

CHARGING of dielectric materials in natural space environments has been the subject of intense investigation over the past several years.[1] However, in situ data on how individual materials behave during geomagnetically quiet or disturbed times are still lacking. Most of the available data have been obtained by either modeling or ground simulation. The validity of these results in the natural space environment has not yet been demonstrated. For this reason, the Satellite Surface Potential Monitor (SSPM) experiment on the USAF P78-2 satellite was designed specifically to measure the surface potentials and bulk currents of various types of common spacecraft thermal control materials in the near-geosynchronous altitude. The on-orbit measurements will provide a framework whereby the validity of the results from various ground-based simulations can be examined. The laboratory study reported here helped explain some unexpected flight results.

## Background

On January 30, 1979, the P78-2 satellite was launched into near-geosynchronous orbit as part of the Spacecraft Charging at High Altitudes (SCATHA) program. Up to now, only a small portion of the SSPM flight data have been analyzed. The survey data indicate that the SSPM instruments are functioning normally. In addition, the initial flight results have been found to contain a number of unexpected features. In particular, the charging levels of the Astroquartz (quartz fabric) and the Kapton samples did not agree with the preflight monoenergetic electron beam calibration results. Previous measurements indicated that quartz fabric acquired a maximum of only a few hundred volts under controlled laboratory simulations. However, the SSPM results obtained during the April 24, 1979 natural charging event[2] showed that quartz fabric charged from a voltage level of −160 V at the onset of the event to about −3500 V, much higher than expected. Furthermore, in laboratory simulations, both Kapton and Teflon, the surface charged to about the same value which is approximately equal to the beam energy minus the second crossover energy on the secondary yield curve for the particular material. The second crossover occurs at about 1000 V for Kapton and 1800 V for Teflon. However, the April 24, 1979 data shows that the SSPM instrument measured −6500 V for Teflon and −1700 V for Kapton. It should be noted that the Teflon sample had acquired an offset voltage‡ of about −1600 V prior to this charging event. The actual voltage increase due to electron injection was approximately −3900 V for Teflon. This difference is too large an effect to be attributed solely to changes in sample characteristics or measurement response differences, and it must represent an intrinsic difference in the responses of the Kapton and Teflon samples to the environment. The following reports the results of several laboratory experiments designed to resolve the observed discrepancies between ground and flight measurements.

## Experimental Set-Up

The laboratory apparatus used in this study is shown in Fig. 1. In order to provide direct comparison with the flight data, ground measurements were made using the prototype SSPM instrument. The SSPM instrument was designed to measure 1) the differential voltage between the sample surface and the spacecraft ground and 2) the bulk current flowing through the sample. A detailed description of the experiment has been given by Stevens and Vampola.[3] The potential of the front surface, the surface that is exposed to the charging environment, is obtained by calibrating the back surface potential against independent front surface measurements. Calibration results for the SSPM instrument indicated good correlation between the front and the back voltages. A more detailed description of the SSPM voltage measurement principle is given in Ref. 4. In both the flight and laboratory samples, the sample is mounted with the metallized back surface cemented to the sample board with conductive silver epoxy. In the case of the Astroquartz, the fabric was heat laminated onto a piece of silvered Telfon on the Teflon side. The silvered side was then cemented with conductive epoxy to the sample board. A small portion of the Teflon film directly above the sensor was cut out to ensure that only the fabric falls within the field of view of the electrostatic sensor. Because there was a concern as to whether the presence of the Teflon backing may in fact alter the charging characteristics of the quartz fabric, laboratory measurements were also performed on samples prepared with no Teflon backing. These samples were prepared by bonding the fabric directly on the sample board with a thin layer of conductive epoxy. Care was taken such that the adhesive did not interfere with the measurement.

## Results

A natural charging event was recorded in sunlight by the P78-2 satellite near local midnight on April 24, 1979. As the spacecraft entered the Earth's shadow, the satellite structure

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*Member of Technical Staff, Chemistry and Physics Laboratory, Laboratory Operations.

†Section Head, Chemistry and Physics Laboratory, Laboratory Operations.

‡The voltage offset appears to be the result of charges trapped in the bulk of the material. Attempts to photodischarge the sample on orbit have succeeded in reducing the offset.

