TANK TESTING OF A 2500-cm^2 SOLAR PANEL

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A. INTRODUCTION

A fairly large, 50 cm by 50 cm solar panel test patch was investigated for Spacecraft (S/C) charging and arcing effects. This was done in the course of verification testing of a new solar panel design for the Tracking Data Relay Satellites or TDRS System. Thus bombardment with monochromatic electrons, whose energy could be varied up to 20 kilovolts, was carried out at the NASA Lewis Research Center, in the 2 m x 2 m tank testing facility.

The objectives of the test were severalfold and somewhat similar to those described by Bogus on the Canadian Technology Satellite type of solar array, reference 1, namely:

(a) to obtain an estimate at what voltage of electron bombardment arcing would be probable;

(b) to find whether the energy content within the arcs would be tolerable or damagingly large;

(c) to repeat and continue an incomplete test on a smaller TDRS solar panel test patch reported upon by Inouye and Sellen, reference 2;

(d) to try and separate thermal and photoeffects;

(e) to ascertain whether silver from the interconnects would be sputtered off during arcing;

(f) to see whether materials used were such as to minimize arcing.

The large electron bombardment facility at Lewis RC is in demand for other projects of higher priority, and thus it was available for TDRS for only a limited time. Despite this, some of our objectives could be accomplished, and this paper reports on several of the observations made.

B. DESCRIPTION OF THE SOLAR PANEL TEST PATCH

The large solar array of the TDRS, being manufactured by TRW Space and Defense Systems for Space Communications Co., consists of two wings, each of 3 panels, each panel measuring 150 inches by 50 inches. These panels are a new design with aluminum honeycomb core and Kapton face sheets. The back face sheet is perforated and painted with graphite-containing epoxy paint of lower than 100,000 ohms/square surface resistivity. The spacing between adjacent solar cells is extremely close with the interconnect stress relief loop protruding above the cover glasses of uncoated ceria-doped glass. See figures 1a) and 1b). In one respect the test patch supplied by TRW Company was different from the flight hardware: the 50 cm by 50 cm test patch has seven columns (3 strings) of ceria-doped cover glasses and five columns (2 strings) of fused silica cover glasses coated with magnesium fluoride, as shown in figure 2. This panel was one of the Life test panels. There are diode boards on the panel and bare Kapton borders (the edges are Kapton tape, painted conductively), and thermistors and connectors are at the upper panel edges. The latter were immediately covered with an aluminum shield; also the bare Kapton borders were covered with aluminum foil for some of the data runs, but not all. Thus the test specimen was adequately large and representative of the real design, but it also had considerable complexity.

C. FACILITY AND INSTRUMENTATION

The 2m x 2m NASA–LeRC electron bombardment test facility is shown in figure 3 and also in reference 3. The panel was centered on the vacuum chamber axis 125 cm downstream from five divergent beam electron guns located on the chamber door. Five guns were used in order to improve the uniformity of the electron flux over the large area presented by the test panel. The guns were arranged in a 30 cm square array with one gun in the center to irradiate the corners and center of the test panel respectively. The accelerating potential for all five guns was provided by a single high voltage power supply. The electron flux contributed by each gun could be adjusted by independent filament current and grid voltage controls. The flux at a plane 12 cm in front of the test panel was monitored by a vertical array of five 10 cm^2 discs which could be swept horizontally across the chamber. The center disc traversed a path through the chamber axis. The vertical separation between discs was 15 cm. The currents intercepted by the discs were measured with Keithley 616 digital electrometers whose analog outputs were displayed on one of two eight–channel strip chart recorders. During electron gun adjustment prior to a test, a swinging shield containing an array of current sensors protected the test panel. The test began when the shield was swung to the chamber wall.

The panel surface potential was monitored with two TREK model 340HV electrostatic voltmeters using model 8052E probes. The probes followed curved paths at a distance of two to three millimeters above the surface of the panel. The outputs from the voltmeters were displayed on one of the eight channel strip chart recorders (BRUSH Co.).

A 15 cm diameter loop antenna located to one side of and upstream from the test panel monitored the discharge activity on the panel. The signal from the antenna was fed into three counters with voltage thresholds of 1, 2, and 5 volts. The frequency of the counts indicated the frequency of discharges with energy greater than that required to trip the counter. A still camera located outside one of the windows on the chamber door was also used to record the discharge activity of the panel. Time exposure photos recorded the visible evidence of discharges taking place on the test panel. The camera's field of view covered approximately 40% of the panel area.

A 12 kW, 2 lamp, Xenon arc solar simulator was available to simulate the solar input to the test panel. It was positioned outside the vacuum chamber and the short wavelength cutoff was approximately 2000 Å so little photoemission could be expected from the test panel.

A low energy plasma source producing ionized nitrogen was used between electron bombardment tests to neutralize the negatively charged panel surfaces.

A temperature controllable cylindrical chamber liner was available to investigate thermal effects on the charging and discharging of the test panel. It was capable of operating over a -190°C to +120°C range.

The solar array test panel was mounted on ceramic posts at its corners to provide DC isolation from the chamber. Fifteen leads from the panel were brought through a multipin vacuum bulkhead feedthrough mounted in the center of a 39 cm diameter dielectric flange. The dielectric flange provided the necessary DC isolation when it was desired to float the panel or place a multimegohm resistance between it and ground. Ten of the leads came from the five strings of solar cells on the panel. These were then connected to a single common lead external to the vacuum chamber and hence thru an electrometer to ground. Three leads came from two thermistors; one lead from the aluminum honeycomb core and backside conductive paint and hence thru an electrometer to ground; and one lead from the aluminum shield thru an electrometer to ground. Alternatively multimegohm resistor strings could be placed between the various elements and ground. Intercepted or leakage electron currents were measured using Keithley 616 digital electrometers with analog outputs displayed on the 8 channel chart recorders.

D. CHARACTERIZATION OF SOLAR PANEL TEST PATCH, WITH METALLIC PARTS GROUNDED

Prior to any electron bombardment, the current–voltage curves of the solar cell strings were obtained at Goddard Space Flight Center. At the LRC facility the electron bombardment was then carried out. For all these experiments, unless otherwise stated, the current flux density in the electron beam, at the sample, was kept at a spatial average of about 3 nanoamperes/cm^2. It varied somewhat across the cross section of the beam at the sample due to its large size, by about a factor of 2.

