STRETCHED LENS ARRAY: THE ANSWER TO IMPROVING SOLAR ARRAY RELIABILITY

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ABSTRACT

Solar array anomalies are a serious issue affecting the satellite industry and are responsible for increased insurance premiums and a negative perception. It is well known that the reliability of solar arrays needs to be improved. This can be accomplished through the use of a solar array that is inherently designed to withstand the most common modes of failures. The stretched lens array (SLA) overcomes traditional solar array anomalies and is reliable and affordable. This paper will focus on orbital array failures and approaches to design against such anomalies. Theoretical modeling and SLA ground testing results will be presented to prove the SLA's resistance to arcing, micrometeoroid impact, and radiation exposure along with its ability to support high voltage operation. The SLA can overcome solar array anomalies and improve the reliability and cost affordability of solar arrays.

INTRODUCTION

Solar array anomalies are a serious issue affecting the satellite industry and are responsible for increased insurance premiums and a negative perception. It is well known that the reliability of solar arrays needs to be improved. This can be accomplished through the use of a solar array that is inherently designed to withstand the most common modes of failures.

The stretched lens array (SLA) overcomes traditional solar array anomalies and is reliable and affordable. The SLA developed by ENTECH Inc. is a refractive concentrator array that uses an 8X concentration to convert sunlight into electricity with efficiency greater than 27%. SLA's unique, lightweight, and efficient design leads to outstanding performance ratings in areal power density (W/m^2), stowed power density (kW/m^3), specific power (W/kg) and overall cost-effectiveness. Its intrinsic design characteristics protect against electrical discharge, micrometeoroid impacts, and radiation degradation. It provides arc-free high voltage operation because the cells are fully encapsulated providing a sealed environment. The SLA is a cost effective solution with 50-75% savings in $/W compared to planar solar arrays. SLA's small cell size, which is 85% smaller than planar high-efficiency arrays, allows the cell circuit to be super-insulated and super-shielded without a significant mass penalty.

This paper will focus on orbital array failures and approaches to design against such anomalies. Theoretical modeling and SLA ground testing results will be presented to prove the SLA's resistance to arcing, micrometeoroid impact, and radiation exposure along with its ability to support high voltage operation. Future flight experiments and testing protocols will be documented and described in an effort to show the SLA is flight ready for mission success. The SLA can overcome solar array anomalies and improve the reliability and cost affordability of solar arrays.

ORBITAL FAILURE ANALYSIS

It is well known that anomalies and failures of satellites are occurring, but the reality is that few people know the exact cause and conditions surrounding these failures. Most satellite incidents occurring in space today are tracked by Ascend's SpaceTrak database which is the space industry's leading events-based launch and satellite database. Solar array anomalies can be separated by year and orbit showing that the number of satellite failures in GEO is significantly greater than any other orbit (see Fig. 1). This is believed to be attributed to electrostatic discharge caused when an array comes out of an eclipse. Operating spacecraft buses at 100 V and above has led to arcing in GEO communications satellites. By analyzing the known anomalies it is possible to pinpoint key issues where attention needs to be placed to find solutions. This information shows that to reduce solar array anomalies an array must be found that can withstand electrostatic discharge. An optimal candidate would be an array that encapsulates the entire cell and cell edges providing a sealed environment without incurring a significant mass penalty. One example of this type of array is the

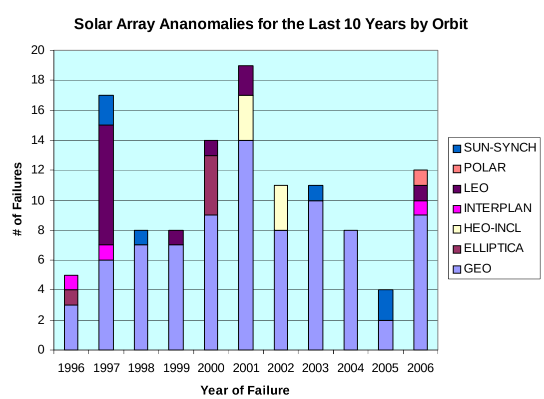

Fig. 1. Solar array anomalies by orbit

Stretched Lens Array (see Fig. 2). Because of the inherent design of the concentrator system, the small-area cells and interconnects are completely encapsulated.