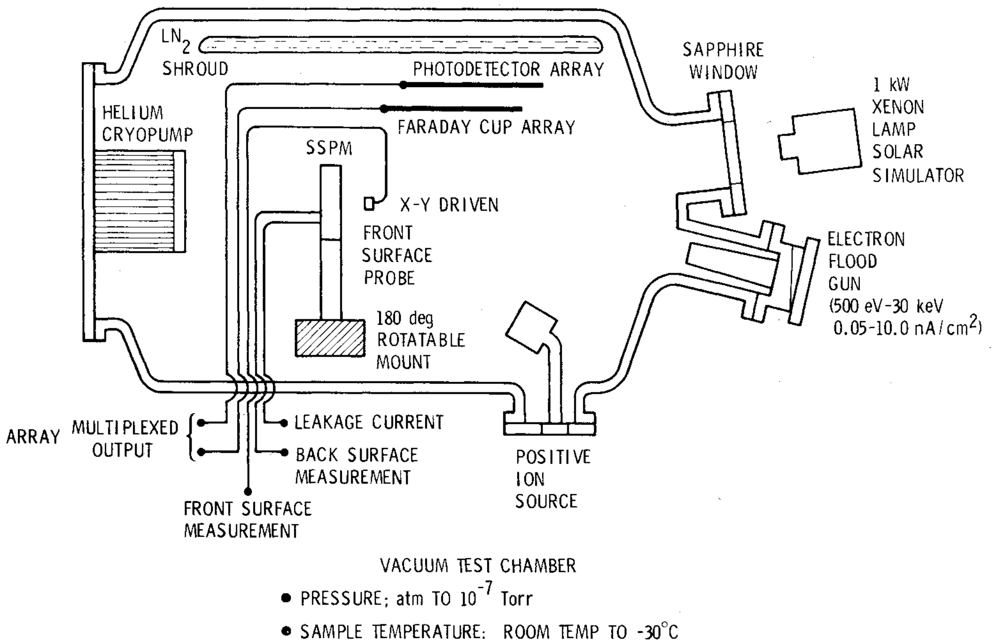


**Fig. 1 Schematic of the space simulation facility.**

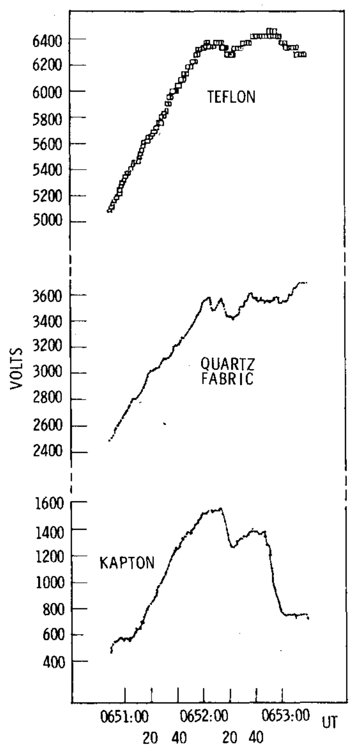


**Fig. 2 Voltage-time profiles observed during the April 24, 1979 charging event.**

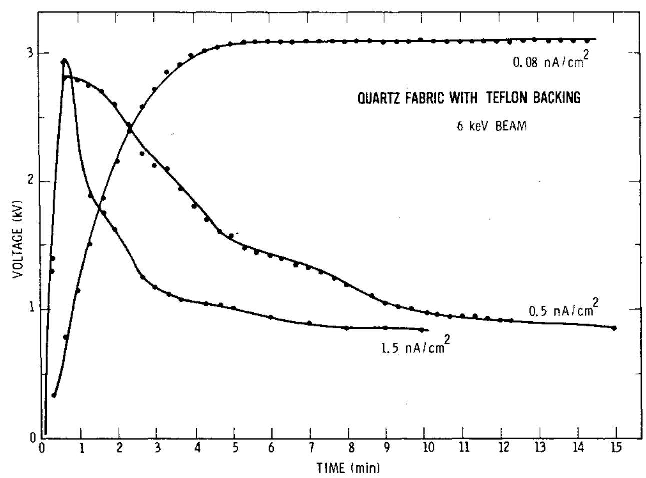


**Fig. 3 Typical response of a quartz fabric sample with silvered Teflon backing under laboratory electron irradiation.**

charged to between 5 and 8 kV as indicated by energy shifts in the ion particle spectra. Voltage-time profiles from three SSPM samples are plotted vs Universal Time (UT) in Fig. 2 just before the satellite entered Earth's eclipse. However, we should note that the results represented in Fig. 2 were obtained from samples which were shielded from direct solar irradiation by the spacecraft shadow during normal operation. All three samples showed that charging was taking place. Specifically, the Teflon sample acquired a higher voltage than the Kapton sample. During the same event, the Astroquartz sample charged to several kilovolts. These observations cannot be explained satisfactorily by results obtained from previous laboratory measurements.