An excerpt from a data scroll taken in the test configuration described in part C is seen in figure 4, demonstrating what was continuously and simultaneously recorded: the time in minutes, the current from the aluminum shield in microamperes, the current from the solar cell strings in microamperes, the current from the honeycomb core and backside paint in tenths of microamperes, the surface charge–up voltages as read by the two TREK electrostatic probes, in kilovolts. Below 12 kV the current traces were mostly smooth, meaning that no arcing was occuring.

Sustained arcing occurred first at 12 keV beam voltage, figure 4. The centers of the ceria-doped glasses are at a lower charge–up voltage 6 ± 1 kV than the fused silica glasses at 9 ± 1 kV, with respect to the grounded interconnects. At a beam voltage of 20 kV the arcing events became, of course, extremely numerous. For modest arcing, as in figure 4 at 12 keV, the direction of the transient current flow through the solar cell strings was usually an electron flow from ground, but the core and backside paint leads sometimes had an electron flow from ground and sometimes a vastly increased spike over and above leakage current to ground. It must be concluded that for as complex a system as this panel several modes of arcing were possible.

One can summarize an entire data sequence in a graph of electron beam voltage versus coverglass voltage and versus currents to ground, of which the only true leakage current is the honeycomb core current, as in figure 5. The coverglass voltage over the central portion of the glasses is used as the parameter for plotting of the graph here and for discussion because it is easily estimated from the TREK probe tracings. There is a much lower voltage at the edges of the glasses where the arcing really occurs, but this voltage is difficult to ascertain from the tracings. It is obvious that after sustained arcing begins at about 12 keV beam voltage the cover glass voltages no longer increase very much with increasing beam voltage. Why arcing from the much less charged ceria glasses begins at about the same beam voltage as from the more highly charged fused silica glasses is not understood, unless arcing from the latter serves as a triggering mechanism.

Calibrated equipment that permits one to obtain data on the arcing transients as to peak current and time duration is available at LRC. The ground current leads are surrounded by one-turn Pearson model 110S transformers which are connected to Biomation 8100 digital waveform recorders. However, to avoid ringing, the ground lines have to be terminated in 50 ohm impedances which cause a decrease in the amount of charge that would otherwise be removed from the cover glasses during a given discharge. Nevertheless, figure 6 shows a few typical discharge transients:

Beam voltage: 12keV

Time duration: 1 to 2 microseconds

Charge content: 1 to 10 microcoulombs

If from the fused silica glasses charged to 9kV, then Energy content: 0.009 to 0.09 joules

Direction of electron current through solar cell strings: most often from ground.

Two questions now arise:

(1) If the ground termination resistance were only a few tenths ohms what would the charge and energy contents in the arcs be?

(2) Are these arcs due to a charge wipe-off from one solar cell, or from a characteristic few, or from the entire panel?

In other words, does the charge and energy content of a given arc depend on the total area of the solar panel? A carefully controlled area experiment, blocking off parts of the panel area with metal masks is needed to settle this question. In the meantime, the fact that our data fits on a charge content versus load resistance graph, figure 7, from a much smaller TDRS type test panel, reference 2, looks somewhat encouraging that only a limited area of cover glasses is involved in a given arc. Moreover, visual observation when beam voltage was 12keV, showed arcs to be associated with a small bright spot surrounded by a bluish glow which, at 12keV only extended over a portion of the field of view, which itself was smaller than the panel.

Time exposure photographs were taken, of which figure 8 is an example showing 20 minutes of arcing in a 20keV electron beam. The arcs occur mostly between the solder strips, interconnects and coverglasses in the same column of cells. Note the very bright arcing between adjacent columns in the upper right-hand corner of this picture. After seeing this picture, it was discovered that a string of 5 cells had inadvertently been left disconnected and floating. This was corrected.

Some other interesting observations were made. Figure 9 shows a charge-up sequence with a 10keV beam. The Kapton border is exposed to the beam this time and charges to its full potential of 7.6kV in a half minute, whereas the coverglasses require five minutes before they become fully charged to 7kV and 4.5kV respectively. Hence differential charging can be most serious during changes in the Space environment-going from sunlight to eclipse and vice versa or beginnings and terminations of geomagnetic substorms.

Measurements were made at 25°C on the volume resistance of the ceria-doped uncoated glasses as compared to the resistance of the fused silica with MgF coated ones:

Fused silica glass resistance in ohms/cm^2 for 0.015 cm thickness, 25°C,

At	250 volts	$R = 3.5 \times 10^{14}$ ohms/cm^2
	1000 volts	$R = 1.9 \times 10^{14}$ ohms/cm^2

Ceria–doped glass resistance in ohms/cm^2 for 0.015 cm thickness, 25°C,

At	250 volts	$R = 4.2 \times 10^{11}$ ohms/cm^2
	1000 volts	$R = 0.9 \times 10^{11}$ ohms/cm^2.

Thus ceria doped glass at room temperature has 2000 times the conductivity of fused silica glass, thus permitting charge reduction by leakage current. The delayed reduction of arcing when the solar simulator outside of the vacuum system was turned on and delayed resumption when it was turned off, was probably due to a still further increased conductivity when heated rather than entirely a photoemissive effect. When the lamps were on: the fused silica stayed stubbornly charged at 16 kV while the ceria glass came down to 3 kV. The ceria glass is therefore a more desirable material from the S/C charging point of view.

E. CHARACTERIZATION OF SOLAR PANEL TEST PATCH; METALLIC PARTS SEMI-FLOATING ON 25,000 MEGOHMS TO GROUND

It was decided to characterize the panel with 25,000 Megohms instead of 0 ohms to ground. In this way one simulates two different "grounds":

(a) The ambient plasma sheath ground = tank walls;

(b) The spacecraft ground = metallic parts potential.

The effect is seen in figures 10 and 11. At a 10 keV electron beam the metallic parts charge to 5000 volts as proved by either the 25,000:1 voltage divider or the high voltage probe readings. When the electron beam voltage is turned off and then the high voltage trace obtained, the negative cover glass voltages with respect to the metallic parts remain, looking like a roof without the house under it and is only between 1 to 2 kV. In a 15 keV beam the metallic voltage is -5500 volts, the fused silica is -12,000 volts, the ceria glass is -11,000 volts, the difference still not being quite enough to cause arcing. At 20 keV beam voltage, the metallic voltages are at -6250 volts, the silica glass is at -14,000 volts, the ceria glass is at about -12,500 volts; the difference with respect to S/C ground being about 8,000 volts and 6,000 volts respectively, and arcing is sustained as in part D described above. This arrangement with the metallic parts semifloating is probably a better simulation of what happens in Space than to ground the metallic parts. In fact the behavior is very much as in a recent report by Koons, Mizera et al., on SCATHA, reference 5. (There on March 28, 1979, a 20 keV substorm caused the S/C to charge to -8,000 volts with respect to the plasma and the materials on the satellite surface potential monitors to various negative potentials in the kV range with respect to the S/C. Two arcing events were recorded as a consequence.) Note that in the dark, even in the 25,000 Megohm to ground arrangement, as in eclipse in Space, the cover glasses are still of negative polarity with respect to the interconnects. Time exposure photographs have verified that under these conditions there is visible arcing. The charge-up voltages and the arcing depend very sensitively on the current density of the beam at a given beam voltage. When the current density was cut from 3 to 1 na/cm^2 at 20 kV, arcing stopped from the ceria glasses, but was still happening in a reduced manner from the fused silica glasses.

