Voltage Threshold and Power Degradation Rate for GPS Solar Array Arcing

Dale C. Ferguson, Ryan C. Hoffmann, Daniel P. Engelhart, and Elena A. Plis

***Abstract*— We present here an investigation of the arcing voltage threshold for GPS-like arrays performed in the Spacecraft Charging and Instrument Calibration Laboratory at the Air Force Research Laboratory's Battlespace Environment Laboratory at Kirtland Air Force Base, New Mexico, USA. Our simulations were done under GPS-like plasma environments in a vacuum-plasma chamber. The arc voltage threshold found is compared with that predicted from the Los Alamos National Laboratory (LANL), detectors, and the question of to what degree were the indium tin oxide-coated cells on GPS properly grounded is discussed. It is shown through the current–voltage testing of the arrays pre- and postarcing that the anomalous power degradation seen on GPS satellites on orbit can be completely accounted for by arcing at the anomalous event rates seen by LANL radio frequency detectors onboard. Implications for arcing and contamination mitigation on future GPS satellites are presented.**

***Index Terms*— Aerospace testing, power system reliability, satellites, solar power generation, surface charge.**

I. Introduction

GPS satellites experience power degradation greater than that which can be attributed to radiation damage on the solar arrays. The preferred hypothesis to date is that the arrays are being contaminated, and the decreased insolation leads to decreased solar array power [1]. However, although a contamination monitor flown showed the signature of contamination, subsequent attempts to eliminate suspected contamination sources have been fruitless [2]. A new hypothesis that the contamination comes from solar array arcing may also explain the occurrence and environmental correlation of false events in the Los Alamos National Laboratories radio frequency detectors on GPS satellites [3]. If the hypothesis is correct, the charge built up on the solar arrays before arcing leads to a value of the arcing voltage threshold for GPS arrays of <2000 V.

II. Experiment

A four-cell sample of GPS-like solar array was tested in the Air Force Research Laboratory (AFRL) and the Spacecraft Charging and Instrument Calibration Laboratory (SCICL). The cell-interconnects-coverglass (CIC) of GPS-IIR solar cells was obtained from Lockheed Martin (Scott Billets) by way of the Naval Research Laboratory (Phil Jenkins), and they were laid down by Neil Snyder (AFRL) under the direction of David Wilt (AFRL). Information about the layup specifics was obtained from Bernie Carpenter (Aerospace Corporation) Although GPS-IIR coverglasses were indium tin oxide (ITO)-coated and nominally grounded, the CICs in our test were ungrounded, in keeping with the fact that many of the GPS-IIR grounding tabs had come off before launch [4].

Although the adhesive bonding the cells to the 2-mil Kapton substrate on GPS-IIR was GE 566 Room Temperature Vulcanization rubber (RTV), the modern equivalent (SCV10-2568 RTV)[1] was used for our tests. And although GPS-IIR specs called for Ethylene tetrafluoroethylene (ETFE)-insulated wiring with a Kapton sleeve, as per Mil-W-81381, the wiring on our test article came with no Kapton sleeve. The layup was then CIC/SCV10-2568/2-mil Kapton/SCV10-2568/aluminum.

The coupon was current–voltage (I–V) tested before exposure to the simulated space environment, and after arc testing was complete.

To make the GPS test article as true to the flight version as possible, it was baked in a vacuum oven at 60 °C for 24 h to drive off any contamination, especially water. It was then immediately mounted to a grounded aluminum stand in the Jumbo vacuum chamber which was pumped down overnight to a base pressure of $<10^{-6}$T. Because of the very low humidity in Albuquerque, and the fact that the days of the experiment were clear and the atmospheric pressure was high, we believe that very minimal water recontamination occurred. A −400 V inverted potential gradient was induced on the cell by using an *ex situ* power supply with a 100-kΩ current limiting resistor in series and a 66-nF capacitor in parallel to decouple the power supply during the arc. All four-cells were unilluminated and held at one potential.

The test article was then exposed to 90-keV electrons (an energy well above the second crossover point for secondary electron emission), and any arcs were detected using both a 200-fps video camera and Pearson coils. In the first test, the Teflon-insulated test leads were left bare and the whole article was under a constant fluence of 10^{-12} A/cm^2. This run produced 850 arcs with an initial arc rate of 2 min^{-1} that then decayed roughly exponentially to 0.5 min^{-1} after 14.8 h. Imaging shows that many, but not all, of these arcs originated on the ETFE Teflon-insulated leads.