### Quartz Fabric

Simulation experiments performed in our laboratory using a monoenergetic electron beam with energies between 6 and 12 keV indicated that quartz fabric has an unusual charging/discharging behavior. Normally, when a well-behaved insulator is irradiated with an electron beam, the surface charges up exponentially to a certain voltage level. After the maximum value is reached and if the beam voltage is unchanged, the surface voltage would remain constant. The whole process resembles that of the charging of a simple capacitor. However, quartz fabric behaves quite differently. Each plot in Fig. 3 represents the time profile of the surface voltage with the fabric being continuously bombarded by 6-keV electrons at three different current densities, 1.5 $nA/cm^2$, 0.5 $nA/cm^2$, and 0.008 $nA/cm^2$. At high charging beam densities ($\sim 1.5$ $nA/cm^2$) the voltage measured on quartz fabric increases rapidly as soon as the beam is turned on ($t=0$) but then it also decreases rapidly after a maximum voltage of $\sim 3$ kV is reached. At a lower beam density ($\sim 0.08$ $nA/cm^2$), the sample slowly charges up to $\sim 3$ kV over a long time period. For intermediate currents, the behavior is similar to the high-current case but decays with a longer time constant. In time, the measured voltage decreases to a steady-state level of a few hundred volts even for the low-current case.

The strong current dependence of the voltage decay rate in quartz fabric is essential to the understanding of the discrepancy between ground and flight measurements. Previous ground measurements using electron beams to charge the quartz fabric were carried out typically at beam densities $\geq 1$ nA/cm$^2$ in order to simulate a severe substorm environment. However, in the April 24 event, the electron current density was estimated to be approximately 100 pA/cm$^2$. It is not surprising that the apparent disagreement may be the result of the vast difference in the intensity of the incident current in the two cases.

It should also be noted that while the fabric was charged to several kilovolts in the laboratory study, numerous small current spikes were observed in the bulk current measurements. These current spikes represent microarc discharges occurring at the fabric. The typical peak current is estimated to be in the microampere region. These discharges carry small amounts of energy and the long- and short-term effects are not well understood.

Measurements of the quartz fabric mounted without the Teflon backing exhibit similar charging behavior (Fig. 4), the differences being in the absolute beam current and voltage required to achieve a comparable level of charging. For the quartz fabric sample mounted without Teflon backing, it takes a lower current and a higher beam voltage to produce the same profile obtained from the sample mounted with Teflon backing. This difference is probably due to a higher sample capacitance and higher sample resistance introduced by the presence of the Teflon backing. Therefore, the results in Figs. 3 and 4 show that it is the quartz fabric, not the mounting material or configuration, that is responsible for the observed unusual beam-induced charging/discharging behavior. In order to simplify the discussion, only results from experiments performed on samples mounted with no Teflon backing in the laboratory tests will be examined in the following section.

To determine the cause of the unusual charging/discharging behavior, quartz fabric was examined using systematic variation of beam voltages and currents. The voltage-time profiles in Fig. 4 indicate that the time it takes the sample to reach the maximum voltage depends only on the beam current density, not on the beam voltage. A plot of the time to reach the maximum voltage vs bulk current shows a quasilinear dependence. This behavior suggests that quartz fabric charges up initially as a normal capacitor. However, after the maximum voltage is reached, the beam then causes the sample voltage to discharge. The voltage decay can be fitted roughly to a simple exponential time dependence from which a first-order rate constant can be extracted. A plot of the rate constant vs beam density at different beam voltages in Fig. 5 shows that the decay process is dependent on both electron beam density and voltage. Higher beam densities and lower beam voltages tend to cause the sample voltage to decrease more rapidly. This behavior suggests that the mechanism responsible for the beam-induced voltage decay in quartz fabric may be related to the secondary electron emission from the $SiO_2$ surface.