Work was done with the Solar Simulator on, outside of the vacuum chamber, shining light from the same side as the electron beam: Arcing frequency decreased, but there was a time lag indicative of heat rather than photoeffects. A similar time delayed remission and resumption of arcing occurred when the experiment was repeated by passing hot air through the chamber shroud, thus heating and later cooling the panel against an LN_2 shroud without any light whatsoever. The ceria–doped glass probably becomes quite conductive with heating, and the effects observed so far are probably thermal rather than photoemissive.

F. WORK WITH A BARE KAPTON SUBSTRATE STRIP NEXT TO THE CELLED TEST PATCH

The solar panels on the TDRS System each have a bare substrate portion without solar cells on the front side of area 50 inch by 15 inch. In order to test this situation, a bare piece of substrate 50 cm by 15 cm, appropriately edged with conductively painted Kapton tape, was butted next to the celled panel. The butt joint was covered with 0.0075 cm thick Kapton tape and the honeycomb cores and backside painted coatings were connected together. Electron bombardment with 20 keV electrons at the usual 3 na/cm^2 flux was done, with the cores and solar cells grounded through electrometers, or through 50 ohms when transients were measured with the Biomation equipment. Arc counts at about -24° (-10°F) and +46°C (+115°F), as well as time exposure photograph were taken at 30 minute intervals. The total bombardment time accumulated during this part of the experiment was roughly 8 hours with order of magnitude of 10,000 arcs occuring. The results were to some degree surprising:

(1) The bare Kapton section had puncture arcs through the Kapton tape over the butt joint despite the grounding together of the cores. Thus stubborn arcing occurs at discontinuities.

(2) Fewer arcs according to the arc counter occurred with the bare Kapton next to the celled panel than without it as seen in table I. However, charge content in most of the arcs is somewhat larger than earlier in the entire investigation. The time exposure photographs, figures 12, and 13 show that at 47°C (115°F) the appearance of the arcs on the fused silica side is concentrated in a definite pattern whereas at -24°C (-10°F) for the silica glass, and at both hot and cold temperatures for the ceria glass the arcing results in more of a diffuse glow. The arc count is less at the higher temperature. At the colder temperature, note the straight line arcing pattern perpendicular to the edge of the solar cells, extending out over the Kapton border for about 2 to 3 mm and outlining the underlying honeycomb. This occurs with or without the bare Kapton piece.

G. CONTAMINATION AS RESULT OF CHARGING AND ARCING

When the panels were removed from the vacuum chamber, following sequence F above, there appeared on the fused silica glasses, but not on the ceria glasses small discolored contamination areas where the arcing had been hitting the glass as seen in the accompanying photograph, figure 14. Auger spectroscopy revealed this to be mostly silicon, carbon and oxygen with other minor trace elements but decidedly <u>not</u> silver from the interconnects. The origin of these materials could be from the RTV's on the panel or from vacuum chamber sources of contamination. The point here is that interaction of the charging and arcing with whatever matter is present, to the fused silica glasses, but not to the ceria, even when the metallic underlayers are grounded, will produce a deposit of contaminants on the glasses. Effect on the current–voltage curves of strings 4 and 5 that were covered with the fused silicia glasses was small, but there was a consistent decrease of output power of 2% as opposed to no change from the ceria glass covered strings.

H. BACKSIDE BOMBARDMENT WITH ELECTRONS

Abbreviated backside electron bombardment gave results, partly similar to front side work.

(1) When the metallic portions were grounded, then a very few arcs began to occur with beam voltage at 12kV as recorded by the arc counters. The solar cell leakage current trace became increasingly "noisy" as beam voltage was increased.

(2) When the metallic portions were on 25,000 Megohms to ground, then the arcs did not begin until beam voltage was 18kV.

(3) Time exposure photography showed no visual evidence of arcs on the Kapton, indicating that they were induced on the front side and that the conductive painting of the perforated backside Kapton was adequate. However, the unpainted harness insulation appeared as emitting light under electron bombardment.

I. CONCLUSIONS

Ceria–doped glass is definitely to be preferred to fused silica glass for reducing charge build up.

In sunlight the TDRS solar panel which has ceria glass on the front and conductive paint (100,00 ohms/square) on the backside is probably a good design for reducing charge–up. In a geomagnetic substorm such as simulated here, there will be arcing at the interconnects during eclipse and transitions into and out of eclipse. This is especially true in view of the very cold temperatures that will be reached by this lightweight array, when the ceria glass will not be as conductive as at room temperature.

The Kapton bare patch, although no very large arcs were measured from it, should still be conductively painted. Any discontinuity on it will serve as arcing center.

The differential voltages on the panel determine when arcing first begins, and the electron beam voltages which cause this, vary, depending upon whether the metallic structure is directly grounded or semifloating. This can explain the variety of beam voltages for arcing inception, reported by different experimentors as between 14 kV and 20 kV and obtained by different techniques (reference 5, Table 1–2).

REFERENCES

1. Bogus, K. P., Investigation of a CTS Solar Cell Test Patch under Simulated Geomagnetic Substorm Conditions. Proceedings of the 1976 Spacecraft Charging Technology Conference; Pike and Lovell Editors, 1977, NASA TMX-73537.

2. Inouye, G. T., and Sellen J. M., TDRSS Solar Array Arc Discharge Tests; Proceedings of the 1978 S/C Charging Technology Conference; NASA Conf. Publ. 2071.

3. Stevens, N. J., et al.; Testing of Typical S/C Materials in a Substorm Environment; Proceedings of the 1976 S/C Charging Technology Conf.; Pike and Lovell Editors, 1977.

4. Koons, H. C., Mizera, P. F., Fennel, J. F., and Hall, D. F.; S/C Charging-Results from the Scatha Satellite; Astronautics and Aeronautics; November 1980, Page 44.

