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IMPACT OF SOLAR ARRAY DESIGNS ON HIGH VOLTAGE OPERATION IN SPACE

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ABSTRACT

As power levels of advanced spacecraft climb above, 25 kW, higher solar array operating voltages become attractive – if not mandatory. Even in today's satellites, operating the power bus at 100 V and above has led to arcing in GEO communications satellites, so the issue of spacecraft charging and solar array arcing remains a design problem. In addition, micrometeoroid impacts on all of these arrays can also lead to arcing if the spacecraft is at an elevated potential. In the future, large GEO communication satellites, lunar bases, solar electric propulsion missions, high power communication systems around Mars can lead to power levels well above 100 kW. As noted above, it will be essential to increase operating voltages of the solar arrays well above 80 V to keep the mass of cabling needed to carry the high currents to an acceptable level. Thus, the purpose of this paper is to discuss various solar array approaches, to discuss the results of testing them at high voltages, in the presence of simulated space plasma and under hypervelocity impact. Three different types of arrays were considered. One will be a planar array using thin film cells, the second will use planar single or multijunction cells and the last will use the Stretched Lens Array (SLA, 8x concentration level). Each of these has different approaches for protection from the space environment and the results of environmental testing are included.
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INTRODUCTION

As power levels of advanced spacecraft climb above 25 kW, higher solar array operating voltages become attractive. Even in today's satellites, operating spacecraft buses at 100

V and above has led to arcing in GEO communications satellites, so the issue of spacecraft charging and solar array arcing remains a design problem. In addition, micrometeoroid impacts on all of these arrays can also lead to arcing if the spacecraft is at an elevated potential. For example, tests on space station hardware disclosed arcing at 75V on anodized Al structures that were struck 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 in light of the Vision for Space Exploration of NASA.

In the future, large GEO communication satellites, lunar bases, solar electric propulsion missions, and high power communication systems around Mars will likely lead to power levels well above 100 kW. As noted above, it will be essential to increase operating voltages of the solar arrays well above 80 V to keep the mass of cabling needed to carry the high currents to an acceptable level. The design of the solar array and its ability to meet the environment in which it will be used will determine mission success.

Three different types of arrays will be considered. One will be a planar array using thin film cells, the second will use planar single or multijunction cells and the last will use the Stretched Lens Array (SLA, 8x concentration). Each of these has different approaches for protection from the space environment. The thin film cell-based arrays have minimal covering due to their inherent radiation tolerance, conventional GaAs and multijunction cells have the traditional cerium-doped microsheet glasses (of appropriate thickness) that are usually attached with Dow Corning DC 93-500 silicone adhesive. In practice, these cover glasses and adhesive do not cover the cell edges. Finally, in the SLA, the entire cell and cell edges are fully encapsulated by a cover glass that overhangs the cell perimeter and the silicone adhesive covers the cell edges providing a sealed environment. All three show major differences when exposed to various environmental conditions.

EXPERIMENTAL CONDITIONS

All our tests were performed in the two large vacuum chambers installed in the National Plasma Interaction Facility (NPIF) at NASA's Glenn Research Center (GRC) [1-3]. Vacuum equipment provided background pressure below 10^{-6} Torr. One Kaufman plasma source was installed in each chamber to generate a xenon plasma with the electron number density n_e=(0.1-10)$\cdot 10^5$ cm^{-3}, temperature T_e=0.6-1.0 eV, and neutral gas pressure p = (0.7-7)x10^{-5} Torr, which could be keeping steady during the experiment. The sample (or set of samples) was vertically mounted in the middle of the chamber (Fig. 1), and it was

Fig. 1: Thin CIGS cell sample mounting

biased with a power supply directly, to measure current collection, or through a capacitor and a 10 kΩ resistor network back to ground to determine the arc threshold. An additional capacitor (0.01 – 1 μF) was placed between array and ground to simulate the spacecraft capacitance. A standard light source was provided in order to measure photovoltaic characteristics before starting the test in a plasma environment. Diagnostic equipment included two spherical Langmuir probes with the diameter of 2 cm, two current probes to measure discharge currents, and one voltage probe to register the voltage pulse on the array during the discharge. In order to find the arcing sites a video camera and VCR were installed.