Further studies indicated that the fabric appeared to have a memory with respect to the charging history of the sample. When the beam is turned off at any point along the charging curve, the sample exhibits only a slight drop in voltage. When the beam irradiation is resumed, the sample immediately assumes the voltage level just before the turn-off and continues to charge or discharge as though there has been no interruption. A similar response is found at any point along the charging curve. At any given time, the sample appears to acquire a more or less permanent charge state determined by the total electron irradiation.

A model that is capable of explaining these unusual observations utilizes the fact that the quartz surface has a high secondary electron emission ratio and that the quartz fabric structure is quite porous. Besides having an extremely large surface-to-volume ratio, the fabric also has a large number of fibers shielded from direct irradiation by the beam. These shielded fibers will only be bombarded by scattered and secondary electrons which have succeeded in penetrating the fabric. These electrons in turn have energies degraded from those of the primary electrons. In addition the kinetic energies of the secondary electrons will further be modified by the potential difference between the emitting surface and the target surface. Thus, it seems reasonable that at some distance into the fabric, there are secondary electrons with a distribution of energies, and many of them will have the appropriate kinetic energy to cause the internal surfaces of the fabric to emit more than one electron per incident electron. Since the fabric is porous, the secondary electrons would eventually leak out, leaving the less mobile positive holes behind. Since at the onset the fabric behaves like a capacitor and charges up negatively, the accumulation of holes would cause the measured potential to become less negative in time, accounting for the observed voltage decay. This model is consistent with all the observations obtained so far and is also consistent with the theoretical and experimental work of Fitting et al.[5] and Mehnert.[6]