5. Rosen, A., Sanders, N. L., Sellen, J. M., and Inouye, G. T.; Effects of Arcing Due to S/C Charging on S/C Survival; TRW Report No. 33631-6006-RU-00; Nov. 14, 1978.

6. TRW Document No. 29000-412-009; TDRSS Solar Array PDA, January 1978, Chapter 4, Pages 8, 40; Chapter 7, Page 9.

7. TRW Document No. 78-872509-032; TDRSS-78-412-208; Life Test Report, Solar Panels after 920 Cycles in Thermal Vacuum, Sept. 28, 1978, Pages 7, Fig. 2-2.

Table I

Arc Counts and Currents to Ground, when Bare Kapton Panel is Butted next to Celled Panel

Time Minutes	Arc Count	i_{shield} x 10^{-6} Amp	i_{cells} x 10^{-4} Amp	$\lvert i_{core, min} \rvert$ x 10^{-6} Amp	Panel Temp.
With Bare Kapton Panel next to Fused Silica					
0	0,0,0				
30	693,218,12	0.33	0.048	0.8	-23°C
0	0,0,0				
30	320,171,10	0.41	0.057	1.45	+44°C
Without Bare Kapton Panel					
0	0,0,0				
30	922,325,30	0.68	0.054	0.55	-22°C
0	0,0,0				
30	380,189,34	0.47	0.059	0.5	+46°C
With Bare Kapton Panel next to Ceria-Doped Glasses					
0	0,0,0				
30	836,166,21	0.28	0.043	0.75	-23°C
0	0,0,0				
30	424,164,17	0.32	0.0645	1.5	+44°C

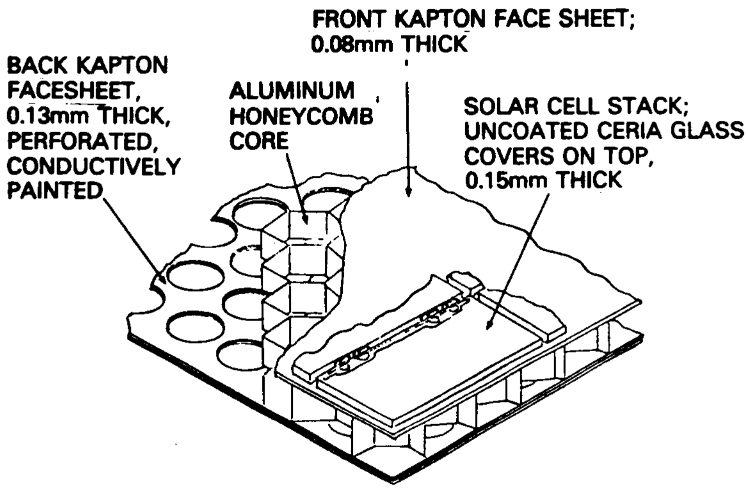


Figure 1a. Cutaway View of Solar Array Cell Stack and Substrate (Reference 6)

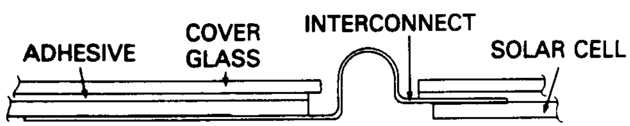


Figure 1b. Cross Section of Solar Cell Stack, Showing Interconnect Stress Relief Loop (Reference 6)

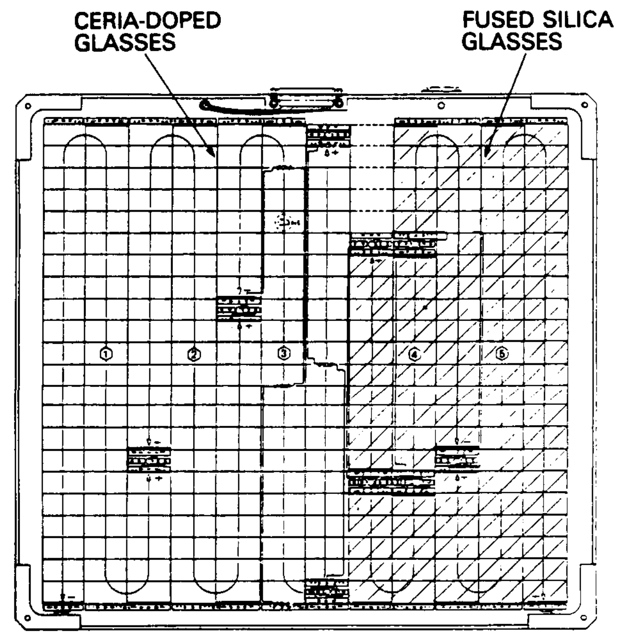


Figure 2. Front Side of Life Test Panel (Reference 7)

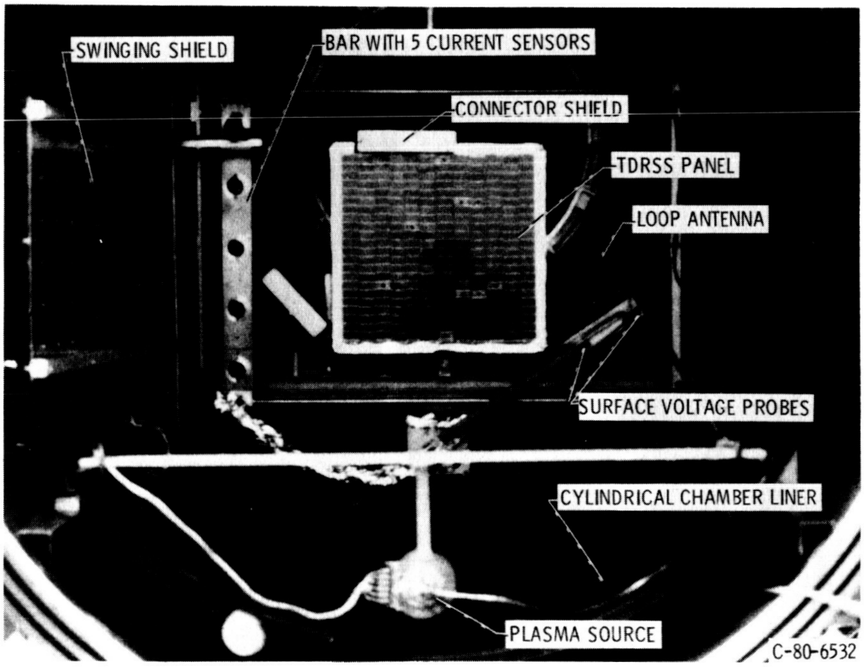


Figure 3. - TDRSS solar test panel in electron bombardment test facility.

