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# TDRSS SOLAR ARRAY ARC DISCHARGE TESTS*

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## SUMMARY

The Communications Technology Satellite (CTS) experienced a fifteen percent power loss, possibly due to spacecraft charging and consequent arc discharge. This paper covers tests that were performed to develop design guidelines and recommended practices for use in the design of solar arrays of similar construction such as that for the Tracking and Data Relay Satellite (TDRSS) spacecraft.

The most interesting results were obtained with the solar array test samples irradiated with electrons on the backside and with ultraviolet on the solar cell side. The test sample was isolated from ground (tank walls) with a 25,000 megohm resistor so that the sample potentials were determined predominantly by the "environmental" fluxes of electrons and UV, with only a minor influence from external diagnostics. An enhanced photo-induced emission of electrons from the solar cell side due to UV irradiation was observed in the preferred test sample configuration in which the backside is coated with a conducting paint. This effect leads to the elimination of a major part of the charge buildup and energy storage which is the source of potentially hazardous arc discharges.

## INTRODUCTION

The current state-of-the-art in designing satellites to be immune to the geomagnetic substorm environment at synchronous orbit altitudes is not a matured engineering discipline. Many geosynchronous and other satellites have experienced anomalous events which have been attributed to the spacecraft charging phenomenon (ref. 1). On CTS, arc discharges resulting from environmental charging are surmised to have caused a partial loss of solar array power (ref. 2). Our main interest from the viewpoint of spacecraft charging is that both TDRSS and CTS solar arrays are deployed with a fixed solar pointing attitude. Both, therefore, have large areas of excellent dielectric (kapton) material exposed only to the ambient energetic plasma, and not to sunlight, on the backside of the solar arrays. Figure 1 shows the configuration of the original TDRSS solar array. The darkside kapton, if unexposed

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to solar UV, constitutes a large capacitor of about 2 microfarads per array. If charged to -10 kV, for example, the stored energy, 1/2 $CV^2$, is 100 joules. Coating this surface with a conducting paint and grounding it to the aluminum honeycomb core of the substrate eliminates the possibility of charging this capacitor. The tests described in this paper confirm the necessity for the conducting backside but also indicate that an additional effect exists which also reduces the stored energy in the large capacitance formed by the solar cell coverglasses on the sunlit side of the solar array.

## TEST APPROACH

Most previous vacuum chamber tests on solar arrays have been performed by irradiating the solar cell side from an electron gun and grounding the solar cells and other metallic portions of the test sample (ref. 3). Typically, the electron source is a hot tungsten wire with an acceleration voltage of 20 kV, the positive terminal of the high voltage power supply being grounded to the tank wall. This grounding scheme simplifies the problem of diagnostic implementation in that the metallic parts are at ground potential. However, the polarity of the charge on the irradiated dielectric surfaces can then only be negative relative to the metallic parts. In the case of solar arrays, particularly for those which are 3-axis stabilized to always point toward the sun, the surfaces of the solar cell coverglasses are "clamped" to zero potential by photoemission of electrons. Thus the polarity of stress due to environmental charging can only be such that the dielectric surfaces are positive with respect to the solar cell itself. That is, the potential of the metallic parts of the spacecraft, including the solar cells, are at a negative potential relative to the far plasma potential (and to the coverglass surface).

The test approach, then, was to simulate this in orbit charging situation of positive polarity and to test various samples to define an acceptable configuration. The samples were subjected to impinging electrons on the backside and to UV on the solar cell side. The metallic portions were all tied together and allowed to "float" by grounding via a 25,000 megohm resistor. Tests performed at the European Space Agency (ref. 4) on CTS-type solar array samples were somewhat similar in that electrons were irradiated on the backside and a solar simulator irradiated the solar cell side. The differences with our approach were that no attempt was made to isolate the metallic parts from the walls of the chamber and that no precautions were taken to assure the UV content of the solar simulator. The solar simulator was included in the European Space Agency tests mainly to investigate thermal effects on the conductivity of the kapton substrate.

### Test Setup

The test setup in the 2' diameter by 4' long vacuum tank is shown in figure 2. The electron gun at one end is capable of providing an electron beam density of 100 na/$cm^2$ at 20 kV. The positive side of the acceleration power supply is grounded to the tank. Since the maximum current density observed in a 3-month period on ATS-5 was 8 na/$cm^2$ with "average" densities of the order of 0.2 na/cm$^2$, the operating current was normally set at 10 na/cm$^2$. A door is provided near the mid-section of the tank to permit the "substorm" to be turned on and off. Faraday cups are provided both in front of the door and in front of the test sample to calibrate the incident current density. Electrostatic voltage probes are provided on swinging arms to provide scans of surface potentials. Various connections to the test sample, the solar cells and substrate core were brought out. In general, however, all of the wires were tied together and treated as a single connection. In figure 2 we show this connection brought out to a 25,000 megohm to 1 megohm voltage divider. In some tests the connection was grounded through a 5-ohm. or .1 megohm, resistor to determine arc discharge pulse waveforms. For the paper chart records shown here, the 25000:1 voltage divider output was fed to an X-Y plotter which generated the X(time) scale of 20 sec/cm internally.

## Test Samples

The following solar array samples were tested:

1. All-metal substrate.
   Substrate: 11.25" x 14"; 48 cells, 6 strings of 8 cells (2 cm x 4 cm cells). Coated with 1.2 to 1.5 mil of catalac black paint on backside.

2. Lightweight substrate with no paint on backside perforated kapton.
   Substrate: 7.25" x 9"; 20 cells, 2 strings of 10 cells (2 cm x 4 cm cells).

2a. Lightweight substrate with 0.5 mil Bostik-Finch 463-6-14 (epoxy) on backside perforated kapton.
   Substrate: 7.25" x 9"; 20 cells, 2 strings of 10 cells (2 cm x 4 cm cells).

3. Aluminum Panel: 11.25" x 14" x .125".

## Tests with the All-Metal Substrate Sample (1)

The test configuration was that shown in figure 2 in which the backside is irradiated with electrons and the solar cell side with UV. The load resistance was 25,000 megohms with a 1-megohm resistor added in series to provide a voltage-divided monitoring point.

Prior to the tests with this sample (1), sample (3), an aluminum plate (11.25" x 14"), the same size as the substrate for sample (1), was put into the chamber to check the level of UV intensity available. The dimensions of the setup are shown in figure 3. The lamps are Pen Ray Model 11-SC-1C units. The result of this test with sample (3) was that a current of 180 na was photoemitted. Assuming that the area illuminated is 7" x 14", or 632 cm$^2$, the current density is .28 na/cm$^2$, or 9.5% of 3 na/cm$^2$, a commonly used value for photoemission. It takes 30 to 60 seconds for the UV lamps to "warm up" to full intensity, especially the first time they are turned on. A limit of about 5 to

10 minutes operation exists because of lamp heating and the resulting loss of vacuum. Further details of the sample (3) tests are given in a later section of this paper.