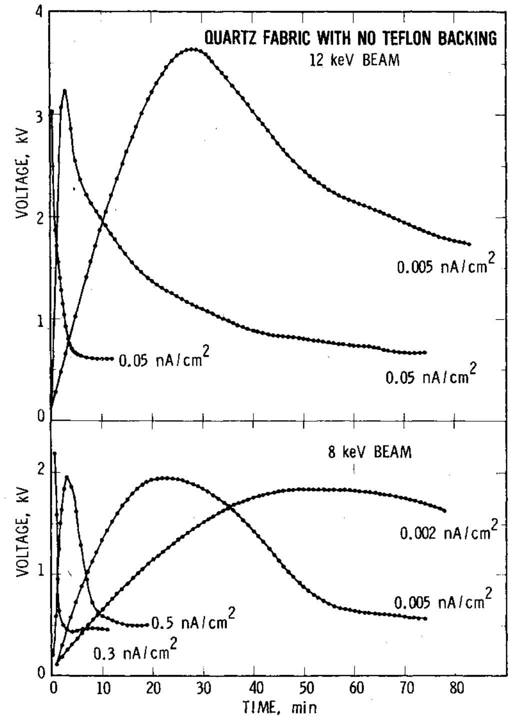


**Fig. 4 Charging profiles of quartz fabric samples without silvered Teflon backing.**

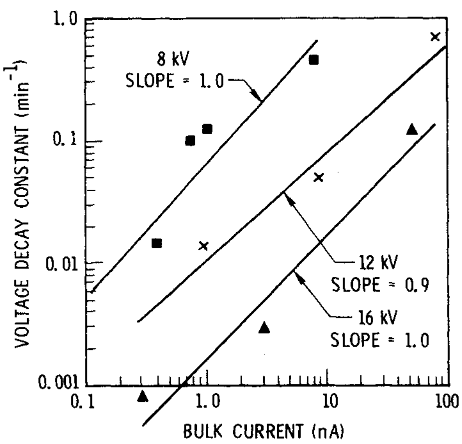


**Fig. 5 Voltage decay rate constant in quartz fabric.**

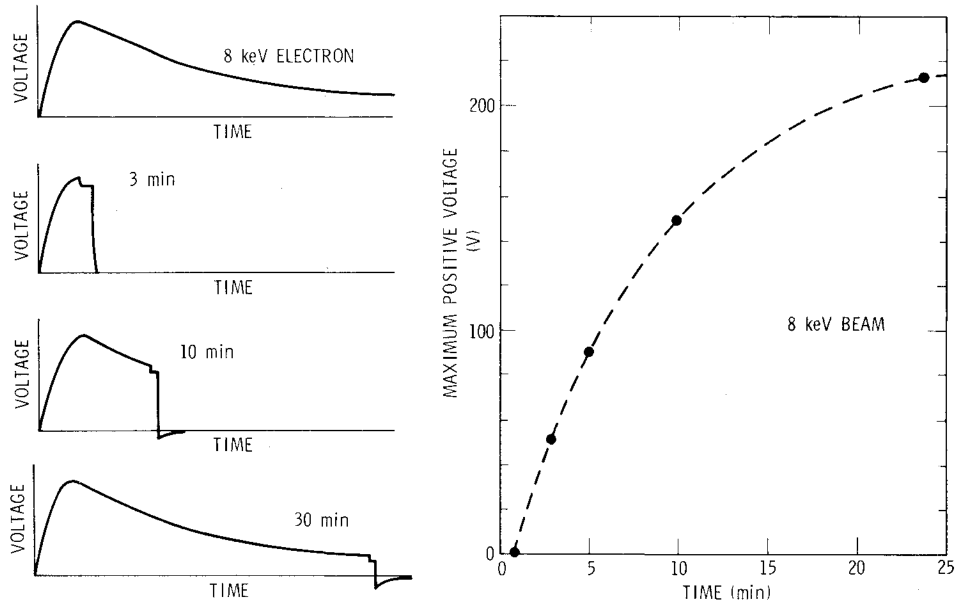


**Fig. 6 Effects of photoillumination and maximum positive voltage obtained as a function of electron irradiation time.**

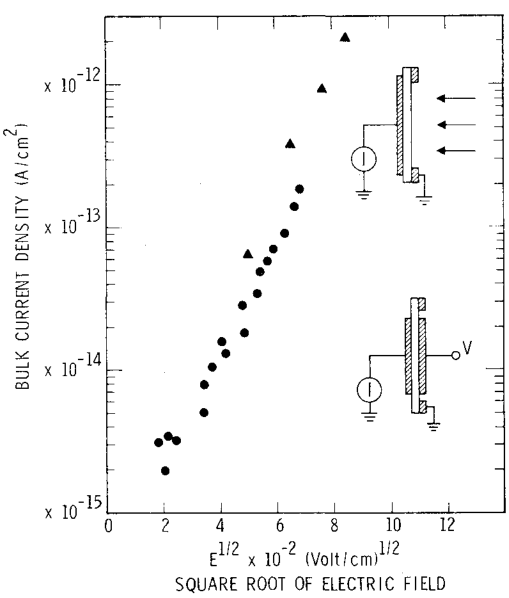


**Fig. 7 Bulk current vs electric field for aluminized Kapton.**

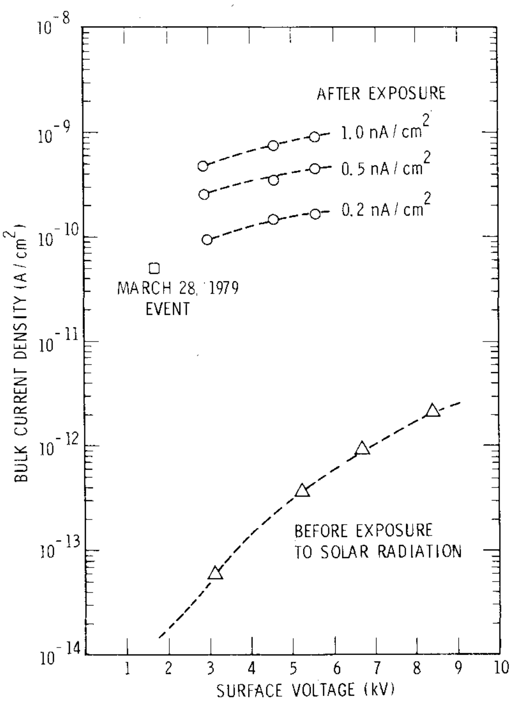


**Fig. 8 The dark conductivity of Kapton as modified by simulated solar light.**

To verify the model, a series of charge desorption experiments was carried out to detect the postulated residual positive charges. With an intense light source (1-kW xenon lamp), the electrons deposited on the quartz surface can be removed by photodesorption. The results indicated that, immediately after exposure to the intense visible and near-uv radiation, the sample exhibits a positive potential but it occurs only during the discharge portion of the irradiation curve. The results are shown in a series of voltage-time profiles in Fig. 6. The topmost curve shows the normal result of continuous electron irradiation with no photoillumination. The other curves show a slight drop in voltage caused by turning off the electron beam and then a sharp drop due to turning on the light, at various points on the voltage-time profile. Increasing with the electron irradiation time, the surface develops a positive potential as a result of photoillumination. With the light on, this positive potential reaches a maximum and eventually decays to zero as the sample becomes completely discharged. Further studies show that the maximum positive voltage due to the build-up of positive charges increases with electron irradiation time (Fig. 6). In addition, the time evolution of the maximum positive voltage resembles qualitatively the time dependence of the beam-induced discharge observed under continuous electron irradiation. These results lend further support to the proposed model.