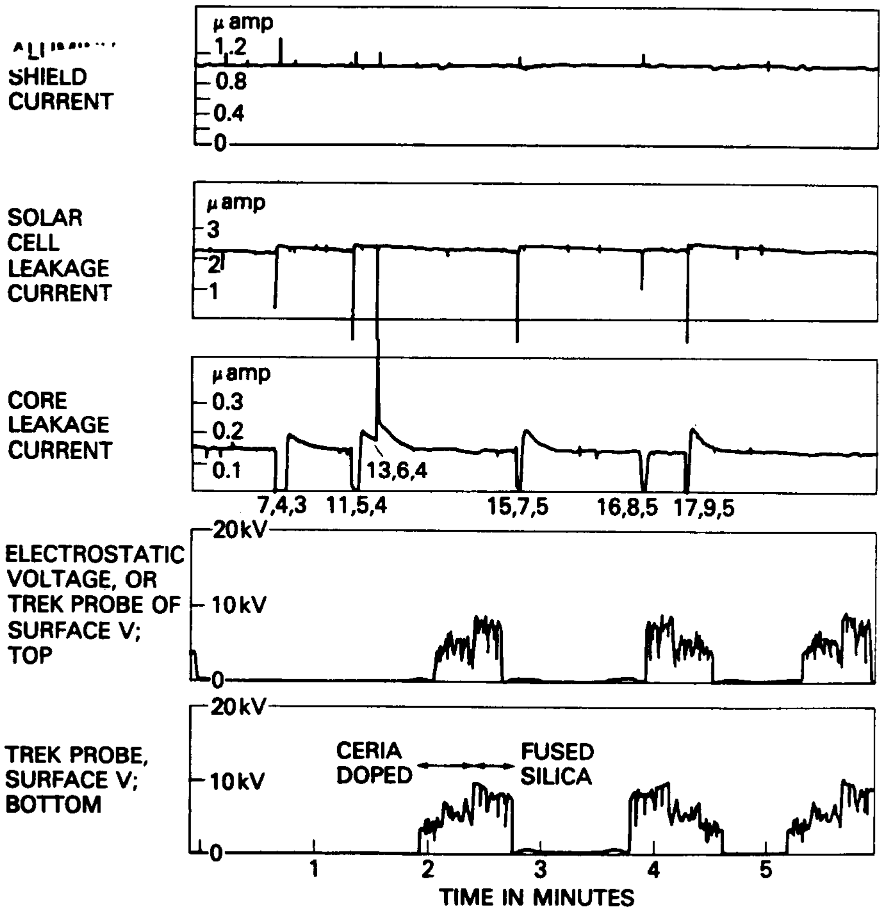


Figure 4. Continuous BRUSH Recording of Currents to Ground, and Surface Voltages, Versus Time; in a 12kV Electron Beam. Kapton Borders Covered with Aluminum.

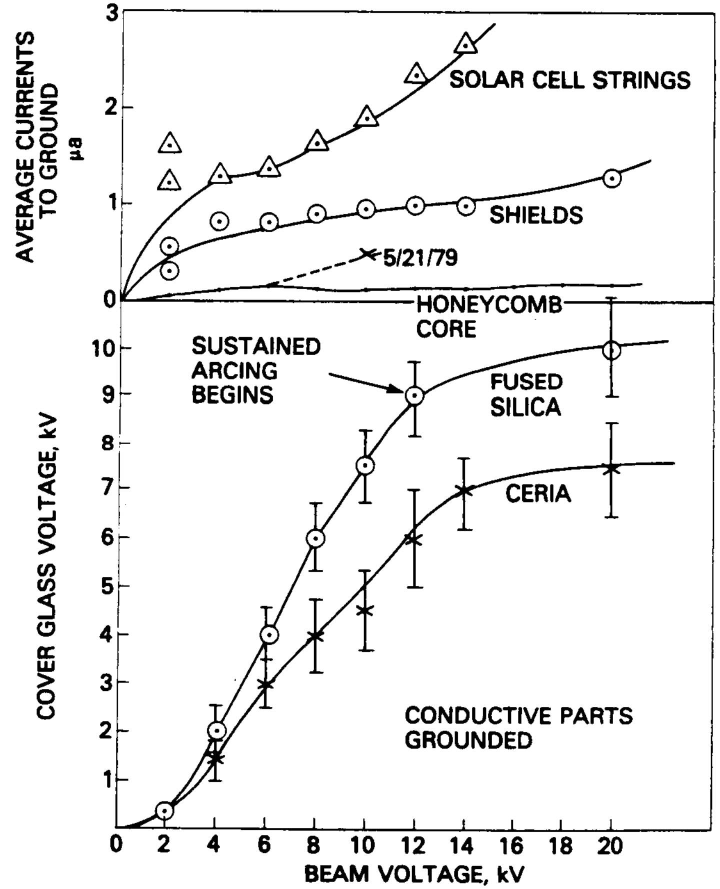


Figure 5. Cover Glass Voltages and Currents to Ground Versus Electron Beam Voltages, 7/11-13/79.