Fig. 2 SLA model in sunlight

SLA BACKGROUND

The SLA developed by ENTECH Inc. is a space solar array that uses refractive concentrator technology to collect and convert solar energy into useful electricity. The 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). SLA's unique, lightweight, and efficient design leads to outstanding performance ratings:

- Areal Power Density: > 300 W/m^2
- Specific Power: > 300 W/kg for a 100 kW Solar Array
- Stowed Power: > 80 kW/m^3 for a 100 kW Solar Array
- Scalable Array Power Capacity: 4 kW to 100's of kW's
- Super-Insulated Small Cell Circuit: High-Voltage (up to 600 V) Operation
- Super-Shielded Small Cell Circuit: Excellent Radiation Hardness at Low Mass
- 85% Cell Area Savings: Up to 75% Savings in Array $/W Versus One-Sun Array

A mini-dome lens concentrator flown on the PASP-Plus mission in 1994 was the first refractive concentrator array. It provided the best performance and least degradation of 12 advanced solar array experiments that flew on the mission in a high radiation orbit [1]. SCARLET, a line focused concentrator, evolved from this and was launched in 1998 on Deep Space 1 and performed flawlessly on a 38 month mission [2]. The stretched lens array is based on SCARLET and retains the essential power-generating elements but eliminates the complexity, fragility, expense, and mass of the glass arches by incorporating pop-up arches [3]. Flexible blanket and rigid panel versions of the SLA have been developed and tested over the last decade. A 3.75 kW scale (2.5 x 5.0 m) building block of the Stretched Lens Array on the SquareRigger platform has been successfully demonstrated as seen in Fig. 3. That demonstration confirmed that the specific power goal of >300 W/kg is achievable.

RADIATION MODELING

Radiation degradation is a solar array anomaly affecting the satellite industry. Radiation shielding can

Fig. 3. A 3.75 kW Stretched lens array on a SquareRigger platform

be increased on the SLA with little impact on array mass, hence providing a "super shielded" system for operation in high radiation environments such as the heart of the Van Allen belts or in those found around Jupiter. This is due to its 8X concentration which reduces the area, hence mass, of solar cells needed for the desired power range. To understand and compare the various radiation environments for these orbits, simulations have been run using The European Space Environment Information System (SPENVIS) The SPENVIS model provides the 1 MeV equivalent electron radiation doses for given orbits and durations. This information, in conjunction with a standardized chart of power degradation of solar cells with electron fluence, permits calculation of the power degradation of the solar cell as a function of cover glass thickness. A high radiation orbit of 5000 km with a 28 degree inclination angle was chosen as an example. Next the mass of the cover glass material must be considered to allow calculation of the end-of-life (EOL) specific power for the array. The peak EOL specific power values for each time period have been obtained for both the SLA and a planar array (see Fig. 4). This assumes a beginning of life areal power density of 300 W/m^2 which is comparable to today's SLA. Note that SLA offers more

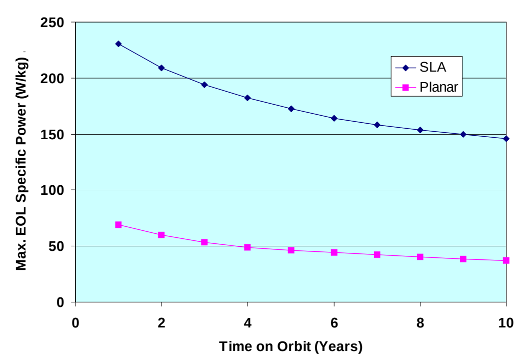

Fig. 4. EOL specific power with optimal shielding

than a 3X advantage over the planar array for 1 year on the time scale, and a 4X advantage over planar for 10 years on the time scale, for this example case (5,000 km altitude, 28 degree inclination, circular orbit). SLA's advantage over planar is apparent especially in high radiation missions. The SLA advantage over a planar array can by displaying by graphing the areal power density variation for the heaviest SLA analyzed versus the lightest one-sun array analyzed (see Fig. 5). It is important to note that the heaviest SLA is 14% lighter than the lightest one-sun array, thus the remaining power advantage of SLA is spectacular. SLA's advantage over planar will grow even larger for higher radiation missions.

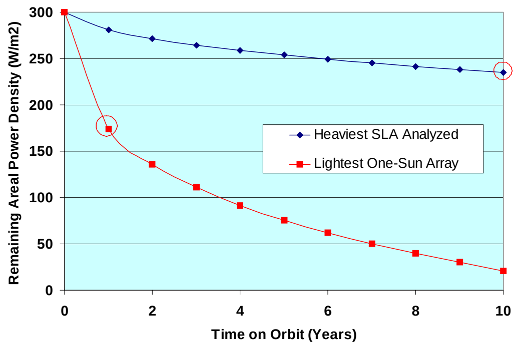

Fig. 5. SLA/planar areal power density comparison

SLA TESTING

The SLA enables high voltage operation and sustainability in the GEO environment which is especially dangerous for solar arrays (see Fig. 1). The issue of spacecraft charging and solar array arcing remains a serious design problem. A beneficial design feature of the SLA is 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 limiting the chance of electrostatic discharge. Ground testing of solar arrays at high voltages can determine potential charging issues that need to be addressed prior to launch. Corona discharge tests have confirmed the durability of this array design for high voltage operation. Currently there is no standard space corona test but Auburn and ENTECH Inc. have performed testing based on guidelines for the terrestrial test from the European community (IEC 343). The purpose of corona testing is to determine the lifetime of solar array designs under high voltage stress in the space environment. Initial long-term ground tests of Stretched Lens Array photovoltaic circuit samples have been performed with samples at very high voltage (2,000-5,000 VDC) under water which crudely simulates space plasma. Auburn has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. The sample is maintained at room temperature under a vacuum of approximately $6x10^{-5}$ torr. One sample underwent testing at 2,250 V for 289 days and showed no change.

