

VOLTAGE THRESHOLD AND POWER DEGRADATION RATE FOR GPS SOLAR ARRAY ARCING

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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 LANL detectors, and the question of to what degree were the ITO-coated cells on GPS properly grounded is discussed. It is shown through I-V testing of the arrays pre- and post-arc, 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 radiofrequency detectors on-board. Implications for arcing and contamination mitigation on future GPS satellites are presented.

1. 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 radiofrequency 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.

2. THE EXPERIMENT

A 4-cell sample of GPS-like solar array was tested in the Air Force Research Laboratory (AFRL) Spacecraft Charging and Instrument Calibration Laboratory (SCICL). The CICs (Cell-Interconnects-Coverglass) of GPS-IIR solar cells were 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 layout specifics was obtained from Bernie Carpenter (Aerospace Corp.) 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 RTV, the modern equivalent (SCV10-2568 RTV¹) was used for our tests. And although GPS-IIR specs called for ETFE insulated wiring with a Kapton sleeve, as per Mil-W-81381, the wiring on our test article came with no Kapton sleeve. The layout was then CIC/SCV10-2568 /2 mil Kapton/SCV10-2568/aluminum.

The coupon was 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 hr to drive off any contamination, especially water. It was then mounted to a grounded aluminum stand in the Jumbo vacuum chamber which was pumped down overnight to a base pressure of < 10⁻⁶ torr. 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 4 cells were unilluminated and held at one potential.

The test article was then exposed to 90 keV electrons and any arcs were detected using both a 200 fps video camera and Pearson coils. In the first test the Teflon test leads were left bare and the whole article was under a constant fluence of 10⁻¹² A/cm². 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 hr. Imaging shows that many, but not all, of these arcs originated on the ETFE Teflon leads.

¹ Trademark of Nusil Technology,

Because of the lack of Kapton sleeves on our ETFE-insulated leads, we chose to eliminate the leads 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 fluence of 3×10^{11} A/cm² and resulted in 333 arcs over the course of 17.5 hr. 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 of about 100 cm² (approximately the total area of the coverglasses). Figure 1 shows the test setup in the Jumbo chamber.

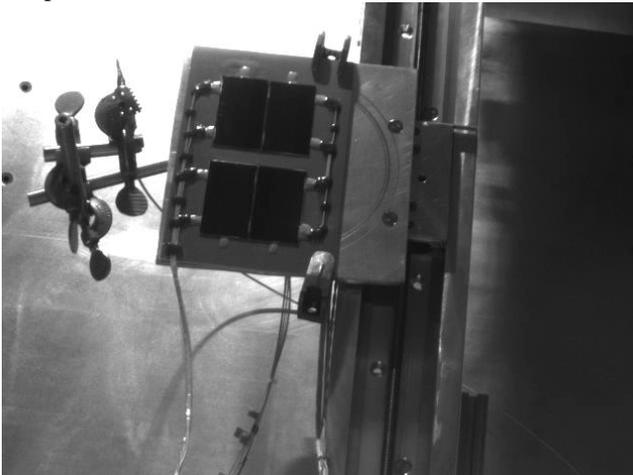


Fig. 1. The four-cell coupon. All four cells are wired in series. The electron beam was face-on in this picture.

3. INTERPRETATION OF RESULTS

In initial testing a 400 V 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 $2.5 \mu\text{C}/\text{arc}$. An interesting Lichtenberg-like figuring was seen on one coverglass corner, near where an arc had been seen in the video. A photomicrograph of it is Figure 2.



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

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. Figure 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.

The question naturally arises – why were 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 material highly resistive and lowered its breakdown strength. 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.