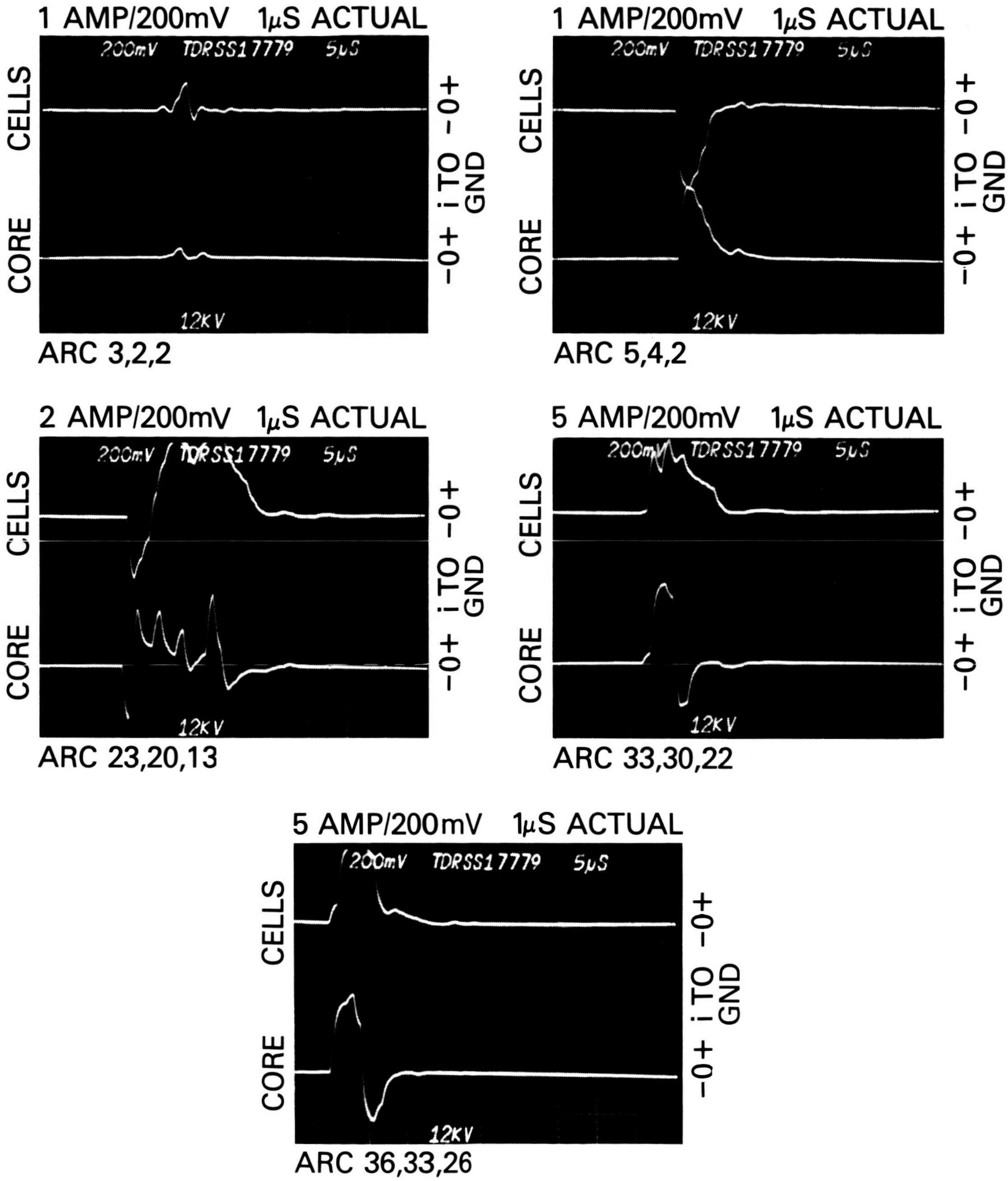


FIGURE 6. Typical Arcing Transients in 12kV Electron Beam, Demonstrating Directional Variety of Current Flows (50 Ohm Resistance to Ground)

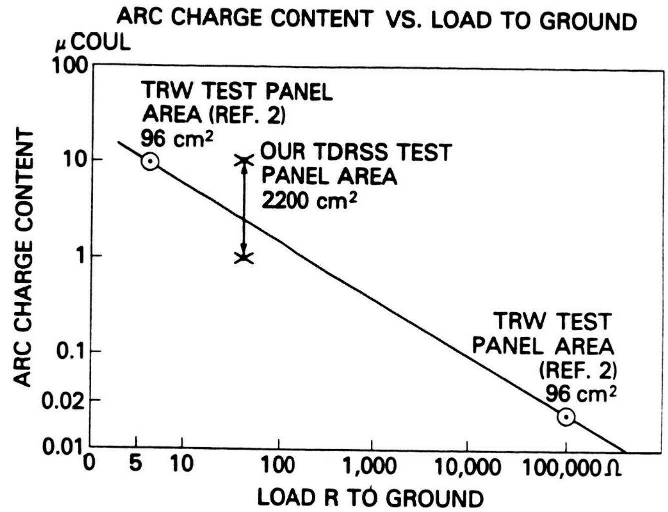
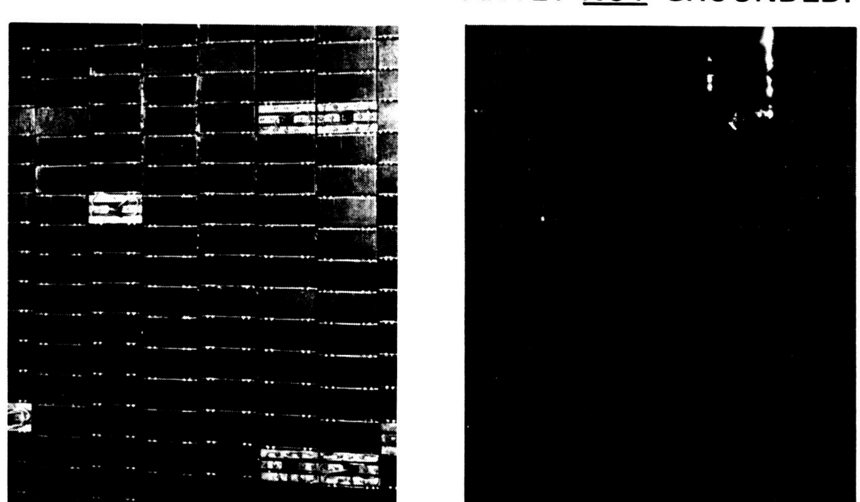


Figure 7. Typical ARC Charge Content
Versus Load Resistance to Ground

(A) 7/13/79
PORTRAIT OF PART OF
PANEL IN ORDINARY
LIGHT

(B) SAME IN 20 MINUTE
TIME EXPOSURE IN 20
keV ELECTRON BEAM.
METALLIC PARTS
GROUNDED, EXCEPT
NOTE MUCH BRIGHTER
ARCS WHERE SEVERAL
CELLS WERE INADVERT-
ANTLY <u>NOT</u> GROUNDED.



