STRETCHED LENS ARRAY (SLA): A PROVEN AND AFFORDABLE SOLUTION TO SPACECRAFT CHARGING IN GEO

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ABSTRACT: Spacecraft charging in geosynchronous orbit is a reality that can be destructive and thus negatively affect the satellite industry as a whole. In the last ten years only 26% of satellite launches went to GEO. However, 41% of all anomalies and failures occurred in GEO including 71% of all solar array anomalies. The majority of these anomalies can be traced to electrostatic discharges that often occur when the satellite emerges from an eclipse period into a solar storm. Yet over the last decade, no effective solution for this problem has been implemented. A practical and affordable solution to GEO charging is the Stretched Lens Array (SLA). SLA technology has been tested and shown to withstand the GEO environment without any electrostatic discharge anomalies. This paper will discuss GEO satellite reliability issues and the solar array concentrator that can overcome them. Theoretical modeling and SLA ground testing will be included.

1 - INTRODUCTION

Spacecraft charging in geosynchronous orbit is a reality that can be destructive and thus negatively affect the satellite industry as a whole. In the last ten years only 26% of satellite launches went to GEO as seen in figure 1.[1] However, 41% of all anomalies and failures occurred in GEO including 71% of all solar array anomalies as seen in figure 2. Solar array anomalies reached a level as high as 32% of the total anomaly reports for GEO missions in two of the last three years. The majority of these anomalies can be traced to electrostatic discharges that often occur when the satellite emerges from an eclipse period into a solar storm. Yet over the last

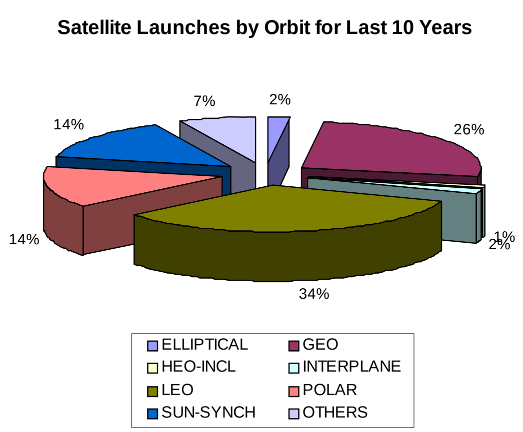

Figure 1 - Satellite Launches by Orbit 1996-2006

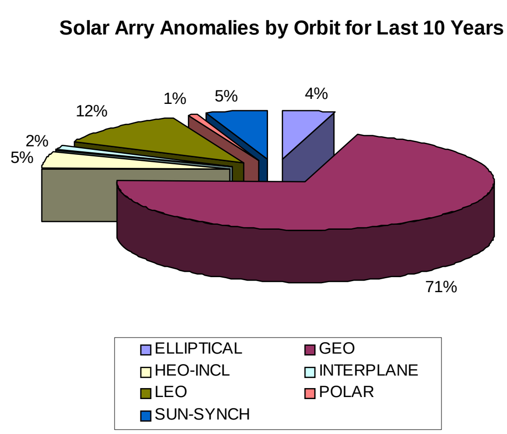

Figure 2 - Solar Array Anomalies by Orbit 1996-2006

decade, no effective solution for this problem has been implemented. The consequences of spacecraft charging have ranged from intermittent anomalous behavior up to catastrophic satellite failure. The number of solar array anomalies on satellites in GEO coincides quite well with the classic infant mortality trend which generally indicates that the design is poor and/or there are defects in array construction. This observation raises fundamental questions about solar array designs, their construction and their testing prior to launch. Nearly all manufacturers have this problem, but new designs are usually rejected due to the belief that flight heritage is the best proof of performance. Various solutions have been tried at extra cost. However, a practical and affordable solution to GEO charging is the Stretched Lens Array (SLA). SLA technology has been tested and shown to withstand the GEO environment without any electrostatic discharge anomalies. 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.

This paper will discuss GEO satellite reliability issues and the solar array concentrator that can overcome them. Theoretical modeling and SLA ground testing have shown that it is resistant to arcing and similar plasma-induced failures. Thus, the purpose of this paper is to discuss the results of testing at elevated voltages in the presence of simulated space plasma and under hypervelocity impact and show that the SLA is a proven and affordable solution to spacecraft charging in GEO.

