HYPERVELOCITY IMPACT TESTING OF SOLAR CELLS IN A PLASMA ENVIRONMENT

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ABSTRACT

As satellite power levels of advanced spacecraft climb above 20 - 50 kW, higher solar array operating voltages become attractive. For Solar Power Satellites, voltages well above 1000V have been suggested. However, micrometeoroid impacts on such high voltage arrays may have catastrophic results. To assess these effects, contemporary GaAs modules and samples of the Stretched Lens Array (SLA) modules were exposed to hypervelocity impact with 100μm diameter soda lime glass spheres at velocities up to 12 km/sec. The two strings of GaAs cells were held at differential voltages above 60V and bias voltages near -200V. A plasma environment typical of Low Earth Orbit (LEO) was also present. The SLA was held at bias voltages up to -1000V. Several types of arcs were observed in the GaAs strings. Higher bias voltages were limited by lack of cover glass overhang, but in the case of the SLA no arcing occurred.

INTRODUCTION

As the requirements for increased power and operating voltage levels for satellites have been identified, serious problems have been encountered that have resulted in the loss of power, science data and the loss of mission. These recently observed high voltage plasma effects have resulted in significant schedule and cost "hits" to current satellites as they attempt to accommodate for these interactions with the space plasma. Tests on space station hardware disclosed arcing at 50V on anodized aluminum structures that were impacted with hypervelocity particles in Low Earth Orbit (LEO) plasmas. Thus an understanding of these effects is necessary to design reliable high voltage solar arrays of the future, especially for Space Solar Power applications. For these very high power systems, low array and cable masses are imperative, and these can only be practically achieved by using high voltages. Yet, we don't know how high a voltage is practical on a realistic solar array in GEO. Most solar arrays arc into the space plasma (sometimes catastrophically) at voltages below 200 to 300V. Thus there is an absence of reliable information on which to base high power satellite designs. A major unknown is the effect of high velocity micrometeoroids on future high voltage arrays. Existing NASCAP-GEO models can provide guidance about solar cell string design, encapsulation approaches and field control for the expected environment, but the effects of micrometeoroid penetration in that environment are not included.

Therefore, the objective of this work is to study the effect of hypervelocity impacts on the design of high voltage solar arrays for use in GEO environments. Both state of the art GaAs modules and the emerging Stretched Lens Array modules were tested.

THE HYPERVELOCITY IMPACT FACILITY

The Hypervelocity Impact Facility (HYPER) at Auburn University Space Research Institute was used to conduct these tests and is shown in figure 1. This unique facility has been used extensively to determine the effects of small particles on spacecraft surfaces. Complete solar cell assemblies are exposed to a flux of impacting particles to determine component damage. Many particles can be accelerated simultaneously, with a velocity distribution roughly typical of the man-made debris spectrum. One exposure in the HYPER facility can correspond to the number of impacts received in a 7-year exposure in space for the same particle size distribution.

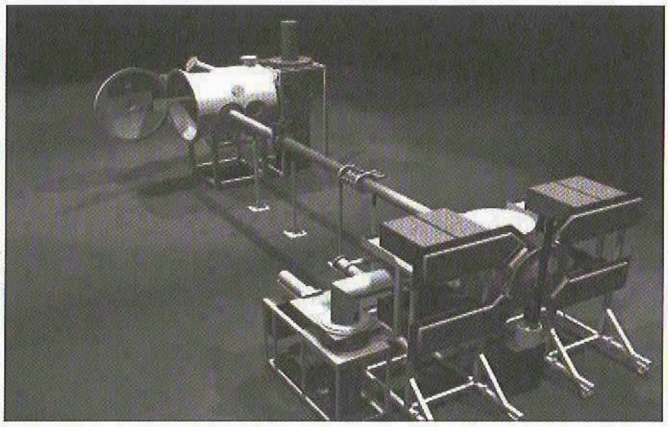

Figure 1: Hypervelocity Impact Facility, Space Research Institute

HYPER's gun is based on an arc discharge and plasma drag, and has a 5-meter flight tube and a 1-meter diameter target chamber. Discharging eight capacitors charged to a potential of 40,000 V fires the gun. This discharge vaporizes an aluminum foil placed behind the impact particle charge. In these tests, soda lime glass particles nominally 40-120μm in diameter were used for the micrometeoroid simulant. A "skimmer cone" is used to select only those particles that will pass through the flight tube and into the target chamber without sidewall contact. Approximately 30 to 70 of these particles will impact the target. A "magneforming" shutter placed in the middle of the 5-meter flight tube eliminates the low speed (<5 km/s) particles and any slow gun debris. In general, peak velocities of 10-11 km/sec were achieved for all of these tests.