Hypervelocity impact tests were performed on an ENTECH, Inc. concentrator solar cell module and the silicone lens material. No surface arcs occurred despite particle impact penetrations of the covers. The SLA lens acts as a meteoroid bumper and thus provides additional protection (see Fig. 6).

Fig. 6. Lens sample after hypervelocity shot

Combined electron and proton testing has been conducted at NASA Marshall Space Flight Center (MSFC) that confirms the durability to those hazards. Testing has shown that the silicone lens material can tolerate $5x10^{10}$ rads of combined electron and proton exposure with only minor degradation. This is equivalent to 10 years on GEO using the current AE8/AP8 environments. Spectral transmittance data from NASA MSFC testing of lens material with UV-rejection coatings shows no damage after more than 1000 equivalent sun hours of combined vacuum ultraviolet (VUV) and near ultraviolet (NUV) exposure. In addition, space tests on MISSE 1 on lens material with early coating compositions show excellent performance with minimal degradation after four years on orbit. All aspects of the SLA have tested durable to the space environment.

FUTURE TESTING OPPORTUNITIES

The first fully functional SLA flight experiment will fly in 2008 on the DOD TacSat IV spacecraft. TacSat IV is currently scheduled for launch in late 2008, when it will be placed in a high-radiation elliptical orbit (700 km x 12,050 km x 63.4 degrees). The Stretched Lens Array Technology Experiment (SLATE) (see Fig. 7) includes a single flexible silicone stretched lens with a 1-micron-thick protective parquet coating focusing onto three series-connected EMCORE triple-junction cells, each with two integral diodes. This will provide validation of the survivability of SLA hardware in a high radiation orbit.

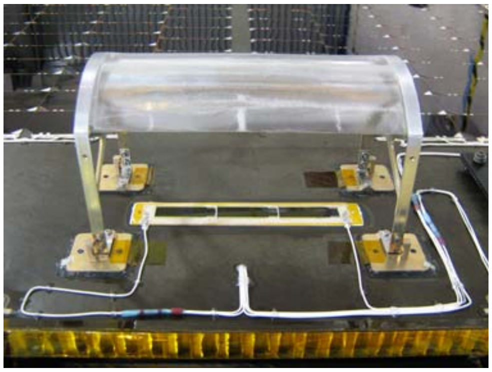

Fig. 7. SLATE-T4 Parquet-Coated Lens and Three-Cell Photovoltaic Receiver Mounted on TacSat IV Solar Array Panel

Another important experiment is a direct drive experiment located at Auburn University. The purpose of this project is to test the compatibility of a 600 Volt DC 1 kW NASA/ENTECH SunLine concentrator solar array for the direct drive operation of a Russian made T-100 1.2 kW Hall thruster provided by NASA Glenn Research Center. The goal of this demonstration is to prove reliable operation of the Hall thruster from the high voltage concentrator array. Testing will include the addition of Stretched Lens Array (SLA) hardware in the chamber at Auburn to measure plume impingement effects at various positions relative to the exhaust axis of the thruster. A schematic of planned testing consists of the direct-drive HET and the SLA test configuration (see Fig. 8).

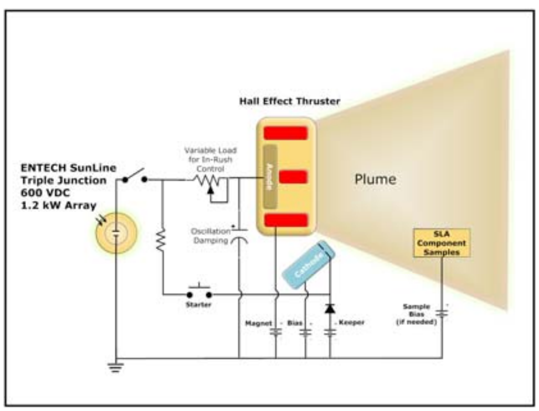

Fig. 8. Schematic of planned direct-driven HET and SLA test configuration.

CONCLUSION

Solar array power levels will continue to increase as lunar bases, solar electric propulsion missions, and higher power communication satellites are developed. As power levels continue to increase more durable arrays that can operate in high voltage operations and in high radiation environments must be incorporated. SLA's small cell size, which is 85% smaller than planar high-efficiency arrays, allows the cell circuit to be super-insulated and super-shielded without a significant mass penalty. This paper focuses on two major orbital array failures and how the SLA is designed to protect against such anomalies. Current and future testing efforts have been described to show the SLA's reliability in any orbit. The SLA can overcome solar array anomalies and improve the reliability and cost affordability of solar arrays.

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