The result of the tests with sample (1) was surprising in that turn on of the UV lamps caused the sample potential to drop from -15 kV to about -1 kV. Figure 4 shows a typical trace obtained at the voltage divider monitor point. At -15 kV with no UV there are occasional discharges to the wall. At -1 kV, the signal is somewhat erratic as though a corona-like discharge were occurring.

This result was surprising in that

- The incident current at 10 na/cm$^2$ and 1016 cm$^2$ (11.25" x 14") is 10.2 μa.
- By Ohm's law, 0.6 μa is drained by the 25,000 megohm load resistor at 15 kV.
- The photoemission current measured previously (on the same sized aluminum plate) was 0.18 μa.
- The photo-induced current must be greater than 0.6 μa and must approach a significant fraction of 10.2 μa.

On the assumption that a 7" x 14" area (632 cm$^2$) of the solar cells is photoemitting, the photoemission current densities are .95 na/cm$^2$ (for .6 μa), and 16.13 na/cm$^2$ (for 10.2 μa). Recalling that the current density observed in the aluminum plate test was .28 na/cm$^2$, the above values are 3.4 times (for .95 na/cm$^2$) and 57.6 times (for 16.13 na/cm$^2$) greater than might be expected, if the front surface were of aluminum. In fact, the photoemitting surface on the solar cell side consists only of the exposed metallic interconnects which comprise only about 5% of the solar cell coverglass surface area. In the steady state, the leakage of the coverglass is so low that all of the photoemission must initiate from the interconnects. The photoemission from this reduced area is effectively 20 times larger, giving current density values 68 to 1152 times greater than those observed on the aluminum plate.

A final test performed on sample (1) was to connect a negative variable power supply directly to the sample rather than to charge it with the electron gun. With the UV lamps or [illegible] rona-like discharge was observed starting at around -500 volts and arcs [illegible] observed at -1 kV. We use the term "corona" only because of the similarity of effects, the enhanced current emission and the consequent lowering of voltage, which are observed in conjunction with real coronas. In our case, we hypothesize that there is no real gas discharge involved, but rather, an enhanced emission of high-field induced electrons with, perhaps, secondary electron emission effects involved. Increasing the voltage up to -1.5 kV increased corona current and the frequency of arcs to several per minute. This was the largest negative voltage applied. Although no photo-induced current measurements were made on this sample, such data were taken on sample (2a) with the power supply and are described in a subsequent section.

The tests and results on the all-metal substrate sample (1) are summarized in table 1. The test results with the UV lamps on, the reduction of the sample voltage from -16 kV to -1 kV, was unexpected. However, this result is very significant in that such an effect would reduce electrostatic stresses across the solar cell cover glass by a factor of 16. The energy involved would be reduced by a factor of 256. Furthermore, if the test level of UV irradiation is extrapolated to the one-sun level, the charging problem essentially disappears as far as the solar array is concerned, since the metallic backside is at the same low potential as the substrate and the solar cells (within 28 or 32 volts). We have tentatively called this photo-induced current multiplication phenomenon a "zenering action." The fact that this zenering action continued, once initiated, even after the UV lamps were turned off is a commonly observed characteristic of coronas and arc discharges.

## Tests with Lightweight Substrate with No Conducting Paint on Backside, Sample (2)

This sample had 20 of the TDRSS type solar cells, two strings of 10 cells, on a 7.25" x 9" lightweight substrate. These cells had ceria glass coverglasses as compared to the fused silica on sample (1), and the interconnect design was also different. Note also that the sample size as well as its illuminated area is less than for sample (1). The backside was uncoated for these tests, and was subsequently spray coated with 0.5 mil of Bostik-Finch 463-6-14 epoxy paint to become sample (2a) which is discussed after this section.

The test configuration was as shown in figures 2 and 3. In figure 3, the outline of the sample (2a) substrate is shown in broken lines on the frontal view. Note ~~that the~~ UV lamp coverage is not the same as for sample (1). Irradiation with the 20 kV 10 na/cm$^2$ electron beam caused the sample voltage to go to about -15 kV as detected on the 25,000:1 voltage divider. Occasional arcs were observed. Turning the UV lamps on and off had no effect. Figure 5 shows a typical monitor trace of the 25,000:1 voltage divider output for this sample.

The test results obtained with sample (2) are summarized in table 2. The observed result of metallic portions of the sample at -15 kV with no "zenering action" from UV irradiation was again surprising in view of the results obtained from the all-metal sample (1). Particularly since the metallic parts were at -15 kV. One possible explanation is that the negative charges embedded on the backside dielectric are immobile and inhibit the flow of electrons in the metallic substrate towards the UV-exposed metallic solar cell interconnects which are "trying" to "corona" to the solar cell coverglass surface. The fact that the metallic portions get to -15 kV rapidly is not surprising, since the backside kapton is 51% open with holes which expose the underlying aluminum honeycomb material.

The implications of the observed -15 kV metallic portion voltage are serious in that these large stresses and stored energy in the coverglass might prove to be damaging to diodes on the solar array. Repeating of this test and further investigation of this configuration is required. This is particularly the case if a requirement to make the backside conductive causes the thermal design to necessitate a drastic redesign of the entire array.

## Tests with the Lightweight Substrate with Conductive Coating on the Backside, Sample (2a)

This sample (2a) is sample (2) with the 0.5 mil Bostik-Finch 463-6-14 epoxy paint sprayed on the backside kapton. The test configuration as shown in figures 2 and 3 has the electron beam irradiating the backside and the UV shining on the solar cell side.

As with sample (2), with the UV lamps off, the metallic portions went to -15 kV with the 20 kV 10 na/cm$^2$ electron beam. Initially after turning on the UV lamps, this sample behaved as sample (2), arcing occasionally and remaining at -15 kV. After a few tens of minutes of UV irradiation, however, it began to behave more like sample (1) in that the sample potential reduced to a few kV negative. Figure 6 shows the initial behavior of this sample. Turning on the UV lamp caused the arcing frequency to increase, with very few arcs occurring when the lamps were turned off. Occasionally, the sample would "try" to zener as is seen in figure 6. On some occasions the zenering continued after the lamps were turned off as with sample (1). Reducing the electron beam current slightly by lowering the electron gun filament voltage from 60 volts to 55 volts caused the sample to behave more nearly as the all-metal sample (1). Figure 7 shows the result of a more careful calibration of the electron beam current flux at the sample as a function of the electron gun filament voltage. At the normal 60 volts, the current density is more nearly 30 na/cm$^2$ than 10 na/cm$^2$, and at 55 volts, about 6 na/cm$^2$. Figure 8 shows some of the traces at the voltage monitor point for this sample. Note that the "zenering" is more gradual and that turning off of the UV lamps allows the potential to gradually rise back to the -15 kV level. Extrapolation of the UV effect observed in this test to the one-sun level would indicate that this sample (2a) configuration is acceptable from the viewpoint of spacecraft charging. The test and results with sample (2a) are summarized in table 3.