Because the primary acceleration process is "plasma drag", there is always a gradient in the velocity of the particle stream. The maximum velocity obtainable and the velocity distribution are a complex function of the particle shape, particle density, absolute particle dimensions, and the gun parameters. Just as in space, there is always a wide range of particle velocities in a given experiment. From the point of view of simulation, this is desirable because it is probably a more accurate representation of the actual conditions in space.

The target chamber is equipped with a streak camera that records impacting particle x-y coordinates and velocities as well as observing any plasma discharges that may occur. A photomultiplier tube (PMT) also observes the sample to provide impact information as well as discharge information. A Mylar film placed in front of the sample allows determination of particle size and LEDs surrounding the sample define sample edges for the streak camera images.

Thus the impacting particle coordinates, size and velocity can usually be obtained. However, in these tests, the presence of arcing during impact produced additional light that tended to obscure subsequent impact events. This was shown in the first impact test where the streak camera film was almost completely saturated due to the arcing events. Extensive image processing was used to discern impact locations and was reasonably successful. On the next shot, the streak camera aperture was reduced by one f/stop. Although better, some saturation still occurred. However, more impact locations were defined. The presence of additional arcing thus affected our ability to accurately determine post-arc impact locations.

The photomultiplier tube that imaged the test plane also observed the arcing. Although impact locations could not be determined with the tube, the signal provided timing and intensity profiles of both the impact and the arc emissions.

Two approaches were used to provide a plasma environment for the impact tests. The primary mode was to use a hollow cathode device provided by the NASA-Marshall Space Flight Center. The cathode was ignited with an Argon gas stream and power reduced to the lowest level that maintained steady operation provided LEO-like plasma conditions. A Langmuir probe placed within a few centimeters of the sample was used to establish plasma densities and energies. A second approach was also developed using a Tesla coil that ionized an argon gas stream to yield plasma. This approach was successful and in fact, provided an excellent LEO simulation of low temperature plasma, confirmed by the Langmuir probe measurements. We believe the results are applicable to the GEO environment as well. In fact, the plasma densities are higher than found at GEO; hence the results represent a more difficult environment than GEO.

The HYPER facility has evolved into a sophisticated method of analyzing the effects of space debris on any material contemplated for use in space. The debris spectrum and the choice of particles that can be used, allow the experimenter to more closely duplicate the natural conditions, which will be encountered in space. The optical diagnostics allow adequate characterization of both the impacting particle stream and the damage inflicted at impact. Inherent in the facility is the ability to look at long-term effects. By choosing the particle size in correlation with the expected number of impacts based on known space flux, it is possible to estimate end-of-life characteristics due to debris in addition to local damage.

SOLAR CELL MODULES

Solar cell modules were obtained from a major supplier of space solar cells. These modules were composed of four state-of-the-art 2x4 cm GaAs solar cells with 150 µm cover glasses that were connected in two-cell series strings. They were bonded to a Kapton substrate supported by a Lucite plate. A picture of one of the modules is shown in figure 2. The series strings are on the left and right sides of the picture, with a gap between them. The supplier measured the efficiency of all 15 modules. These data are shown in figure 3. The amount of cover glass overhang and the spacing between the series strings were measured at Auburn. These data were used to select modules for testing.