2 - GEO SATELLITE RELIABILITY ISSUES

Solar arrays are arguable the most critical component to satellite success because they are responsible for supplying reliable and predictable power to the satellite over the entire mission life. However, solar array reliability has become a serious issue over the past decade. From AirClaims's Ascend SpaceTrak database, more than 117 solar power system anomalies have been reported from 1996 to 2006. Eighty-three (71%) of these have occurred in GEO. In the last ten years only 26% of satellite launches went to GEO, therefore, the launch to failure rate is unprecedented as seen in figure 3. This is not necessarily the best comparison since the anomalies do not just occur on the satellites that are launched that year but it does prove that anomalies in GEO are a serious issue. The majority of these anomalies can be traced to electrostatic discharges that often occur when the satellite emerges from an eclipse period into a solar storm. Anomalies can indicate a complete failure for either deployment or operation of the satellite or can just cause a temporary loss of communication with the satellite. The majority of anomalies are non-repairable and affect the operation of the satellite on a permanent basis.

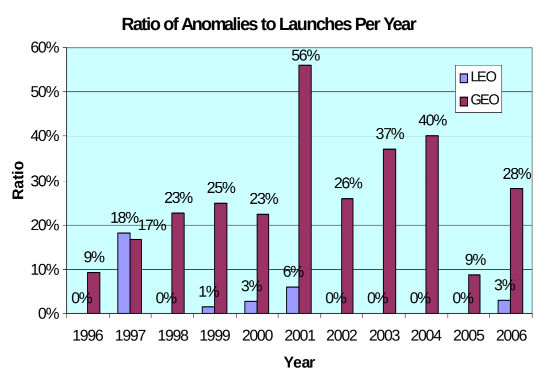

Figure 3 - Ratio of anomalies by year by orbit

The number of solar array anomalies on satellites in GEO coincides quite well with the classic infant mortality trend as shown in figure 4. This generally indicates that the design is poor and/or there are defects in array construction. This observation raises fundamental questions about solar array designs, their construction and their testing prior to launch. Nearly all manufacturers have this problem, therefore, it is unlikely due to defects in construction. However, new designs are usually rejected due to the belief that flight heritage is the best proof of performance. Various solutions have been tried at extra cost. A practical and affordable solution to GEO charging is the Stretched Lens Array (SLA).

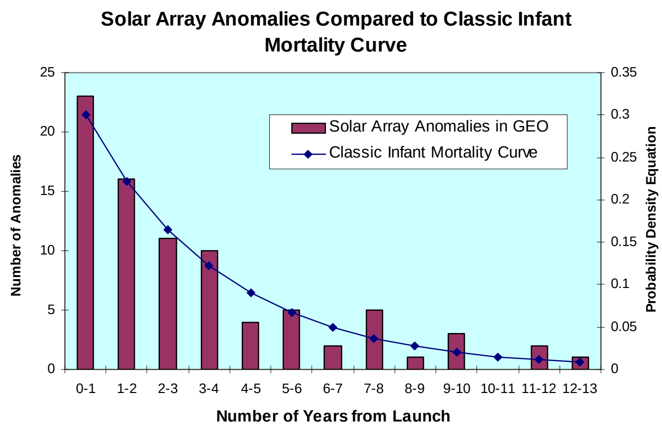

Figure 4 - Years b/w launch and solar array anomaly in GEO

3 - STETCHED LENS ARRAY ATTRIBUTES

The SLA developed by ENTECH, Inc. is an array that uses refractive concentrator technology to collect and convert solar energy into useful electricity. This concentrator uses a stretched Fresnel lens (8.5 cm aperture width) that refracts the incident light onto high-performance multi-junction photovoltaic cells (1.0 cm active width) as can be seen in figure 5. The first refractive concentrator array was developed and flown on the PASP-Plus mission in 1994-95 proving quite successful. It included a number of small advanced arrays with a mini-dome lens concentrator.[2] In the late 1990's, a new line-focus Fresnel lens concentrator was developed that was easier to manufacture and was more cost-effective than the mini-dome lens concentrator. Between 1998-2001 the SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array was flown on the Deep Space 1 NASA mission and performed reliably over the lifetime of the mission.[3] The Stretched Lens Array (SLA) is an evolved version of SCARLET, retaining the essential power-generating elements and flight heritage of earlier models. SLA's unique, lightweight, and efficient design leads to outstanding performance ratings (>80 kW/m^3 stowed power, >300 W/m^2 areal power, and >300 W/kg specific power) and cost-effectiveness (50-75% savings in $/W compared to conventional solar arrays). Details of SLA's construction fulfill the critical requirements needed to withstand the spacecraft charging of GEO orbits. 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. SLA's small cell size which is 85% smaller than planar high-efficiency arrays, allows shielding to be added without detrimental mass effects.