## Further Tests with Sample (2a)

The preliminary TDRSS design guidelines were established on the basis of the foregoing test results. The following tests were performed subsequently on sample (2a) to obtain a better understanding of the phenomena observed. As noted earlier, additional tests should be performed on the sample (2) configuration also. A verification test on the final TDRSS solar array design is also required.

The following test was run on sample (2a) to define the photo-induced current as a function of the potential of the metallic portions of the sample. A variable 250 V to 15 kV supply was used to bias the sample as shown in figure 9. As the lamps were turned on, an initially large capacitive charging current is seen as in figure 10. When this current reached a steady state value, the lamps were turned off, and this change constituted a measure of the photo-induced current. The results, as shown in figure 11, indicate an initially linear 8 na/volt increase of current with bias voltage. Near -1 kV arc discharges begin to occur, and the curve begins to flatten.

Figure 11 is a plot of the steady state photoemission and does not include the transient displacement current which charges up the coverglass capacitance. If one assumes that the interconnects comprise 5% of the coverglass area, the current from the interconnects would be much smaller than any of the measured currents shown in figure 11:

$$I = (.05 \cdot 160\ \text{cm}^2) \cdot (.28\ \text{na/cm}^2) = 2.24\ \text{na}$$

The currents of the order of 100 na shown in figure 11, on the other hand, would not account for the dramatic decrease of potential observed with sample (2a) or sample (1) where currents of 1-10 μa would be required. The current required for "zenering" is affected by the displacement or capacitive charging currents of the solar cell coverglass. Figure 10 indicates that these currents may be in the microampere range. These currents will flow away (electrons leaving) from the sample if the capacitance is discharged by arc breakdown. These arc discharges are observed when the power supply voltage is in the order of -1 kV. Measurements of the coverglass surface potential after turning off the negative power supply show voltages in the order of 500 volts. This also is an indication that voltage stresses of greater than 500 to 1000 volts cannot be maintained with this polarity.

Figure 12 shows discharge oscilloscope traces taken across the capacitivity coupled 5 ohm resistor shown in figure 9. The peak discharge currents range from 0.6 to 3.6 amperes as the sample voltage is raised from -1750 volts to -15 kV, and the widths were in the order of 2 to 4 microseconds. The peak pulse current does not appear to be linearly related to sample voltage. Peak pulse current vs sample voltage is shown below:

| Sample Voltage (kV) | 1.75 | 2.0 | 2.5 | 5.0 | 10.0 | 15.0 |
|---|---|---|---|---|---|---|
| Peak Current (amps) | 0.6 | 0.8 | 0.9 | 1.6 | 2.8 | 3.6 |

## Test with Aluminum Plate Sample (3)

The aluminum plate (11.25" x 14"), used to obtain a measure of the photoemission level from the UV lamps as described in the tests on the all-metal substrate (1), was tested to determine whether enhanced photo-induced currents would be obtained at high negative potentials. The initial photoemission tests on this sample were made with a -22 volt bias.

With the 20 kV 10 na/cm$^2$ electron beam, the sample (3) potential went to about the same -15 kV as the other solar array samples. No arcs were observed whether the UV lamps were turned on or not. The voltage traces for this test are shown in figure 13. Note that the UV effects are barely perceptible. Summary of tests and results on aluminum plate sample (3) are listed below:

- Electron bombardment on one side and UV irradiation on the other side. 20 kV 10 na/cm$^2$ beam; ∿9.5% of one-sun UV.

- Sample potential went to ∿ -15 kV.
- No arc discharges with or without UV.

The fact that this sample (3) did not exhibit the enhanced photo-induced emission current observed with all-metal sample (1) and the conductivity coated backside lightweight sample (2a) is an indication that some process involving dielectrics on the UV irradiated side is a necessary condition for enhanced emissions to occur.

The test results with sample (2) which had solar cells on it, but no conductive coating on the backside, indicate that a conductive backside tied to the metallic parts of the array is a necessary part of the acceptable array design. The test on the sample (2) substrate without the solar cells on it also indicate that a conducting backside is necessary.

## SUMMARY AND CONCLUSIONS

The tests and results performed to develop TDRSS solar array design guidelines for immunity to the geomagnetic substorm environment at geosynchronous altitudes are summarized in each section. The preliminary design guidelines and recommended practices based on these test results are given table 4. The guidelines and recommendations are consistent with a survey of our inhouse experience with spacecraft charging effects and with information exchanges with outside institutions such as NASA, European Space Agency and Canadian Research Centre. The tests described here provide data which back up these recommendations and our experience, both analytical and experimental, indicate that these guidelines are reasonable. Being a relatively recently discovered (or acknowledged) phenomenon and a field of active research, it is impossible to write a definitive design guideline document for immunizing against geomagnetic substorm charging effects. Much work is being performed at the present time on the engineering as well as scientific aspects of the spacecraft charging phenomenon at many organizations. Specific design and immunity verification problems on each spacecraft program will have to be solved on an individual basis until the technology has matured to an adequate level.

## REFERENCES

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## TABLE 1. SUMMARY OF TESTS AND RESULTS ON ALL-METAL SUBSTRATE SAMPLE (1)

- Electron bombardment of backside, UV on solar cell side. -20 kV, 10 na/cm$^2$ beam; $\sim$9.5% of one-sun UV.
- Sample metallic portions brought out of tank and grounded through 25,000 megohms ($2.5 \cdot 10^{10}$ ohms).
- Sample voltage was $\sim$ -16 kV, occasional arcs with no UV.
- Voltage dropped to $\sim$ -1 kV with UV; noisy.
- Voltage remained low when UV was turned off.
- Preceeding sequence starting with high negative voltages may be repeated by closing doors and stopping the electron beam.
- Power supply directly on sample, no electron beam, shows "corona" starting at -500 volts, arcing at -1 kV. Increased arcing frequency and increased "corona" current at -1.5 kV.
- Aluminum plate the same size as all-metal substrate (11.25" x 14.25") showed 0.8 μa photoemission current with -22.5 volt bias. Photoemission current density calculated to be .28 na/cm$^2$, or about 9.5% of that expected in orbit (one-sun).
- Photo-induced currents are 68 to 1152 (or even larger) times greater than might be expected from aluminum plate test (interconnect area only).
- For one-sun conditions this extrapolates to 35 to 580 times or 10.2 na/cm$^2$ to 173 na/cm$^2$ (on an overall area basis including coverglass area).

## TABLE 2. SUMMARY OF TESTS AND RESULTS ON UNPAINTED LIGHTWEIGHT SUBSTRATE SAMPLE (2)

- Electron bombardment and UV irradiation as for sample (1): 20 kV 10 na/cm$^2$ beam; $\sim$.95% of one-sun UV.
- Sample(2) is smaller (7.25" x 9" substrate, 20 cells) than sample (1).
- Sample metallic portion at $\sim$ -15 kV; occasional arc discharges.
- Turning on UV lamps has no noticeable effect.
- Essentially the same results were obtained with the substrate for sample (2) with no solar cells put on it.