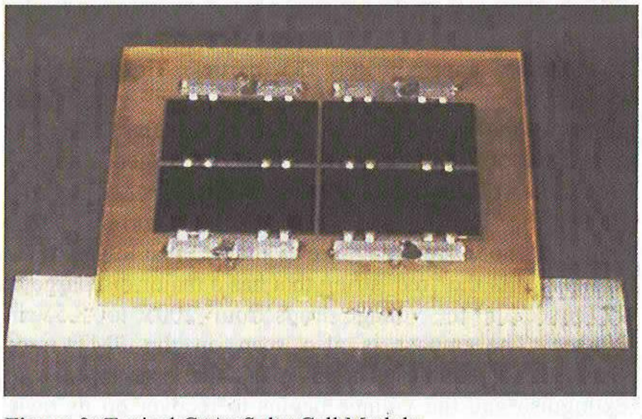

Figure 2: Typical GaAs Solar Cell Module

Efficiencies were above18% except for two modules that had low efficiency strings caused by poor fill factors. Open circuit voltages were tightly clustered (2.010+/-0.007V). Similarly the short circuit currents were also well grouped (0.252+/-0.002A). Fill factors were all near 80% except for the two modules mentioned previously. These were certainly typical of state-of-the-art GaAs cells and modules.

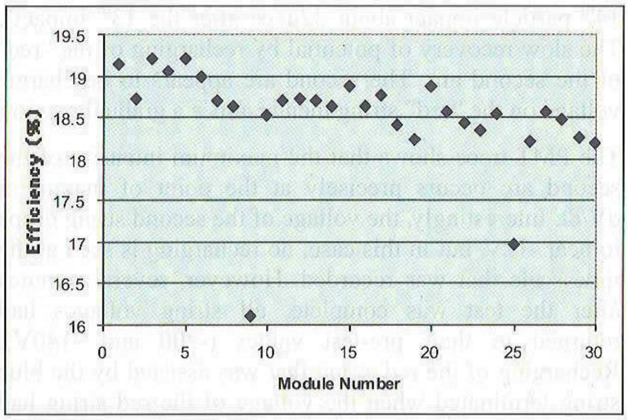

Figure 3: GaAs Module Efficiencies

When inter-string spacing and cover glass overhang were measured, a wide range of results was apparent. Inter-string spacing varied from a low of 707µm to a maximum of 1235µm, however within any one sample, the maximum spread was generally between 100 and 200µm. Of most interest was the cover glass overhang on the cell corners in the region between the series strings. It is in this region where the electric field gradient will be greatest due to the differential bias between the strings. When the samples were measured, we found that all samples had at least one cover glass with zero over hang. Of the 15 samples, eight had only one inter-string cover glass with zero overhang, five had three zero overhangs, one had two with zero overhang and one sample had six of the eight corners with zero overhangs. One sample had a -37 µm "under hang" (where the cell was not covered by the cover glass) along with two zero overhang corners.

For the case of the ENTECH, Inc. SLA module, the cells were all fully covered by cover glass with no areas of bare cells showing. This was expected to lead to very high voltage biasing conditions. Because of the zero overhang conditions in the GaAs samples, the likelihood of biasing them to high voltages (above 200V) was felt to be minimal. To test that assumption, the module with six zero overhang corners was selected for the first shot.

TEST RESULTS

Shot SSP-1: The initial test was conducted on a GaAs sample with six areas of zero cover glass overhang in the region between the series strings. Because of the large number of "zero-overhang" areas, high voltage biasing of the sample was difficult. The two cells in each series string were shorted together and a bias applied to them. Each string could be biased independently of the other so both a maximum bias voltage and a differential voltage between the two strings could be maintained. In order to determine the maximum voltage possible in the plasma, one string, called the "red string" (color of wire) was initially biased to -300V. Arcing was observed at that point and the voltage was then gradually reduced to a level where no arcs were observed over about a ten-minute period. This stable point occurred at -200V. The other series string ("blue") was then biased to -140V in order to establish a 60V differential between the strings. The 60V differential bias was selected to be what is generally believed to be the arcing threshold. The hollow cathode source provided the plasma environment.

SSP-1 Diagnostics: Event times listed are relative to the firing of the gun. Based on post-shot inspection of the PMT trace, approximately 35 particles impacted the target. An arc was observed on the "red" string after impact of the 13th particle at 1273μsec into the shot. After a delay of 56μsec, the "blue" string discharged. Figure 4 shows the voltage traces from the two strings and figure 5 shows the PMT output. Because the current traces saturated, no current data are available. The lowest trace in figure 4 is the "red' string that has a major discharge at 1273μsec and the voltage drops from -200V to -8.5V in 20μsec. The impact is also seen on the PMT trace (labeled 13th impact). However, the arc appears to extinguish and the voltage begins to recover on its own. At 56μsec after that first arc, a second arc begins at a voltage differential of -126.6V. This event does not appear to be associated with any particle impact (note the 14th particle impact about 32μsec after the 13th impact). The slow recovery of potential by recharging of the "red" string suddenly accelerates momentarily exactly at the onset of the second arc. The second arc appears to be charging the "red" string. This is an unexpected phenomenon. The voltage on the "red" string then resumes a gradual rise to the -200V level.