#### Aluminized Kapton Films

The dark conductivity of Kapton films has been examined in detail as part of our laboratory effort. The results show that the current vs voltage (I-V) characteristics of Kapton obtained in the laboratory depend critically on the history of exposure of the sample to simulated solar light. This observation has also been reported by Coffey et al.[7] For samples which have not been exposed to solar light, the I-V curve is nonlinear. In fact, the current varies exponentially as the square root of the applied electric field. Two independent experimental techniques were used to determine the I-V curves as shown in Fig. 7. The first technique made use of a metal-insulator-metal sandwich structure. The steady-state current from one of the metal electrodes to ground was measured with an electrometer, while the other was biased to the appropriate voltage. The I-V plots obtained in this manner are in good agreement with those obtained by the second method in which the biased electrode was replaced by an electron beam. The electron beam charged the sample surface to the desired voltage which was measured by the back field techniques, and the bulk current was then measured with an electrometer. The good agreement between these two independent methods (see Fig. 7) shows that the I-V curves are not affected by electrode configuration and, hence, the conduction mechanism is a bulk property.

Further studies of the dark current in Kapton indicate that exposure to simulated solar light causes the sample to undergo large and long-lasting changes[7] in its electrical properties. As shown in Fig. 8, after illumination, the bulk current in the dark exhibited a three-orders-of-magnitude increase over that of the unexposed sample. The plot at the bottom represents the dark I-V curve of unexposed Kapton (△). Exposure to simulated solar light shifts the dark I-V response to higher current (○). This enhancement effect which persisted for hours at a test chamber pressure of $10^{-6}$ Torr was also observed in the I-V measurement (represented by the square in Fig. 8) of the SSPM Kapton samples in space on March 28, 1979 when the P78-2 satellite went into the eclipse of the Earth just prior to a geomagnetic substorm. Both the currents and the voltages of all the SSPM samples were monitored during this event and the detailed description of the material behavior are described in the previous paper. The surface voltages of the Kapton samples located on the belly band went from less than minus several hundred volts to about $-1700$ V as a result of charged particle injection for a long period. Throughout this period, the bulk current stayed relatively constant at about 50 $pA/cm^2$. This current is about three orders of magnitude higher than the bulk current of an unexposed Kapton sample at the same surface voltage but agrees quite well with the dark enhanced bulk current in Kapton obtained in the laboratory after illumination.

In the laboratory, the photoenhanced bulk current was reduced considerably after the sample was exposed to air. This atmospheric effect and the extremely long deactivation time of the enhanced current in vacuum suggest that exposure to strongly absorbed light induces a large density of metastable defects in Kapton. Extrapolating the laboratory result linearly to a space vacuum of $<10^{-12}$ Torr leads to the conclusion that once a Kapton film has been exposed to solar radiation in space, for all practical purposes, its bulk conductivity is modified permanently. Furthermore, this change in conductivity appears to be cumulative and should be considered in modeling the charging behavior of Kapton in the space environment.

The change in dark conductivity of Kapton can only partly explain the unexpectedly low surface voltage of Kapton observed in space. As charging models and preliminary laboratory results indicate, the surface voltage of Kapton is highly dependent on the combined effect of secondary electron emission and the energy and intensity distributions of the particle environment.

## Summary

An unexpected high voltage was observed on the SSPM quartz fabric sample during the April 24, 1979 natural charging event. This observation does not agree with previously reported laboratory measurements. The discrepancy is now attributed primarily to a newly observed beam-induced charging and discharging property in quartz fabric and to the fact that this unusual charging profile is highly dependent on the incident current density. Furthermore, this unusual behavior is found to be related to the formation of positively charged regions within the fabric as a result of secondary electron emission.

In the case of Kapton, after exposure to solar radiation, the dark current in the Kapton samples in vacuum is found to increase by three orders of magnitude over that of the unexposed samples. Although this dark current enhancement alone may not be sufficient to account for the data from the SSPM Kapton sample, this information is crucial to the formulation of a charging model for Kapton in space applications.

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