Because of the lack of Kapton sleeves on our ETFE-insulated leads, we chose to eliminate the leads

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D. C. Ferguson and R. C. Hoffmann are with the Air Force Research Laboratory, Kirtland Air Force Base, Albuquerque, NM 87117 USA.

D. P. Engelhart is a U.S. National Research Council Fellow, Kirtland Air Force Base, Albuquerque, NM 87117 USA.

E. A. Plis is with the Assurance Technology Corporation, Carlisle, MA 01741 USA.

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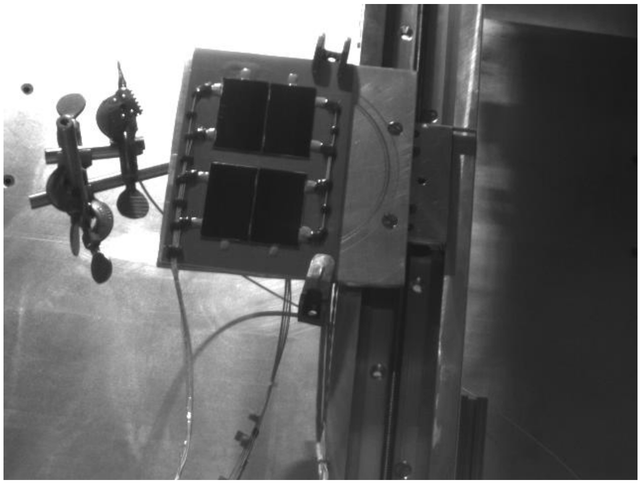

Fig. 1. Four-cell coupon. All four cells are wired in series. The electron beam was face-on in this picture.

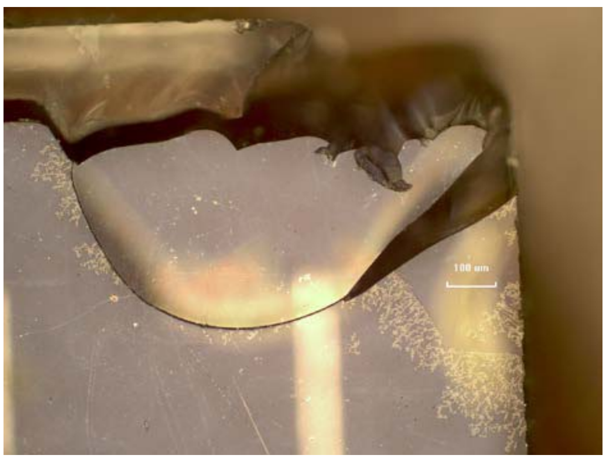

Fig. 2. Lichtenberg-like figuring of an arced coverglass corner.

from arcing by covering them in Kapton and taking a second data run. This run was also exposed to 90-keV electrons, but at a higher flux of 3×10^{-11} A/cm^2 and resulted in 333 arcs over the course of 17.5 h. The arc rate for this run was a constant 0.3 min^{-1}. Imaging of this run confirms that none of the arcs were a result of the Teflon wiring. The average total charge released in each arc was calculated, by integrating the current pulse from the Pearson coils, to be 6×10^{-7} C/arc—far less than the 2.6×10^{-5} C stored in the capacitor, and corresponding to a discharged area at 400 V of about 100 cm^2 (approximately the total area of the coverglasses). Fig. 1 shows the test setup in the Jumbo chamber.

III. Interpretation of Results

In the initial testing, a -400 V arc initiation voltage threshold was established. Still frames from video showed that most arcs appeared on the ETFE-insulated wiring, although at least one arc was along one exterior edge of a cell. In this test, the arc onset voltage was about -400 V and the charge per arc averaged 2.5 μC/arc. An interesting Lichtenberg-like figuring was seen on one coverglass corner, near where an arc had been seen in the video, and its photomicrograph is shown in Fig. 2.