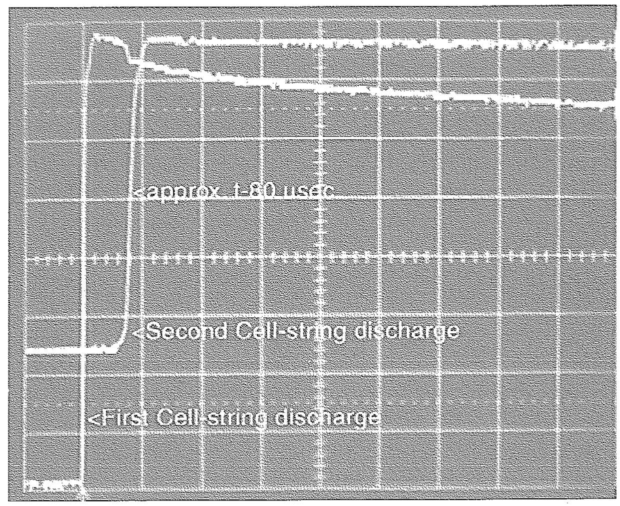

Figure 4: SSP-1 voltage traces, red and blue strings

The PMT trace shows that the maximum intensity of the second arc occurs precisely at the point of maximum dV/dt. Interestingly, the voltage of the second string drops to near -12V, but in this case, no recharging is seen at the time scale that was recorded. However, several minutes after the test was complete, all string voltages had returned to their pre-test values (-200 and -140V). Recharging of the red string that was assisted by the blue string terminated when the voltage of the red string had increased to -21V and the voltage of the blue string had decreased to -87V or at a voltage differential of 66V.

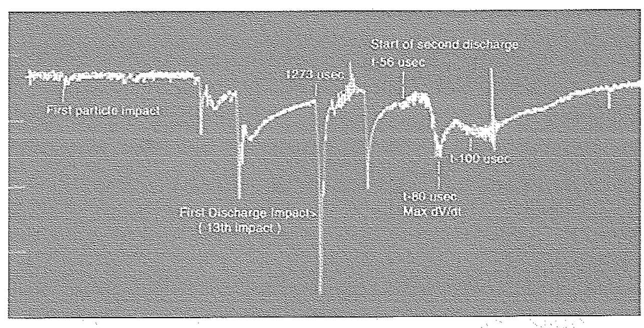

Figure 5: Photomultiplier traces for shot SSP-1

Because of the saturation of the streak camera image and alignment of the LEDs, only the x-coordinate was recorded. However, it was possible to determine the streak coordinate line along which the plasma flashes were observed. In the first arc event (1273 μs), several possible impact sites were near the line, but only one fell on the line. That was on top of the "red" string bias wire solder connection as shown in figure 6. We did not observe signs of an electrical discharge at this site. Some of the sites near the line appeared to nearly penetrate the cover glass, but no arcing evidence was apparent there either. The second plasma flash event was observed on the streak camera record appearing to start and stop at nearly identical times as the electrical discharge event on the "blue" string.. When the streak coordinate line was determined, it passed over the "blue" string of cells. There were no craters along this line, but the line passed through the solder connection point of the blue wire. Hence it is possible, but not confirmed, that the second discharge may have been initiated from the end of this wire.

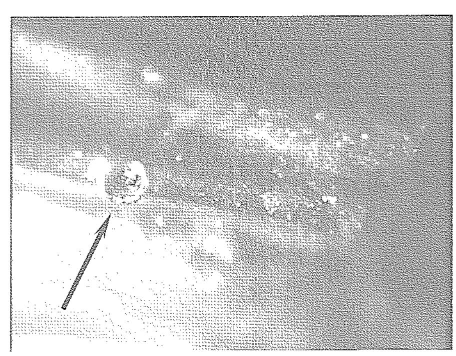

Figure 6: Impact site on the solder connection (SSP-1)

In summary of this first test, the unexpected phenomenon was observed wherein a second arc, not associated with an impact event, served to partially recharge the recovery of the voltage that occurred in the first impact-related arc event. Shapes and light emission patterns of the two events are noticeably different.