A B

Figure 8. Arcing Shown in 20 keV Electron Beam,
During 20 Minute Time Exposure

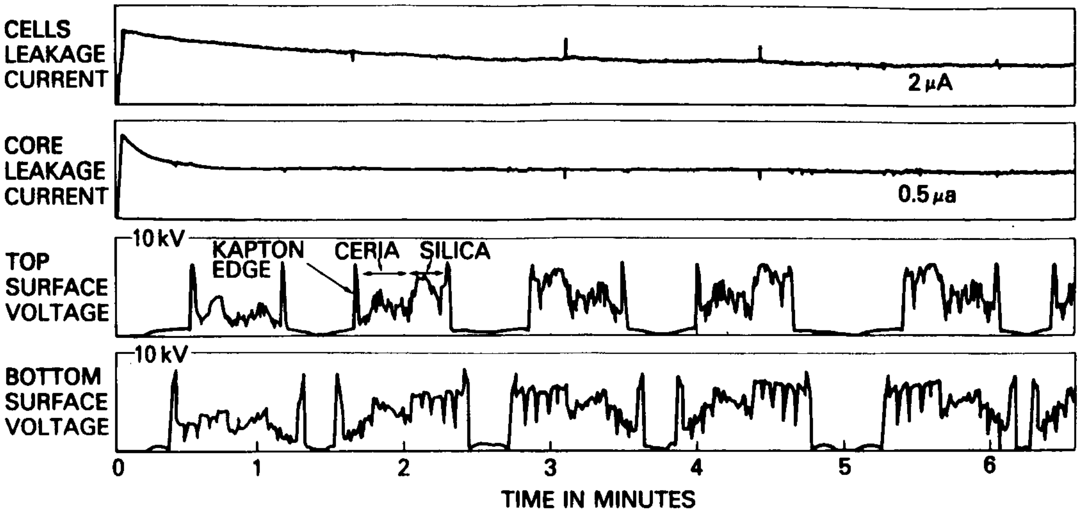


Figure 9. Charging Sequence of Panel Versus Time, Exposed Kapton Edges Charge Up Immediately, Cover Glasses More Slowly. 10 keV Beam.

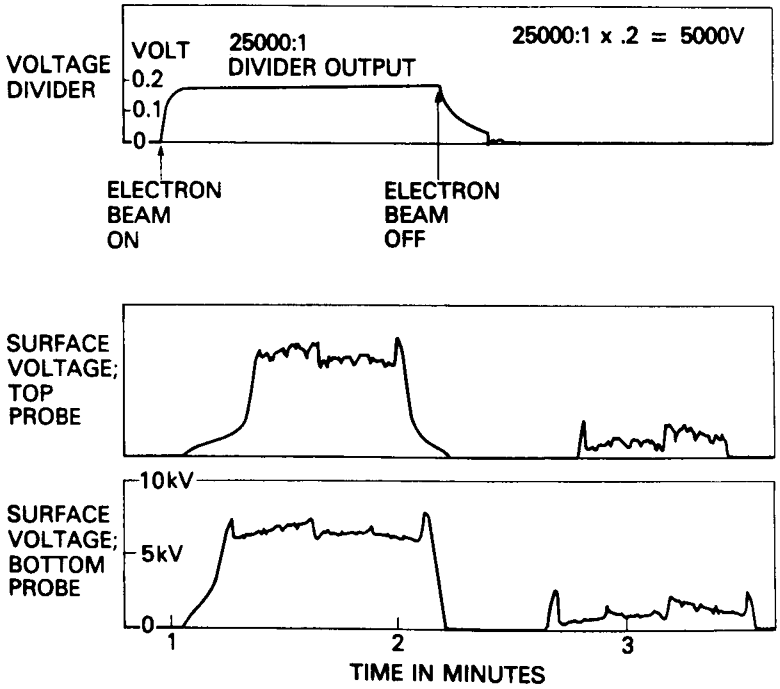


Figure 10. Solar Panel in 10 keV Electron Beam on, then off. 25,000 Megohm from Metallic Parts to Ground, 6/28/79.

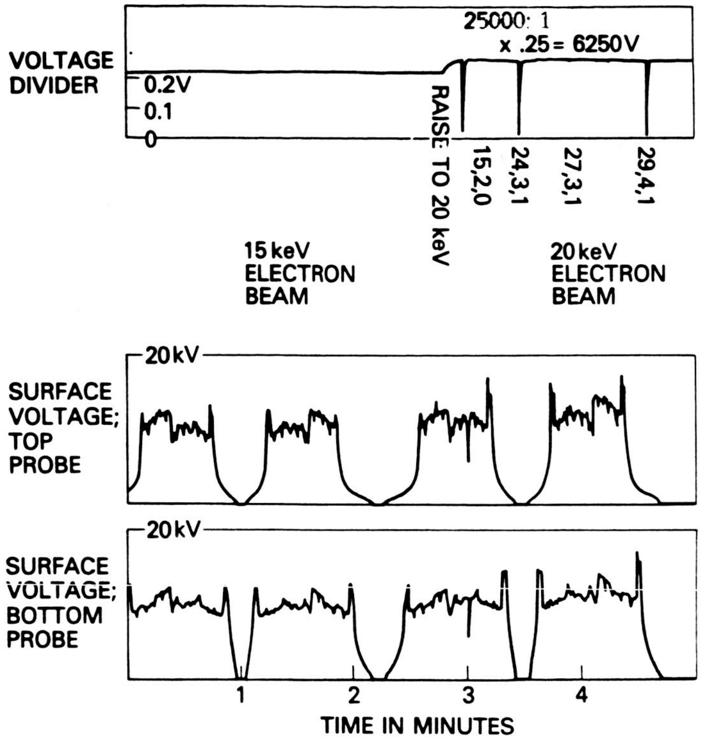


Figure 11. Solar Panel in 15 and in 20 keV Electron Beam. 25,000 Megohm from Metallic Parts to Ground, 6/28/79.

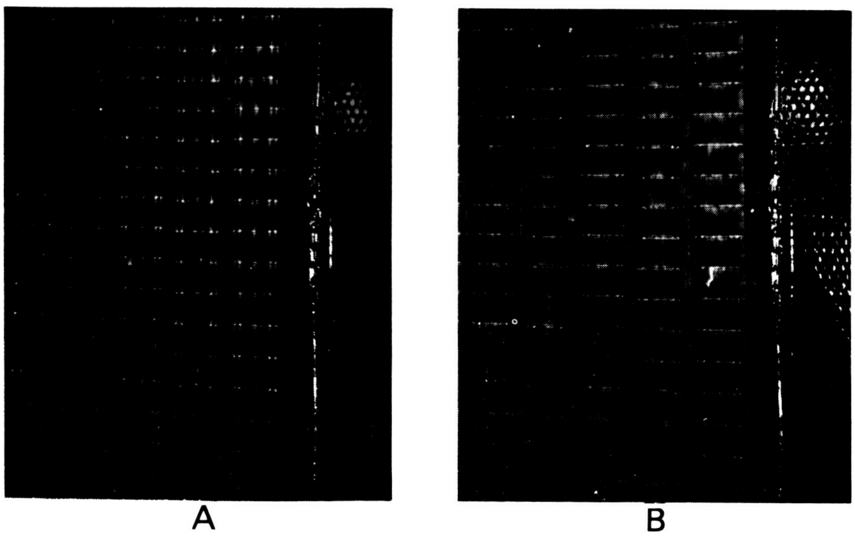


Figure 12. 30 Minute Time Exposure Photographs, Bare Kapton Butted Next to Fused Silica - Glassed Portion of Celled Panel.