TABLE 3. SUMMARY OF TESTS AND RESULTS ON LIGHTWEIGHT SUBSTRATE WITH CONDUCTIVE COATING ON BACKSIDE, SAMPLE (2a)

- Electron bombardment and UV irradiation as for samples (1) and (2); 20 kV 10 na/cm$^2$ beam; ∿ 9.5% of one-sun UV.
- This sample (2), 7.25" x 9" substrate with 20 cells, but with backside spray coated with .5 mil of Bostik-Finch 463-6-14 epoxy paint.
- The resistance measured with 1" diameter discs laid on the paint measured ∿ 10$^5$ ohms.
- To the substrate from one of the discs, the resistance was measured to be 0.5 to 1 times 10$^4$ ohms.
- The enhanced photo-induced electron emission was observed as for sample (1) but was not as pronounced.
- The incident electron beam was recalibrated and this showed that with 10 na/cm$^2$ and a one-sun UV irradiation, this configuration would result in a low stress design for the TDRSS solar array.

TABLE 4. PRELIMINARY DESIGN GUIDELINES AND RECOMMENDED PRACTICES

1. The back surfaces of the solar array panels must be conductive.
2. The conductive back surface must be connected to structure.
3. The aluminum honeycomb core must be grounded to structure.
4. The solar panel edges must be covered with conductive tape and grounded.
5. The solar cell coverglass may be fused silica or ceria glass.
6. The solar array wiring may be on the frontside or the backside—the backside is preferred.
7. The blocking and shunt diodes may be located on the frontside or the backside—the backside is preferred.
8. The blocking and shunt diodes should have the largest possible forward current ratings.
9. Design verification tests must be performed.