Figure 5 - SLA in sunlight

4 - SLA GROUND TESTING

Ground testing of solar arrays at high voltages can determine potential charging issues that need to be addressed prior to launch. Testing should include corona discharge and hypervelocity testing, yet standardized testing procedures currently do not exist. Terrestrial test IEC 343 is the only basis on which guidelines can be determined for a corona test. Initial ground tests were performed with samples at high voltage under water. However, this may not be appropriate to space. Corona testing under a vacuum and plasma is being developed with help from NASA-MSFC engineers but many factors need to be considered including electrons and protons, DC verses AC, frequency, voltage, etc. Auburn University has been working to design a new long life corona test for the space industry to determine the lifetime of solar array designs under high voltage stress in the space environment. Exposed solar arrays can collect large currents from the space plasma. Corona testing will detect the emergence of small defects in the insulation system that occur due to the voltage stress across the insulation layer(s) which could subsequently lead to catastrophic failure.

4.1 - Corona Testing

A receiver must be developed that can operate over the full mission durations without corona breakdown. A fully encapsulated cell circuit, using redundant insulation layers below the cell and glass/silicone layers above the cell, is configured to provide moderate (3-5 V/micron) gradients through the insulating layers to minimize voltage endurance failures. A sample SLA receiver is shown in figure 6. ENTECH has fabricated and tested a number of such single-cell SLA receiver samples at very high voltage levels (2,250 to 4,500 V) in an underwater hi-pot test for very long periods of time. The water is a crude simulator of space plasma and is effective in finding insulation defects. The high voltage difference is maintained between the cell circuit and the carbon-fiber radiator sheet, which is surrounded by and in intimate contact with the water. Figure 7 presents the SLA results to date compared to DuPont voltage endurance results for typical Kapton HN film subjected to long-term high-voltage stress.

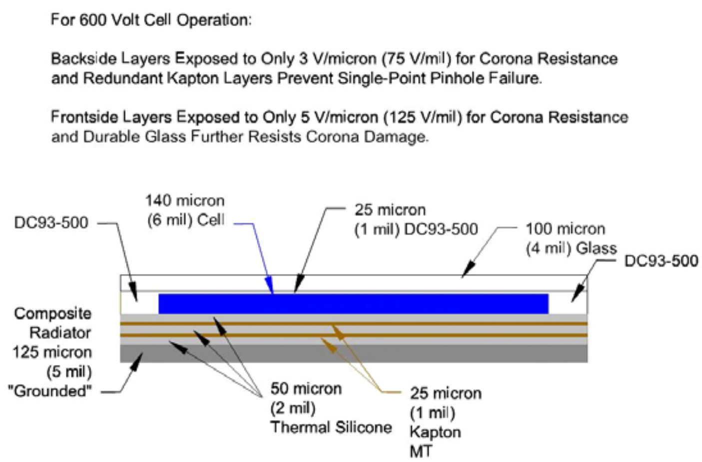

Figure 6 - Test sample configuration

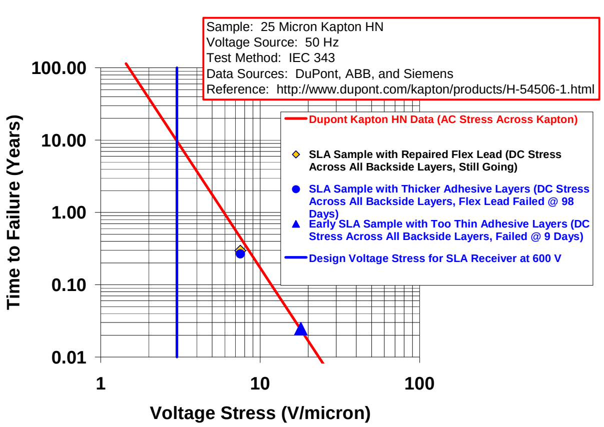

Figure 7 – Results of underwater hi-pot testing

To complement ENTECH's underwater hi-pot testing, Auburn has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. The set-up of the new test system is quite simple and can be seen in figure 8. It consists of a power supply kept constant at 2,250 VDC, a vacuum chamber, a cell sample, and two resistors. The sample is maintained at room temperature under a vacuum of approximately 6×10^{-5} torr. This set-up tests the insulation properties of the cell sample under a DC voltage bias. A failure indicates that a path from the high voltage source to the ground has occurred through the insulation which could lead to failure of the array.