<u>Shot SSP-2:</u> The GaAs sample for this test had two "zero overhang" areas directly across from one another. Test conditions were nominally the same as SSP-1. The hollow cathode was operated at its minimum stable operating voltage and current. The velocity of the first particle impacting the target was 10.2 km/sec. By putting appropriate attenuators in the current signal line for both strings, good current traces were observed. In addition, the shutter for the streak camera was reduced by one f/stop. This helped us identify impacts, but arc emission still made impact location less accurate than usual. In the following paragraphs, a detailed description of the PMT, voltage and current traces is provided along with less detailed oscilloscope traces.

<u>SSP-2 Diagnostics:</u> Event times listed are relative to the firing of the gun. As shown in figure 7, about 2μs after what is believed to be the 8th particle impact (853.4μs), the PMT observed a slow noisy increase in light level peaking at 855.2μs and decreasing to a minimum by 857μs. Then, at 858μs, the PMT measured an increase to the light level, peaking at approximately 864.6μs, and then decaying to a minimum by 871μs. Immediately after 871μs, the optical level increased rapidly with a rise-time that is characteristic of a hypervelocity particle impact plasma flash. However, when nearing the first peak intensity at 871.6μs, a noisy signal pattern emerges within the waveform indicative of electrical discharges. After approx. 8μs, the signal decays rapidly to a minimum at 879.4μs where the waveform remains noisy until 890.0μs. There is a very high correlation between the PMT trace shown here and the current trace shown below in figure 9.

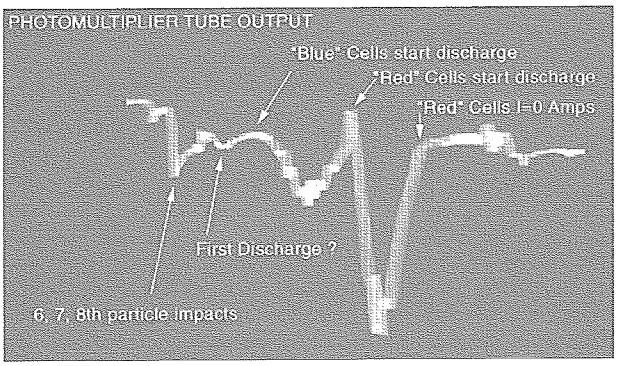

Figure 7: PMT Trace for SSP-2

The voltage and current traces for shot SSP-2 are shown in figures 8 and 9 respectively. In the voltage trace shown in Figure 8, the "blue" (-140V) string began a gradual discharge from -139.5V starting at 857.8μs. It reached a minimum voltage of -31.7V at 870.8μs. At that point there was a sudden increase to -58.3V at 871.8μs. After that the voltage decreased to -52V and remained constant. The "red" (-200V) string begins to discharge just after 870.8μs, at essentially the same time the "blue" string begins a rapid recharge. The voltage reaches -126V at 872μs, just when the recharging of the "blue" string ends. The voltage differential at this time is 68.3V. Thereafter it continues its discharging, reaching 0V at 886μs. The current trace for this shot is shown in figure 9. The "blue" current measured 0.0A at 854μs, started to change at ~856.8μs, reaching -10.0A at 865.6μs, peaking negatively at -11.25A at 868.1μs, decaying to -8.45A at 870.8μs, zero-crossing (0.0A) at 871.15 μs. From then on the positive current rebound, reaches +4.7A at 871.9μs, decaying to +0.30A at 873.0μs then remaining steady at approximately +0.30 A until 886.6μs. Thereafter it gradually reduces to 0A.