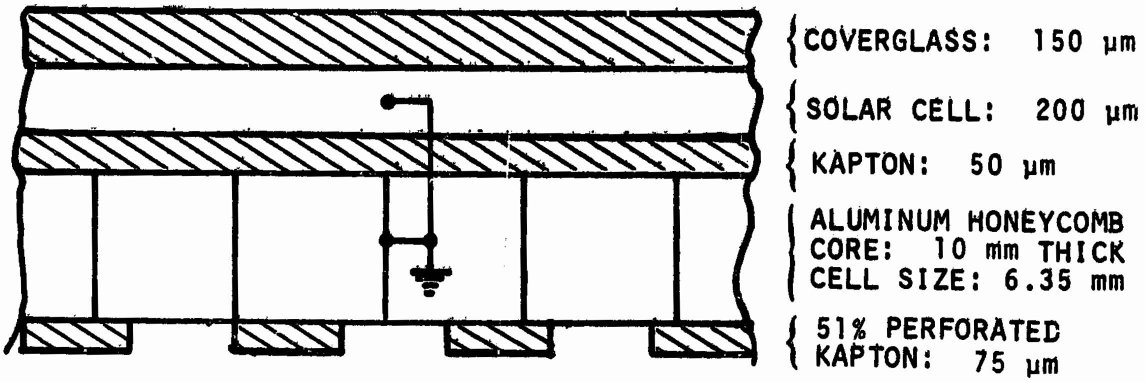


Figure 1. TDRSS SOLAR ARRAY CONFIGURATION

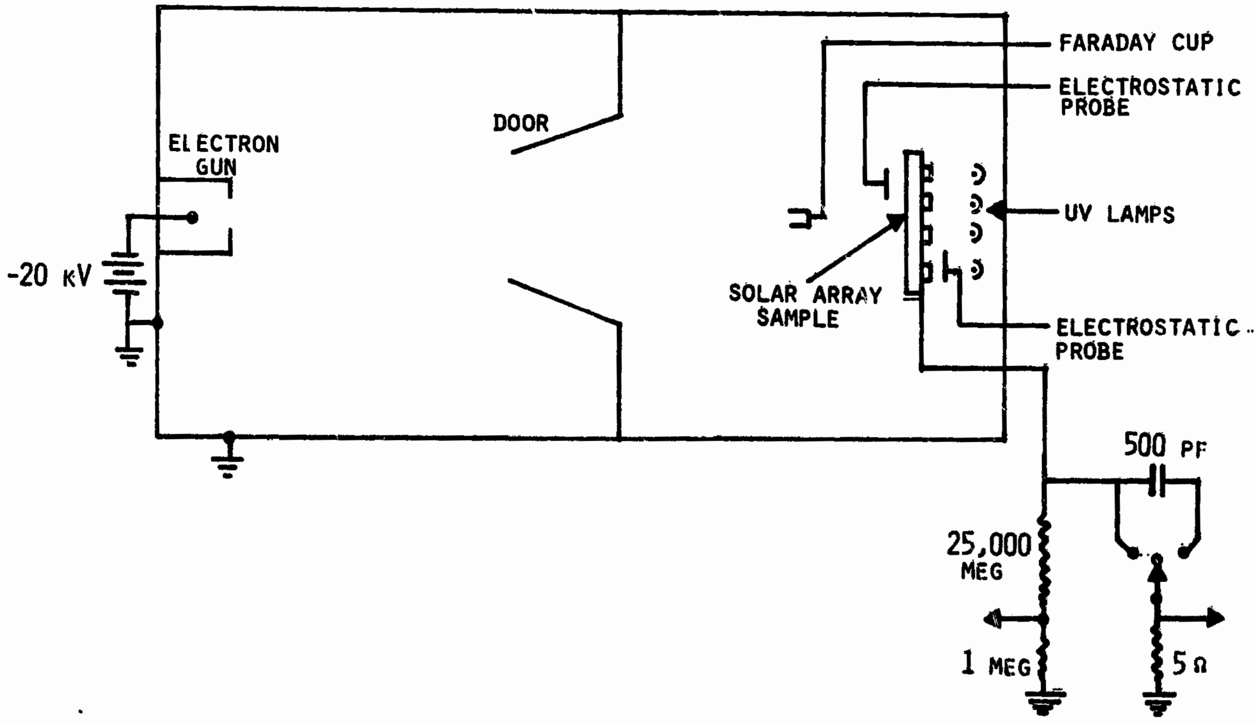


Figure 2. TEST SETUP IN 2' x 4' VACUUM TANK

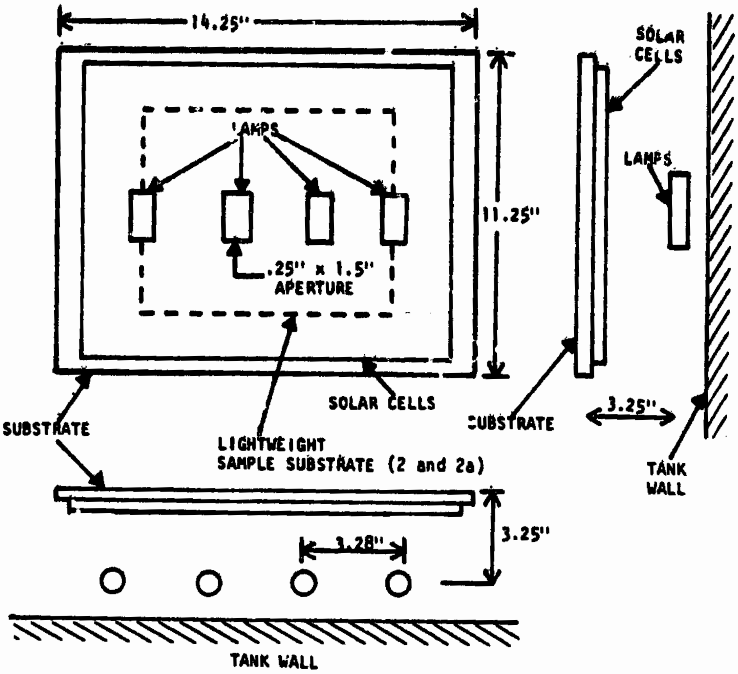


FIGURE 3. ALL-METAL SAMPLE (1) TEST CONFIGURATION SHOWING UV LAMP GEOMETRY

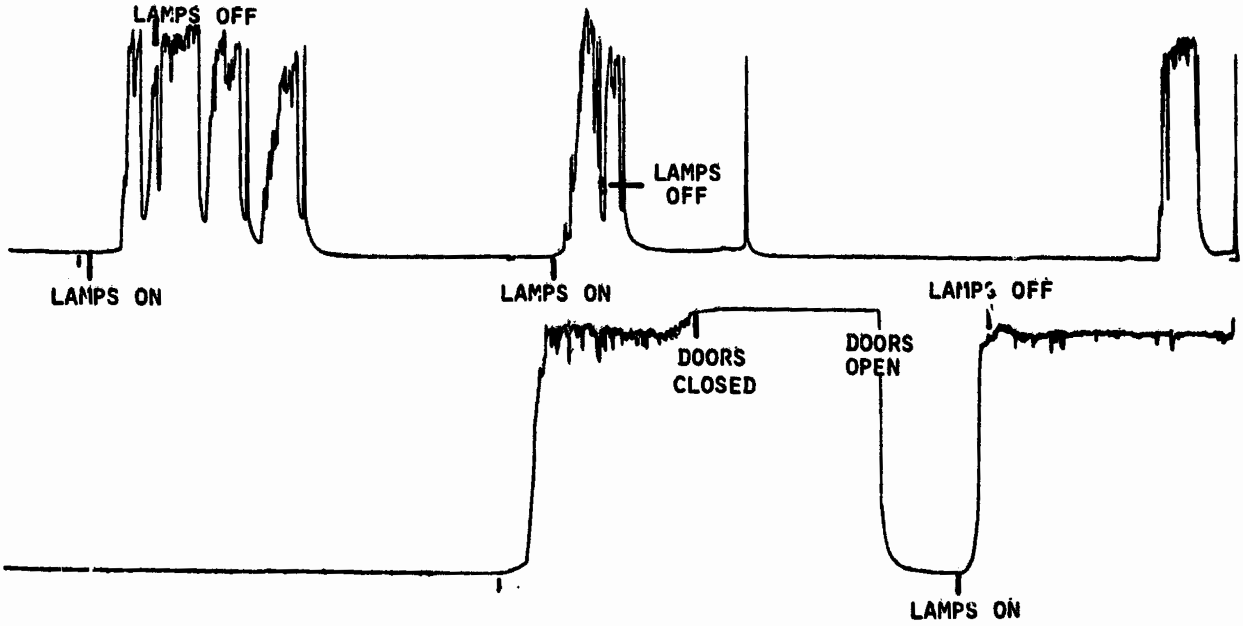


FIGURE 4. ALL-METAL SAMPLE (1) VOLTAGE TRACES. TWO TRACES ARE SHOWN. THE LOWEST PORTION OF EACH TRACE CORRESPONDS TO ∿ -15 kV. THE HIGHEST PORTIONS OF THE TRACES ARE ∿ -1 kV. THE HORIZONTAL PERIOD IS ABOUT 10 MINUTES PER TRACE.

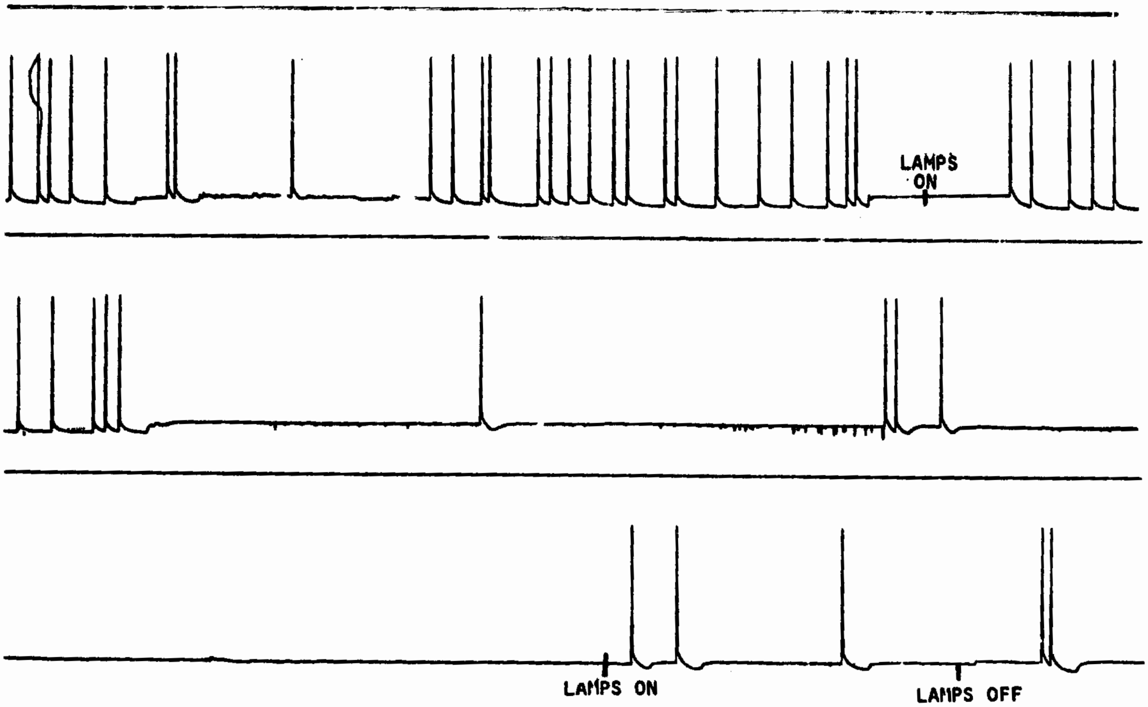


FIGURE 5. VOLTAGE TRACES WITH LIGHTWEIGHT SUBSTRATE SAMPLE (2) (NO CONDUCTIVE COATING ON BACKSIDE). VOLTAGE TRACES SHOW THAT UV LAMPS DO NOT CAUSE "ZENERING" ACTION.