THIN FILM SOLAR CELL TESTING

Ten different samples of the CIGS thin film photovoltaic modules (TFPM) were tested in simulated LEO environment. These samples had different areas, coating thicknesses, ITO layers, and some of them had magnesium fluoride covering. Current collection was measured for all samples before and after the breakdown tests by biasing each sample with the power supply.

These samples are significantly different from conventional space solar cells so an example is used to demonstrate some of the issues with use of these cells in space. For one of the cells, the thickness of dielectric (SiO_2) over the junction is 10 μm, and this insulator is covered by conducting layer of the ITO with a thickness 70.4 nm. Thus, the potential difference between the solar cell and top coating can reach the magnitude of the operating voltage in LEO where floating potential of a spacecraft is not higher than a few volts negative. In GEO, the potential drop between the solar cell and coating will never exceed operational voltage but the potential drop between coating and surrounding plasma can be much higher (by absolute magnitude) because of highly negative floating potential of the spacecraft.

For this particular sample, the field strength can reach $3x10^7$V/m when the sample is biased to 300V. Theoretically, the breakdown field for SiO_2 is $6x10^8$V/m, thus no breakdown should be observed below 6000 V. However, this test demonstrated arcing (breakdown) with bias voltages between -150 and -300V. To measure breakdown voltage each sample was biased negatively with respect to the chamber starting from -100V. Voltage steps varied from 20 to 100V depending on observed ion collection current. The duration of each step varied between 10 and 20 minutes. One of the nine samples did not arc at a voltage as high as -900V however.

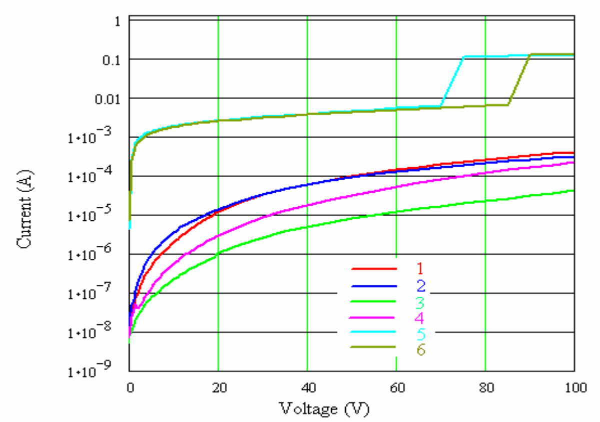

Fig. 2: Collection current for six thin film samples

Data are presented in Fig. 2 for six virgin samples with equal areas (69 cm^2). Collection current densities varied from sample to sample but all the magnitudes were at least ten times lower than for a bare conductor. The samples with 37 µm and 20 µm dielectric coatings demonstrated the lowest current collection and acceptable efficiency of about 7%. However, these samples demonstrated also the sharp increase in collection current

Fig. 3: Snapover event on thin film cell

(snapover) measured after the breakdown test. These snapover events were observed and recorded. One such event is shown in Fig. 3. In all these measurements, collected currents were much lower than PV currents generated by TFPM under standard illumination.

<u>Summary of Thin Film Cell Test Results</u>

These tests demonstrated that the thickness of insulation must exceed 20µm in order to withstand voltage above a few hundred volts in LEO plasma. Secondly, the efficiency of thin film solar cells must be at least doubled before their specific power will reach magnitudes comparable with multijunction photovoltaic cells. Thirdly, in addition to the thickness requirement, the dielectric materials used to encapsulate the cells must have a high mechanical elasticity and high radiation hardness to prevent development of cracks and pinholes on TFPM surface. It is suspected that such surface deformities are responsible for the breakdowns observed at relatively low biases. Unless the coatings are continuous over the surface of the cell, the initiation of electrostatic discharges on the cells with high negative potentials with respect to the space plasma can fully destroy a thin film solar array. Finally, ground tests in simulated LEO and GEO environments allow the validation of TFPM designs and issues. These tests should be continued with present day samples to see what improvements might have been achieved.