A. 20 keV Electron Beam, Panel at +46°C

B. 20 keV Electron Beam, Panel at −24°C

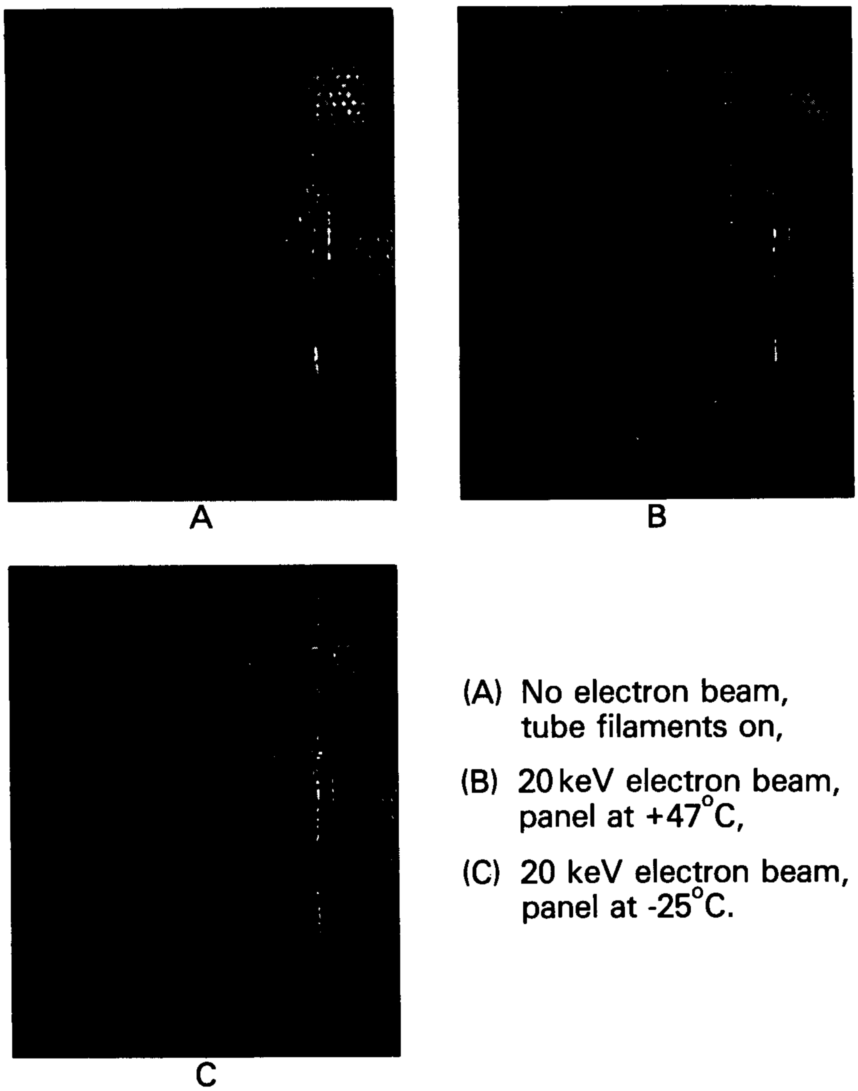
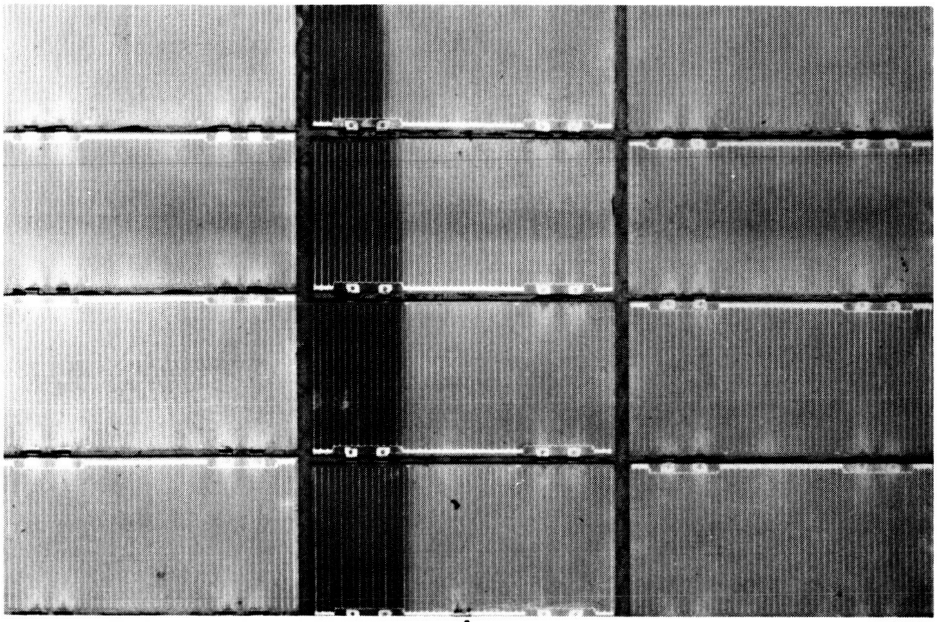
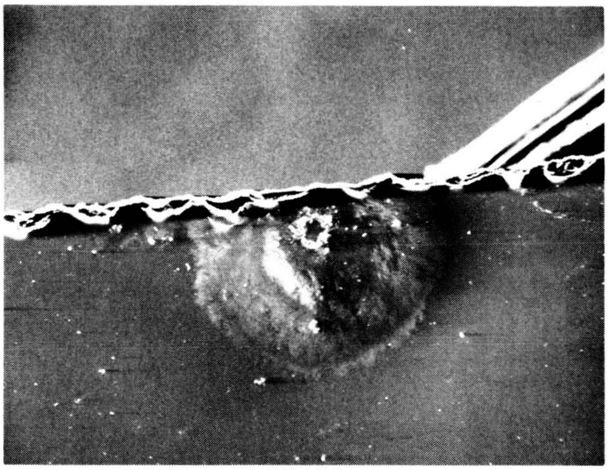


Figure 13. 30 Minute Time Exposure Photographs, bare Kapton Portion Butted Next to Ceria - Glassed Portion of Celled Panel



A



SEM 320X

B

Figure 14. A. Photograph of Contamination Deposit on Silica Glasses After Long-Term Arcing
B. Scanning Electron Microscope Picture (320X) of Same