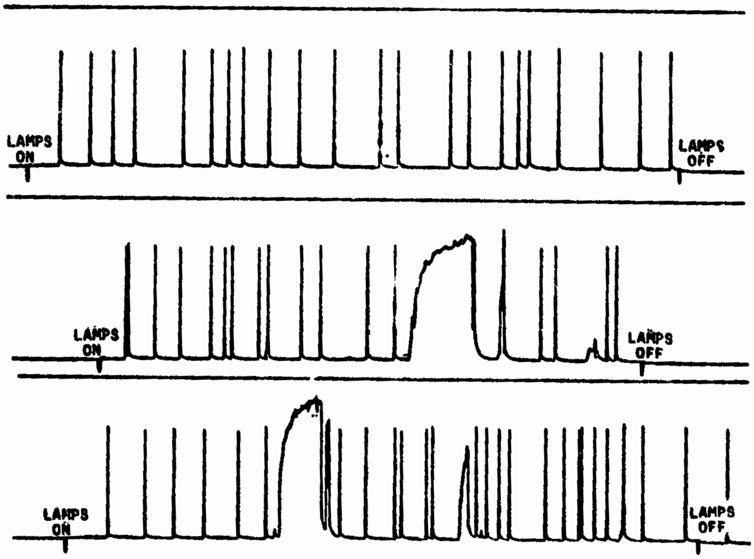


FIGURE 6. INITIAL VOLTAGE TRACES OBTAINED WITH SAMPLE (2a). NOTE THAT TURNING ON THE UV LAMPS INCREASES THE OCCURRENCE OF ARC DISCHARGES AND OCCASIONALLY SHOWS A TENDENCY OF ZENERING.

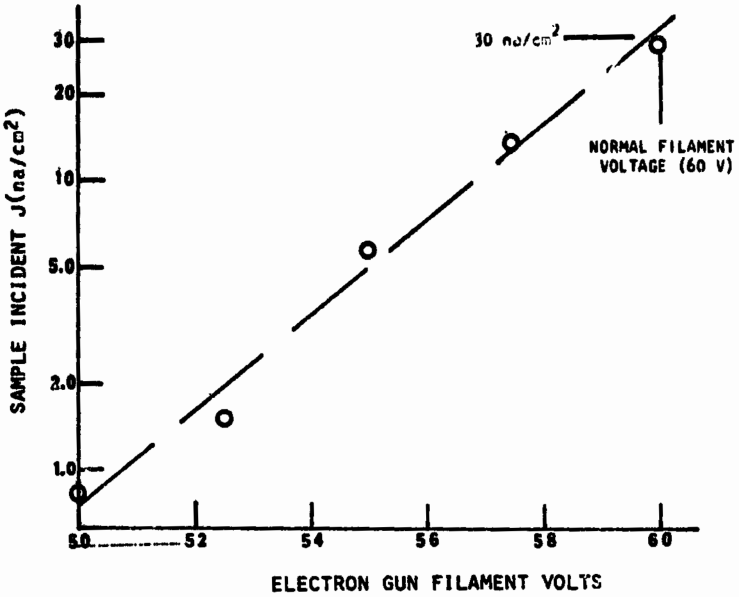


FIGURE 7. SAMPLE INCIDENT CURRENT DENSITY VS ELECTRON GUN FILAMENT VOLTAGE.

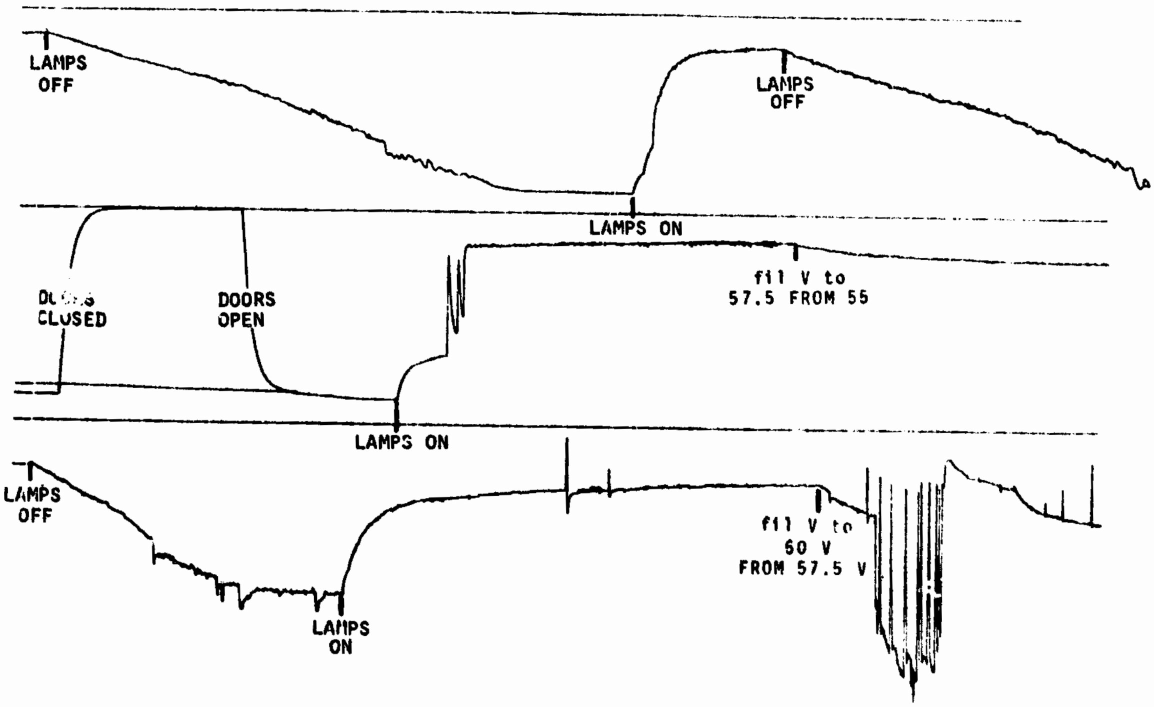


FIGURE 8. VOLTAGE TRACES WITH SAMPLE (2a) (LIGHTWEIGHT SUBSTRATE WITH CONDUCTIVE COATING ON BACKSIDE). VARIABLE ELECTRON BEAM CURRENT DENSITY FROM 6 TO 30 na/cm$^2$.