ONE SQUARE FOOT MODULE WITH INTEGRAL COVER GLASS

Boeing and NASA teamed to develop and test an integrally-covered, 34 V “tile” with a 1 ft^2 integral cover glass [4]. This project was aimed at achieving a design that could be used for “direct drive” solar electric propulsion missions and achieve voltages in excess of 500 V without arcing. This “Solar Tile” was made with tightly packed, multijunction solar cells beneath a single 1 ft^2 cover glass and interconnected with Kapton®/copper flexible circuitry. All these features were aimed at reducing fabrication cost of space arrays. The single tile was seen as a building block element of a larger, higher voltage array.

Because the single cover slide encapsulates the entire bus voltage circuit and the glass is conductively coated and grounded, this design offers excellent protection against high voltage arcing and environmental interaction. The design is independent of the cell types used and can fit in to high volume, robotic production. This tile design had passed low-earth orbital qualification tests including acoustic, shock, thermal cycle and thermal vacuum cycle tests. However, this unit used mechanical cells for these tests. The test item is shown in Fig. 4. The tile measured 27.5 x 35 cm and was mounted on a rigid substrate

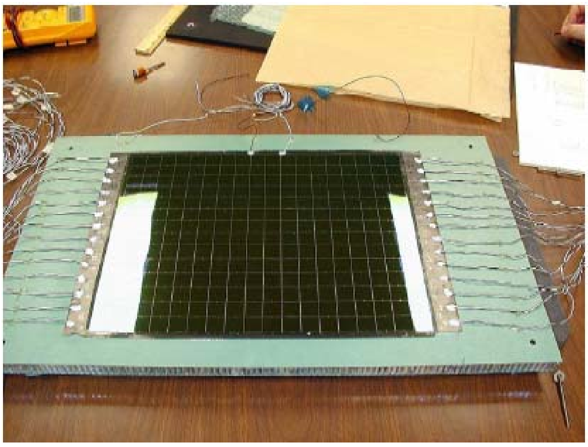

Fig. 4: The 34 V test article

for testing. The integral glass cover extended over the edges of the cells in all four directions, albeit with differing amounts of “overhang”. The overhang was filleted to the substrate with the cover glass bonding adhesive on all edges. This sample was used for preliminary testing to assess processes and issues in fabrication of this tile.

Summary of Solar Tile Test Results:

In these preliminary tests, the 34V module arced once at -300 V on the right hand side of the unit. Later, it arced again at -650 V, In over six hours of additional testing, no arcing was seen between -300V and -950V. At 1000V, small arcs at the Kapton were observed, but were not observed visually. Based on these preliminary results and understanding changes needed in the design a 500V tile was developed and is shown in Fig. 5. This sample arced once at -600V but

Fig. 5: 500 V design “Solar Tile”

was extinguished quickly. Some halo discharges were seen at about -750V. No physical damage was observed nor was any electrical performance degradation measured up to the test limit of -1100V. Thus this module successfully passed the goal of sustained operation at -600V. It is also tolerant to plasma charging. The one arc that was observed is attributed to initial water evolution from the silicone adhesive.

GAAS SOLAR CELL COUPON TESTS

Fifteen modules with four state-of-the-art 2x4 cm GaAs solar cells with 150 µm cover glasses were tested under bias and with hypervelocity impacts [5]. The cells were connected in two-cell series strings with a gap between them. The cells all had efficiencies averaging 18.5% and the amount of cover glass overhang and the spacing between the two series strings were measured. 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 where the electric field gradient will be greatest due to the differential bias between the strings. All samples had at least one cover glass with zero over hang in this region. 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.

Each cell string was shorted and a differential bias applied across the two strings in a plasma environment. In all cases, arcing occurred at voltages above 200V, due mostly to the lack of cover glass overhang we believe. One string was biased at -200V and the other adjusted to -140V to maintain a 60V differential between them. A hollow cathode source provided the plasma environment.