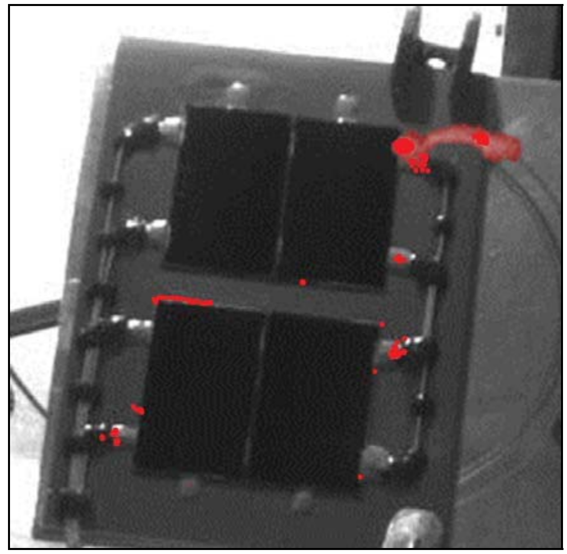

Fig. 3. Test coupon, with non-ETFE arcsites marked in red.

To encourage arcing at places other than the (out-of-spec) Teflon-insulated wiring, subsequent tests were performed with all ETFE covered up by Kapton tape. Afterward, the arcs were mainly seen on the RTV bonding the wiring to the substrate. Fig. 3 shows the test setup with arc-locations shown in red. One arc (upper right) jumped to the aluminum backplate, although most were well localized. Apart from the exposed RTV, cell edges and corners were preferred arcsites.

Because only the bias voltage at arc initiation was measured, but not the surface potential on the coverglasses or exposed RTV, we could not say that the differential voltage for arcing onset was 400 V. In order to settle this question, another test was performed in SCICL in February, 2017. In this test, the sample was floated in a 20-keV electron beam at a flux of 7×10^{-12} A/cm^2. A Trek probe was used to measure alternately the potential on the coverglasses and the cell circuit. The potentials tracked almost exactly together, probably because in our case the ITO coating may have inadvertently been grounded to the cell underneath. The first arc occurred when the absolute potential was -1760 V, at 8219 s after the electron beam was turned on. Three arcs occurred at about the same potential (-1820 +/$-$ 60 V), separated by about 3000 s. Thus, we can confidently ascribe an arc threshold voltage to our GPS-like sample as -1760 V. Because there was a very little differential potential between the coverglass and the cells, we believe these arcs to have been on the RTV as well. We show these results in Fig. 4.

However, the question naturally arises—why were there so many arcs on the RTV? The answer may lie in the nature of the RTV. Although basically a red silicone rubber, SCV10-2568 is highly impregnated (10%–15%) with microscopic glass beads to lower its density. This was also true of GE 566 (the original GPS–IIR RTV). Ordinarily, one would consider the silicone rubber matrix to dominate the breakdown strength and conductivity of the material, but previous tests performed in SCICL on a conductive matrix with microscopic glass beads (that was intended to be a flexible, conductive, coverglass material) showed that the presence of the beads made the mate-

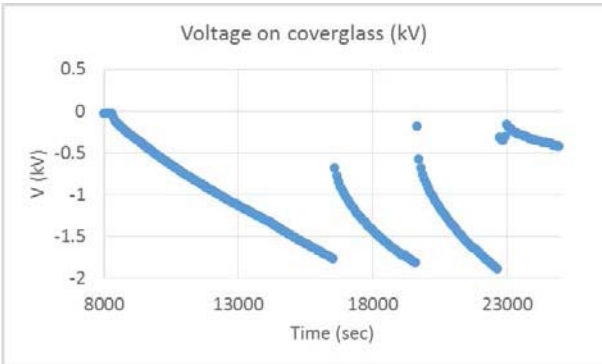

Fig. 4. Arcing threshold experiment. Cell voltage nearly identical. Arcs near 16500, 19600, and 22600 s.

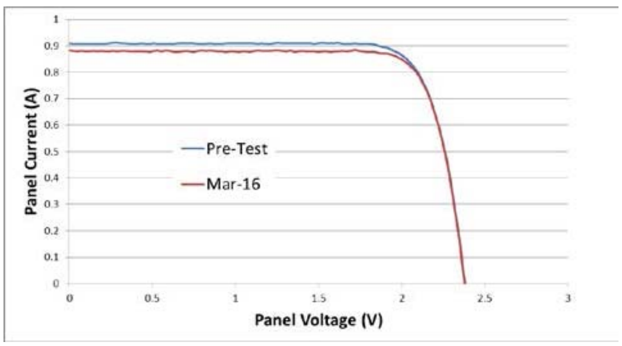

Fig. 5. Four-cell panel I–V curves before (pretest) and after arcing (March 2016).