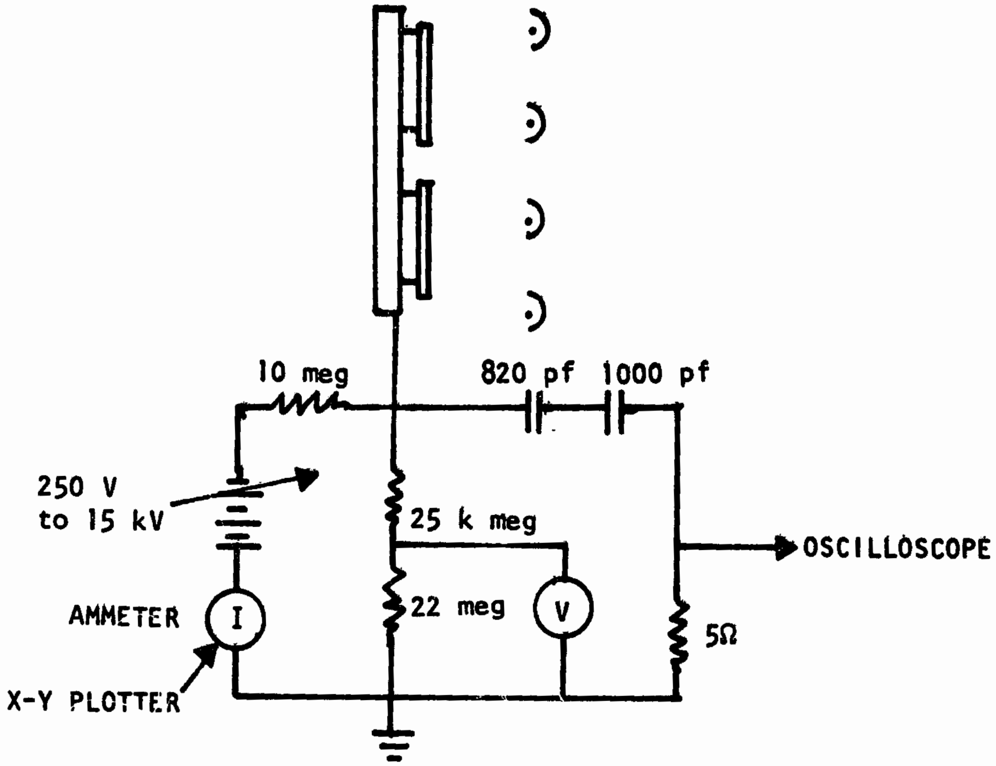


FIGURE 9. CIRCUITS TO MEASURE PHOTO-INDUCED CURRENT VS POTENTIAL.

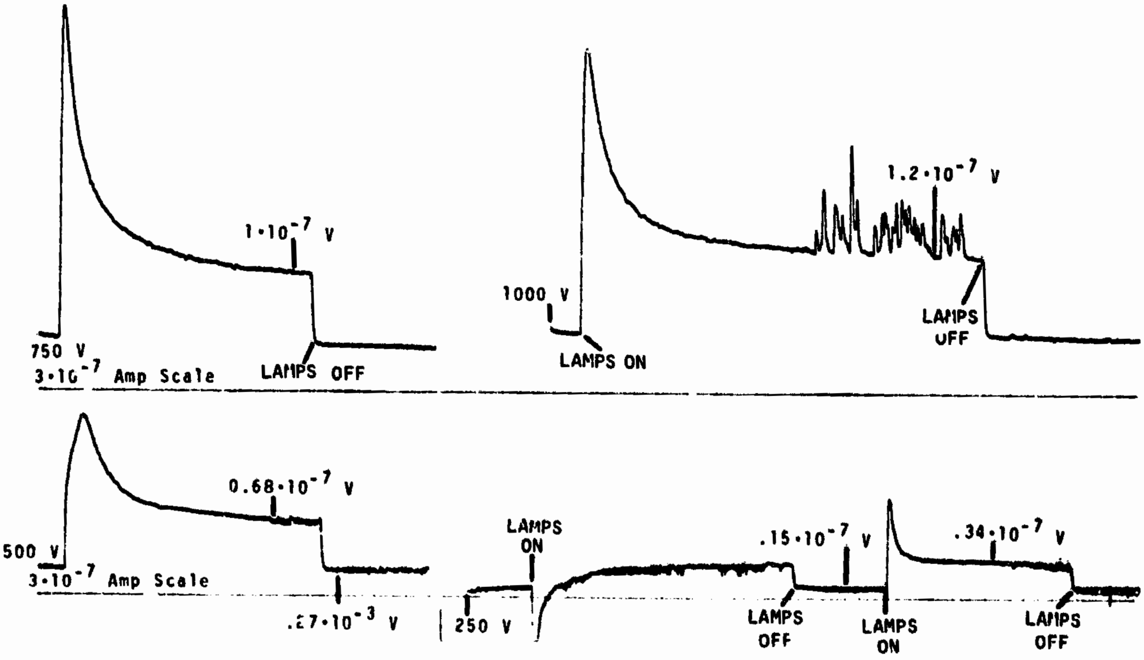


FIGURE 10. PHOTO-INDUCED CURRENTS FROM SAMPLE (2a) VS SAMPLE VOLTAGE.