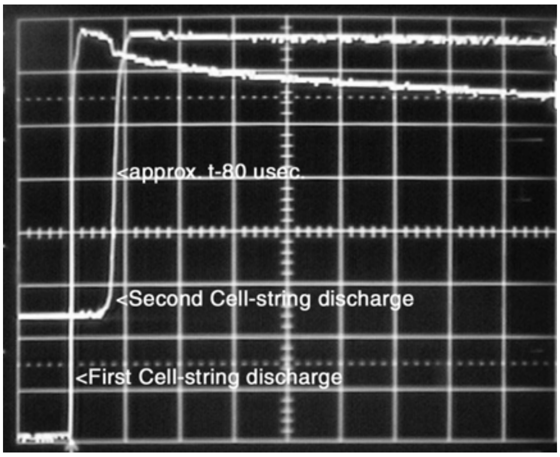

Fig. 6: Voltage traces showing arc feeding arc

Fig. 6 shows an unexpected phenomenon that 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. These results confirmed that less than full coverage of the cell surface by the cover glass would not allow cells to reach high voltages. Also, under hypervelocity impacts, different phenomena can also occur as shown by the arc-feeding phenomenon described above.

STRETCHED LENS SOLAR ARRAY TESTS

A set of tests was run using a concentrator solar cell module supplied by ENTECH, Inc. This module consists of a series string of concentrator multijunction solar cells completely covered with cover glass. The overhang extended well beyond the cell boundaries and was also filled with silicone. A Tesla coil was used to provide the background plasma which was an excellent simulation of low temperature plasma confirmed by a Langmuir probe. Maximum particle velocities were between 9.4 and 11.6 km/sec were achieved. In the first two tests the sample was biased at -400V and -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 Fig. 7 with the location of that one small arc noted by the circle.

No surface arcs occurred despite particle impact penetrations of the covers. All the cell surfaces and edges were fully insulated from the plasma. The sample was also exposed to rear-side impact test shot with bias voltage at –1027V. Although there were many impacts no arcing was observed.

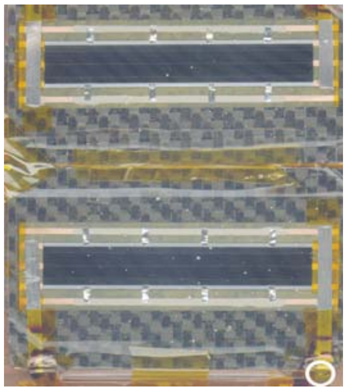

Fig. 7: Stretched lens array module after testing

One final consideration for solar arrays that can operate at voltages of 600V and beyond is to design the rest of the array to withstand *corona* breakdown due to long term stress under high voltage. Designs are being tested to confirm array designs that will provide long term stability for extended electric propulsion missions.

DESIGN THEORY FOR SOLAR ARRAYS IN GEO, LEO AND TRANSFER ORBITS

Primary arcs, or trigger arcs as they sometimes are called, occur when the electric field at discontinuities becomes great enough for a burst of electrons to be emitted, initiating the arc. Arcing typically occurs when the underlying cell or conductor has a highly negative potential compared to the overlying or adjacent dielectric surface. In LEO conditions, the plasma surrounding the solar cells provides both charges to keep dielectrics discharged and a short Debye length to entrain and accentuate electric fields. Arc voltage thresholds are thus usually lower under LEO conditions than in GEO.

Typical discontinuities at which arcs may occur include the cell-cover glass interface, the interconnect-cover glass interface, the cell or interconnect-adhesive interface, and burrs or surface irregularities on conductors. Under LEO conditions, the adjacency of the surrounding plasma makes the interfaces into the so-called "triple points", where insulators, conductors, and plasma meet. These are the worst actors from an arcing standpoint. Arcing may be prevented under all circumstances if there are no exposed high voltage conductors.

<u>GEO guidelines:</u>
Guidelines for preventing arcing under GEO conditions have been known for at least 20 years [6]. Since in GEO there is little surrounding plasma, its complicating effects are not important, and one should concentrate on keeping the potential of the cell or interconnect and cover glass the same. Bulk charging of the entire spacecraft is unimportant, compared to the differential charging of cover glass and cell. Thus, it is recommended for GEO to coat the cover glass surfaces with a somewhat conductive coating, such as ITO, so that differential charging will be bled off. For GEO, because the charging currents from high energy electrons are low (typically less than about 1 na/cm^2) conductivities required to bleed off the charges are very low. Purvis et. al. recommend surface resistivities higher than about 10^{-9} ohms/square, and bulk resistivities higher than about 10^{-10} ohm-cm. These are many orders of magnitude less than the resistivities of glass, Kapton, or Teflon, and can be achieved with ITO coatings or conductive polymers.