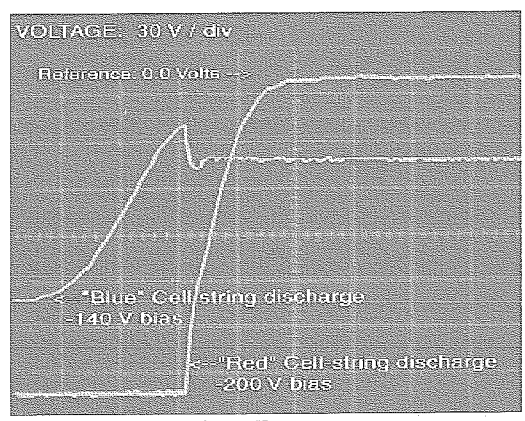

Figure 8: SSP-2 Voltage Trace

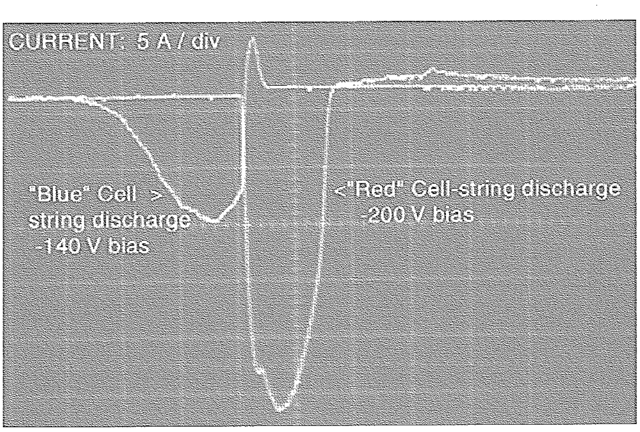

Figure 9: Current trace for shot SSP-2

The current in the "red" (-200V) channel starts a rapid linear change at 870.8μs, from 0.0A to -24.6A at 872.0μs where it hesitates, decreasing only slightly to -24.3A at 872.275μs. Then, at a slower rate, the current continues to increase from -24.6A at 872.5μs to a negative maximum of -28A at 873μs. From here it crosses 0.0A at 878.7 μs and moves positively to approximately +1.35A at 880μs and decreases slowly to +0.6A at 906μs to approximately zero at 1250μs.

<u>ENTECH Shots:</u> A set of tests was run using a concentrator solar cell module supplied by ENTECH, Inc. This module consists of a series string of Spectrolab-supplied concentrator multijunction solar cells. These

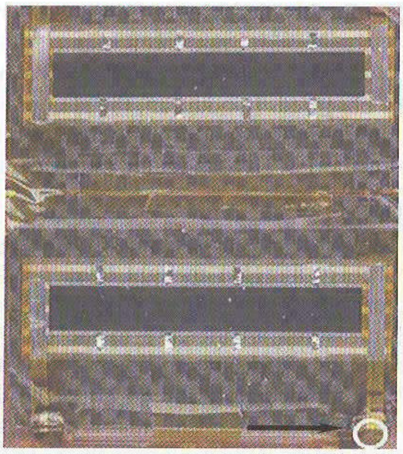

Figure 10: ENTECH, Inc. SLA module after testing

cells were completely covered by a cover glass and had been hi-pot tested at ENTECH to a bias of 2250V. The overhang extended well beyond the cell boundaries and was also filled with silicone. This sample was placed in the Hypervelocity Impact Facility and exposed to two shots. Because of some damage to the hollow cathode, a Tesla coil was used to provide the background plasma. This plasma was an excellent simulation of low temperature plasma confirmed by a Langmuir probe. In the first shot, particle velocities were only 9.4 km/sec while in the second test a maximum of 11.6 km/sec was achieved. In the first test the sample was biased to -400V and in the second, to -438V. In a third test the voltage was increased to over -1000V with a voltage differential between the strings of 60V. The test sample in the last test is shown in figure 10 with the location of that one small arc noted by the circle.

No arcs occurred on the module surface despite complete particle impact penetrations of the cover glasses. In all cases only one small arc was observed. The one arc that did occur was on a biasing lead interconnect that was covered with thin Kapton tape. It is important to note that in this sample, the cell surfaces and edges are fully insulated from the space plasma environment. The only arcs that could occur on the sample surfaces would have come from cover glass penetrations. Although there were these penetrations, none caused arcing. The ENTECH sample was also exposed to rear-side impact test shot with bias voltage at –1027V, many impacts with no arcing.