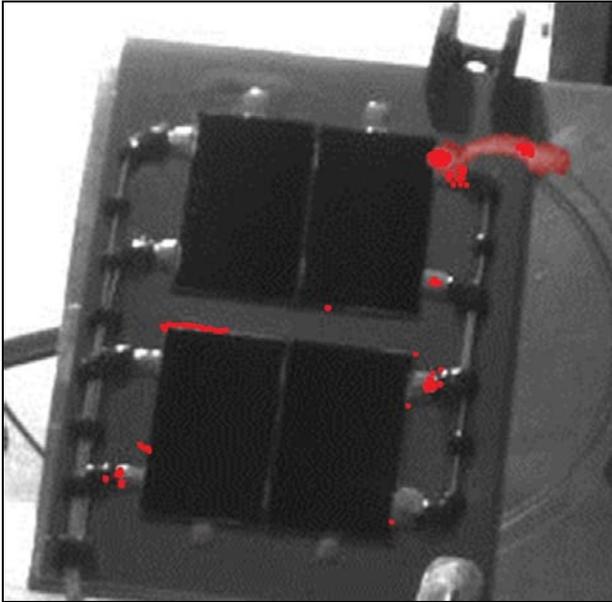


Fig. 3. Test coupon, with non-ETFE arcsites marked in red.

The testing reported here is on solar cells with 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 ungrounded cells occur on the RTV insulation, not on the interconnects or other traditional arc sites.

4. CONTAMINATION RESULTS

Array I-V (current-voltage) characteristics were measured by Neil Snyder and David Wilt at AFRL before (pre-test, Sep 3, 2015) and after arcing (Mar 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 Figures 4 and 5 are the results, labeled Pre-Test and Mar-16. A total of 3748 arcs were experienced by the panel in all of the arcing tests combined.

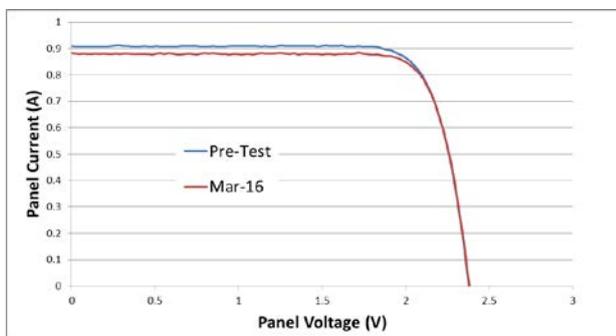


Fig. 4. 4 cell panel I-V curves before (Pre-Test) and after arcing (Mar-16).

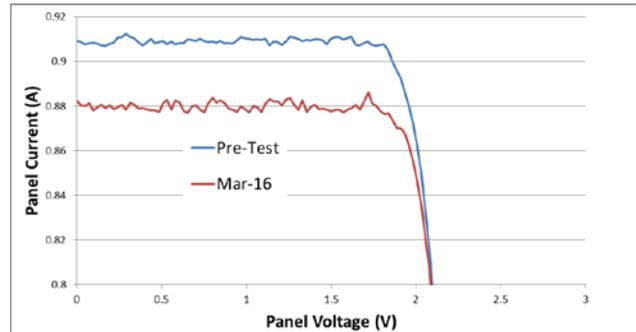


Fig. 5. Blowup of Figure 4. Panel current changed by ~ 0.03 A due to arcing.

Thus, the power had degraded by $(0.91-0.88)/0.91 = 3.3\%$ due to ~ 940 arcs/cell. This corresponds to a $9.0 \times 10^{-4} \%$ efficiency loss per arc, or a $3.6 \times 10^{-3} \%$ 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 radiofrequency detectors on GPS satellites, one can find that in-space the efficiency loss per arc on each cell should be $2.3 \times 10^{-3} \%$. 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.

5. CONCLUSIONS

A space-like test of a 4-cell GPS-like solar array showed that the arc threshold was less than 400 V, and that most arcs occurred near solar cell edges or corners or on the SCV10-2568 RTV used to glue the cells and wiring to the Kapton substrate. Each arc discharged the coverglass area of the array. The threshold voltage of < 400 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 post-arcing I-V measurements on the 4 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 [5], properly grounding the coverglass ITO coatings, and/or use of a more conductive RTV adhesive.

6. ACKNOWLEDGEMENTS

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