An emerging trend, which must be discouraged, is to use thin anti-reflective coatings (such as MgF_2) on top of the GEO conductive cover glass coatings. This concentrates electric fields in the thin MgF_2, which may respond by glowing due to electron tunneling, breaking down continuously, or otherwise relieving the enormous electric fields it must see under charging conditions. Surface charging in GEO is just that, a surface problem, and cannot be controlled by covering conductors with thin insulating layers such as anti-reflective coatings. The use of partially-conductive anti-reflection coatings is one possibility.

<u>LEO guidelines:</u>
In LEO, conditions are different. In order for conductive coatings to bleed off the high charging currents, surface resistivities of up to 10^{-3} ohms/square must be achieved. With conductivities this high, parasitic plasma currents may be a problem, as this implies that all of the array area will be "snapped-over", or collecting current as if it were completely conductive. The arc voltage threshold in LEO may be low enough that the current collected on a high voltage array may charge the spacecraft negative to more than the arc threshold. In consequence, most LEO array designs do not use conductive cover slides, but concentrate on raising the arc threshold or lowering the magnitude of the vehicle potential. Mitigation techniques are enumerated in the NASA Low Earth Orbit Spacecraft Charging Standard [7].

Encapsulating the array conductors, (either through very large cover glasses or caulking the cell edges and/or interconnects), prevents the array from charging to high negative voltages and prevents the surrounding plasma from contacting the discontinuities where arcs may occur. Encapsulation, however, incurs the risk that voids may allow neutral pressures to build up and cause Paschen or corona-type arcing. A variation of the encapsulation technique uses highly overhanging cover glasses or closely spaced cells to prevent plasma from being able to contact the cell edges, but still allow neutral gases to escape. Closely-spaced cells may, however, exacerbate the sustained arcing problem, where a trigger arc transitions into an arc between adjacent strings and is powered continuously by the array circuit current. Still another technique for LEO is to use low voltage arrays (or positively grounded arrays) to keep the vehicle potential below the arc threshold with respect to the surrounding plasma.

<u>LEO to GEO transfer orbit guidelines:</u>

Transfer orbits from LEO to GEO are difficult from an array arc-prevention perspective because of the very different design techniques used for the two different charging environments. A typical GEO solution may exacerbate the LEO problems, and vice versa. Here, it is probably best to limit the LEO charging through low voltage arrays (often not an option), positive grounding, or encapsulation, and to use poor insulators (in the 10^{-9} to 10^{-5} ohms/square range) to bleed off surface charges in GEO.

SUMMARY AND CONCLUSIONS

This paper has described testing of various types of solar cells in simulated space plasma environments. The samples ranged from thin film cells, to integrally-encapsulated cell arrays, to strings of individual cells to fully encapsulated concentrator solar cell modules. The results were clear and persuasive. In all cases where the cells under test were fully encapsulated, bias voltages as high as -1000V could be applied without arcing. Without full coverage (e.g. in thin film cells and in GaAs cells with limited areas of cover glass overhang, most samples showed arcing in the 200 – 400V range.

Details were provided for the guidelines for solar array designs for LEO, GEO and Transfer Orbit conditions. The most rigorous design comes with the transfer orbit case. Key points are the need to keep the potential of the cell or interconnect and cover glass the same in GEO by using a slightly conductive cover glass. In LEO, encapsulating the array conductors, (either through very large cover glasses or caulking the cell edges and/or interconnects), prevents the array from charging to high negative voltages and keeps the surrounding plasma from contacting the discontinuities where arcs may occur. The LEO-GEO transfer orbit is the most complex. However a combination of encapsulation, use of a positive ground and a slightly conductive cover glass should limit charging problems.

Under the guidelines presented above, solar arrays reaching voltages of 600 V are achievable, thus enabling the direct-drive electric propulsion option. The final barrier under study is to define designs that have long term stability and will resist corona breakdown.

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