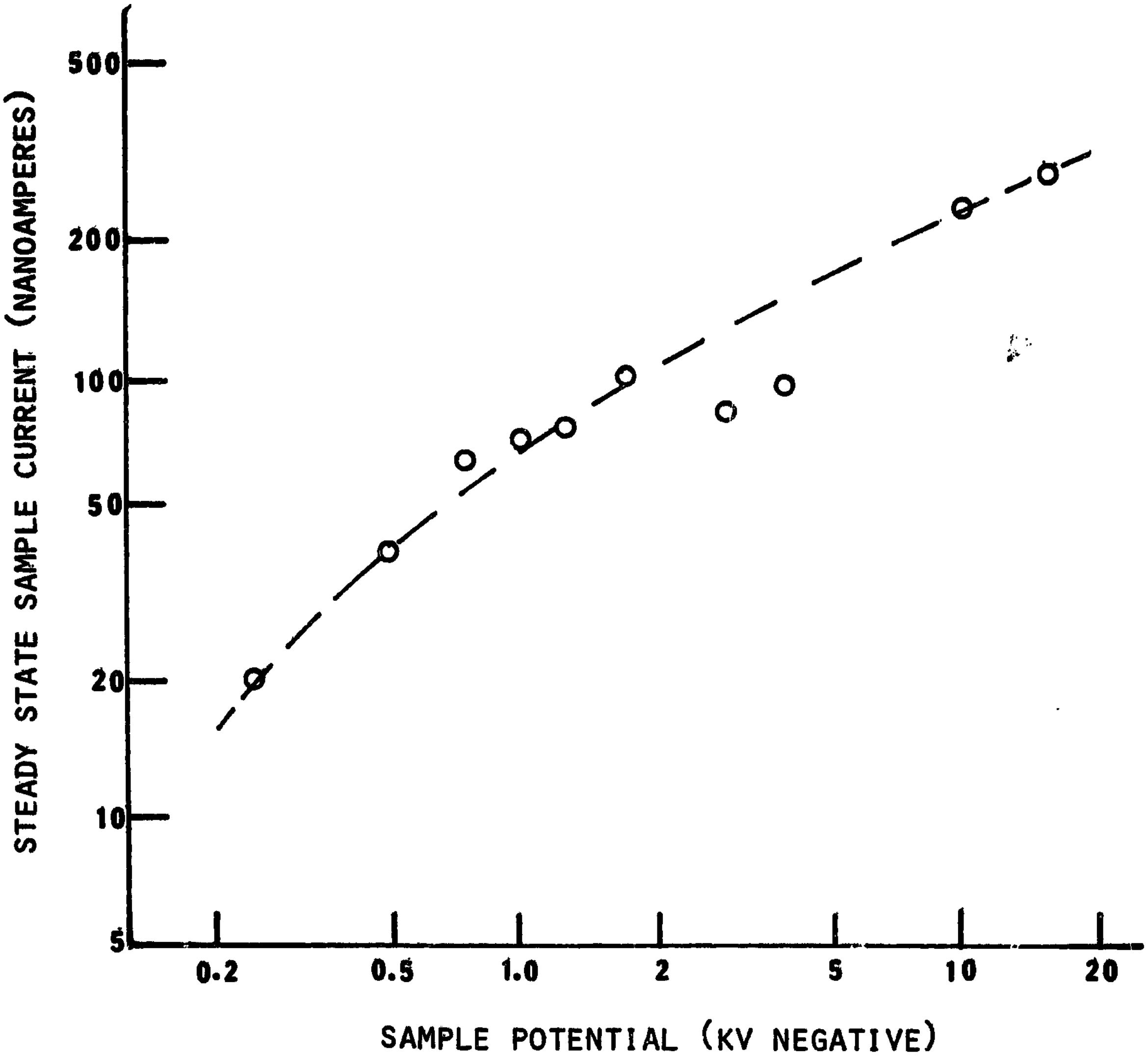
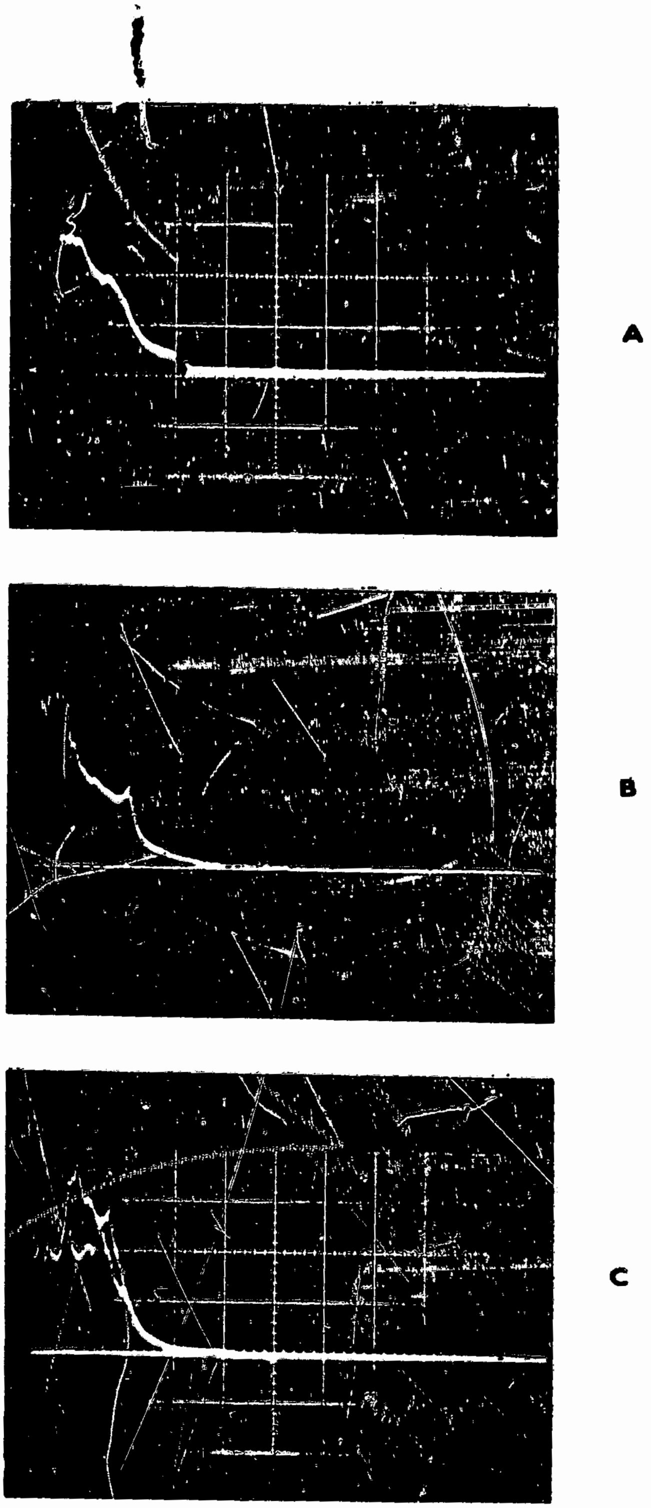


FIGURE 11. STEADY STATE SAMPLE (2a) PHOTO-INDUCED CURRENT VS POTENTIAL



A

V = -1750 Volts
R = 5 ohms
.2 amp/cm Vertical
1 μs/cm Horizontal

B

V = 5000 Volts
R = .5 ohms
.4 amp/cm Vertical
1 μs/cm Horizontal

C

V = -15 kilovolts
R = 5 ohms
1 amp/cm Vertical
1 μs/cm Horizontal

FIGURE 12. ARC DISCHARGE WAVEFORMS OBTAINED WITH SAMPLE (2a).

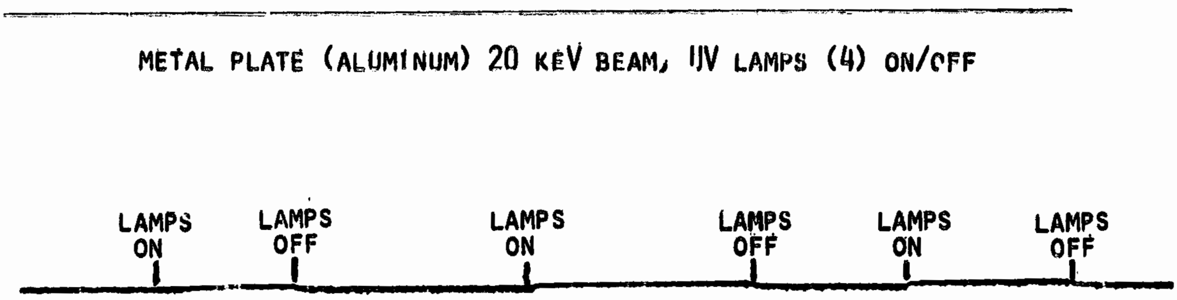


FIGURE 13. VOLTAGE TRACES WITH AN ALUMINUM PLATE SAMPLE (3)

The following papers were not presented at the conference but are included here for additional information.