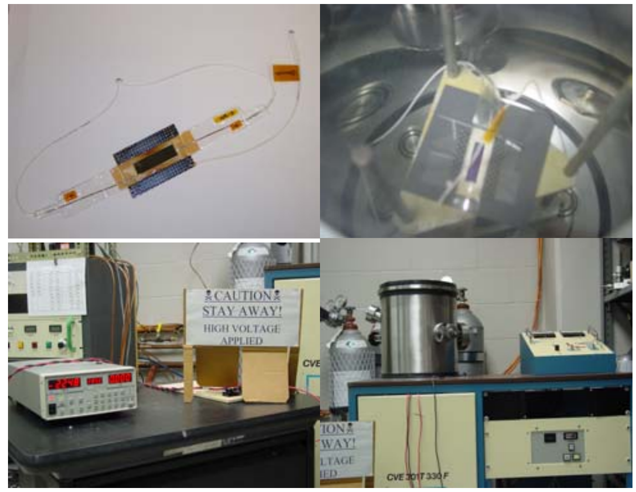

Figure 8 - Corona Testing set-up including sample, vacuum chamber and power supply

Testing of high-voltage SLA photovoltaic receiver materials and assemblies started at Auburn in August 2006. The first set of samples unexpectedly failed prior to reaching 2,250 volts. This was caused by failure of the sealing around the space-rated Teflon wire used to apply the bias. A new approach for sealing these wires was developed that overcame this problem and a new set of cells were put in the chamber. The new samples are currently under testing at 2,250V. However, a failure of the cooling system to the vacuum pump terminated the experiment and the resulting high temperature in the chamber damaged that sample. The cell was showing no problems under bias, confirming that the sealing process was successful. The second cell was put under test on January 5, 2007 and is still running strong. The cell will remain under voltage bias in the vacuum chamber until failure occurs. As this test continues, correlations between this test in vacuum and the underwater test can be made.

4.2 - Hypervelocity Testing


Figure 9 - Stretched lens array module after testing

Micrometeoroid impacts on solar arrays can lead to arcing if the spacecraft is at an elevated potential therefore, hypervelocity testing of the solar array is necessary. A concentrator solar cell module supplied by ENTECH, Inc was tested at Auburn University's Hypervelocity Impact Facility. The module consisted of a string of concentrator multijunction solar cells in series completely covered with cover glass. The overhang extended well beyond the cell boundaries and was also filled with silicone providing a sealed environment. The background plasma was provided by a Tesla coil and confirmed by a Langmuir probe. Maximum particle velocities between 9.4 and 11.6 km/sec were achieved. The sample was biased at -400V and -438V in the first tests. The voltage was increased to over -1000V in the third test with a voltage differential between the strings of 60V. The test sample in the last test is shown in figure 9 with the location of that one small arc noted by the circle.[4] Figure 10 shows the magnified view of the sample after the shot.

No surface arcs occurred despite particle impact penetrations of the covers. All the cell surfaces and edges were fully insulated from the plasma. The lens provided shielding. 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.

Figure 10 - Sample after Hypervelocity shot

5 - CONCLUSION

Spacecraft charging in geosynchronous orbit is a reality that can be destructive and thus negatively affect the satellite industry as a whole. It is paramount to keep the potential of the cell or interconnect and the cover glass the same in GEO thereby reducing the occurrence of arcing. Through extensive ground testing an understanding of charging effects is obtained which enables design of reliable high voltage solar arrays for the future. Power level needs will continue to increase as lunar bases, solar electric propulsion missions, and higher communication systems will be needed. Finding solar array designs to withstand the GEO environment will lead to arrays that will match the requirements for future high voltage mission success. The SLA is an optimal candidate because 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 proving a sealed environment. The SLA is a practical and affordable solution to GEO charging. SLA technology has been tested and proven to withstand the GEO environment without any electrostatic discharge anomalies.

6 - BIBLIOGRAPHY

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