DISCUSSION

The results for the SSP-2 bear special discussion. The immediate event of a particle impact does not appear to have directly initiated the first discharge seen in the "Blue" (-140V) bias channel. However, it is possible that charge carriers contained in the plasma were produced by the prior three impact events. Those events included a bright impact at 848.8μs, followed by two smaller impacts at 849.8μs and 851.6μs. These three events could have initiated the discharge event that started at 853μs that was optically detected by the PMT. This optical-discharge event does not appear to have immediately affected the solar cell strings because it was not detected by the solar cell electrical diagnostics except as a ½ bit ADC noise shift. This might have been a discharge between the plasma in the chamber provided by the hollow cathode plasma source and some other charge accumulation such as a capacitive build-up of charge at the solar cell surface. This discharge may have in turn provided the charge carriers triggering the "Blue" string discharge.

The discharge of the "Blue" string caused the voltage on that string to decay at rate and waveform shape comparable to that of the "Blue" string discharge of test SSP-1 also biased at -140V. Despite this being the first cell string to discharge, it did so at a moderate rate unlike that of the SSP-1 test "Red" string with -200V bias being the first discharge of that test. This may suggest that the dynamics of discharge events observed may be electric potential related; i.e. moderate potentials cause gradual discharges whereas higher potentials lead to abrupt discharge rates.

The discharge of the "Red" string in this test was originally thought to have been initiated partially by an impacting particle at 871μs. However, on further examination of the PMT waveform, the optical intensity did not decay immediately as is characteristic of impact flashes. Rather, it had a noisy sustained peak for approximately 8μs followed by decaying to a noisy baseline for about another 10μs. Another particle impacting at this time could have initiated the discharge that allowed the optical signature to last longer than usual. Due to the degree of optical saturation of the streak camera film, it was impossible to determine if another particle impacted at this time.

Of more interest is to examine the potential difference between the two strings during the discharge of the "Red" string. At approximately 870.8μs, the "Blue" string potential was -31.7V and "Red" string was -200V, or a 168.3V differential ("Red" over "Blue") when the discharge on the "Red" string starts. Compare this with the onset of the second discharge event of test SSP-1 of a 126.6V differential ("Blue" over "Red"). There is indication that the discharge of current from "Red" to "Blue" string occurred that partially recharged the "Blue" string. Its voltage rapidly goes from -31.7V to -58.3V before this current "conduit" closes. The potential difference at the moment when this connection stops is approximately 68.3V (126.6 to 58.3V). This is very close to that of 66 V from test SSP-1 when that conduit also apparently closed.

The second discharge in this test of the "Red" string had a rapid rise-time comparable to that of the "Red" string of SSP-1 (see comment above about voltage magnitude). Also, note that the "Blue" string again, as in test SSP-1, holds a nearly constant voltage while the "Red" string recharges during the time the waveform data is recorded. Several minutes after the test, both strings had recovered their full initial bias potentials.

Finally, tests on the SLA sample proved conclusively that proper cover glass overhang and edge sealing provide insulation from the space plasma. Bias voltages over 1000V were achieved with no arcing either from front or rear side impacts.

SUMMARY

From the series of tests performed here, several conclusions may be drawn. Based on the testing done to date, it appears as if solar arrays with unprotected contacts are susceptible to arcing independent of hypervelocity particle impacts. Although cover glasses were penetrated during HYPER testing and other cell contacts also damaged, no arcing occurred at those sites to the best of our detection ability. The GaAs samples had numerous areas with zero cover glass over hang so bias voltages above -200V could not be obtained. With larger cover glass overhang and better insulation of bare interconnects it may be possible to achieve voltages near 1000V on regular solar cells. The SLA samples had both cells and contact strips that were fully insulated. These samples showed no arcing upon hypervelocity particle impact at velocities as high as 11.6 km/sec and bias voltages up to -1000V. Thus it appears that these preliminary tests have uncovered basic design approaches that can lead to high voltage (up to at least 1000 V) solar arrays. This finding coupled with careful theoretical analyses promise a new era of high voltage array designs for high power applications.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Dr. Dale Ferguson of the NASA Marshall Space Flight Center for this work partially supported under Contract NAS3-99200 (from the NASA Glenn Research Center). Support by Mark O'Neill of ENTECH, Inc. is also acknowledged.