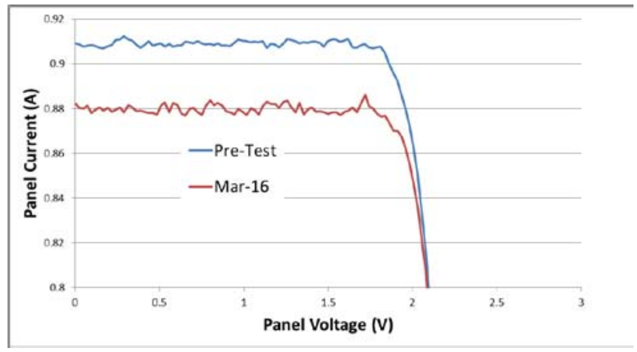

Fig. 6. Blowup of Fig. 4. Panel current changed by ~0.03 A due to arcing.

rial highly resistive and lowered its breakdown strength [5]. It is our opinion that this is also true of the RTV commonly used to adhere CICs to the substrate in flight arrays, and may be an unintended arcsite in space applications. Further testing must be performed to confirm this hypothesis.

The testing reported here is on solar cells with nominally ungrounded ITO. The flightlike condition probably has most cells grounded. That condition has yet to be tested. However, it is clear that many arcs on the cells tested occur on the RTV insulation, not on the interconnects or other traditional arc sites.

IV. Contamination Results

Array (I–V) characteristics were measured by Neil Snyder and David Wilt at AFRL before (pretest, September 3, 2015) and after arcing (March 16, 2016). The measurements were made with a Spectrolab X-25 solar simulator. Three I–V scans were made each time and the results were averaged. The scans after arcing were significantly different from those before arcing. In Figs. 5 and 6 are the results, labeled “pretest” and “March-16.” A total of 3748 arcs were experienced by the panel in all of the arcing tests in 2016 combined.

Thus, the power had degraded by (0.91−0.88)/0.91 = 3.3% due to ~940 arcs/cell. This corresponds to a 9×10^{-4}% efficiency loss per arc, or a 3.6×10^{-3}% efficiency loss per arc if all arcs had happened on one cell.

In [3], estimates of the efficiency loss per arc were made in order to obtain the 1.5%/yr GPS power loss seen on GPS satellites. Scaling these numbers by the appropriate factors to account for the difference in the number of cells and the anomalous event rate seen in LANL radio frequency detectors on GPS satellites, it is found that in space the efficiency loss per arc on each cell should be 2.3×10^{-3}%. Comparing this number to that found above from testing, it appears that the arcing hypothesis can account for all of the anomalous GPS power degradation, with a comfortable margin to account for approximations in the on-orbit estimate.

V. Conclusion

A space-like test of a four-cell GPS-like solar array showed that the arc threshold was about −1760 V absolute charging, and that most arcs occurred on the SCV10-2568 RTV used to glue the cells and wiring to the Kapton substrate or near solar cell edges or corners. Each arc discharged about the coverglass area of the array. The threshold voltage of 1760 V is consistent with an estimated GPS arcing threshold on orbit of <2000 V [3]. Because of the substantial arc rate from the RTV, it is hypothesized that at least some of the GPS arcing on orbit is from the RTV, and that some of the contamination that degrades the GPS solar array performance over time comes from arcs on the RTV as well as from the arcs from silver interconnects. If the RTV arcs on-orbit, there could be widespread ramifications across the spacecraft solar array manufacturing industry.

Pre- and postarcing I–V measurements on the four-cell coupon confirm that the power degradation seen per arc in testing is sufficient to explain the anomalous power degradation on GPS satellites.

Because the anomalous power degradation seen on GPS satellites amounts to some 25% over a satellite lifetime, designers have oversized the arrays to have sufficient end-of-life power. Mitigating the arcing can, in effect, lead to a 25% power gain at end-of-life or a 20% reduction in the array size for the equivalent end-of-life power.

Mitigation techniques may include the use of more conductive coverglasses [6], properly grounding the coverglass ITO coatings, and/or use of a more conductive RTV adhesive.

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Authors' photographs and biographies not available at the time of publication.