DURABILITY OF THE SLA IN HIGH VOLTAGE, HIGH RADIATION ENVIRONMENTS

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ABSTRACT: A solar array must be able to withstand the hazardous space environment and be able to operate reliably over a long period of time to be considered for space applications. The capability to withstand high voltage operation is another emerging factor required by space solar arrays as power levels continue to increase. The Stretched Lens Array (SLA) uses concentrator technology to offer outstanding measures of performance while at the same time offering protection against radiation, micrometeoroids, and electrostatic discharges common in high voltage operations. Thus it is especially well suited for electric propulsion missions and operation in high radiation environments such as the Van Allen belts or in those found around Jupiter. This paper will describe SLA past testing and flight history along with detailing two future SLA testing opportunities. The SLA is a durable array that can operate in high voltage, high radiation environments.

Keywords: concentrators, reliability, high-efficiency

1 INTRODUCTION

A solar array must be able to withstand the hazardous space environment and be able to operate reliably over a long period of time to be considered for space applications. The capability to withstand high voltage operation is another emerging factor required by space solar arrays as power levels continue to increase. The Stretched Lens Array (SLA) uses concentrator technology to offer outstanding measures of performance while at the same time offering protection against radiation, micrometeoroids, and electrostatic discharges common in high voltage operations. 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 preventing the most common failure mechanism of arcing.

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. Thus it is especially well suited for electric propulsion missions and operation in high radiation environments such as the Van Allen belts or in those found around Jupiter. Ground testing has proven SLA hardware is resistant to the harsh space environment. Testing methods include combined electron and proton testing, combined vacuum ultraviolet (VUV) and near ultraviolet (NUV) exposure, hypervelocity impact tests, and corona discharge tests, among others, which have confirmed the durability of this array design for high voltage and high radiation operation. All aspects of the SLA have tested durable to the space environment.

This paper will describe SLA past testing and flight history along with detailing two future SLA testing opportunities. One is a SLA flight module known as SLATE-T4 which will provide validation of the survivability of SLA hardware in a high radiation orbit. Another important experiment is a direct drive experiment between a 600 Volt DC 1 kW concentrator solar array and a Hall thruster. Plume impingement effects on the SLA hardware will be included in the discussion. The SLA is a durable array that can operate in high voltage, high radiation environments.

2 SLA BACKGROUND

2.1 SLA flight history

SLA is a unique ultra-high-performance, ultra-light, cost-effective photovoltaic concentrator array using refractive concentrator technology. Unlike reflective concentrators, these refractive Fresnel lens concentrators can be configured to minimize the effects of shape errors, enabling straightforward manufacture, assembly, and operation on orbit. By using a unique arch shape, these Fresnel lenses provide more than 100X larger slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators [1]. 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 [2]. 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 [3]. 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 [4]. The SCARLET array performed flawlessly and within 2% of its projected performance over the entire Deep Space 1 mission validating the use of solar-powered ion propulsion for extended space missions. Both missions can be seen in Fig. 1.

Flexible blanket and rigid panel versions of the SLA have been develped 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. 2. That demonstration confirmed that the specific power goal of > 300W/kg is achievable.

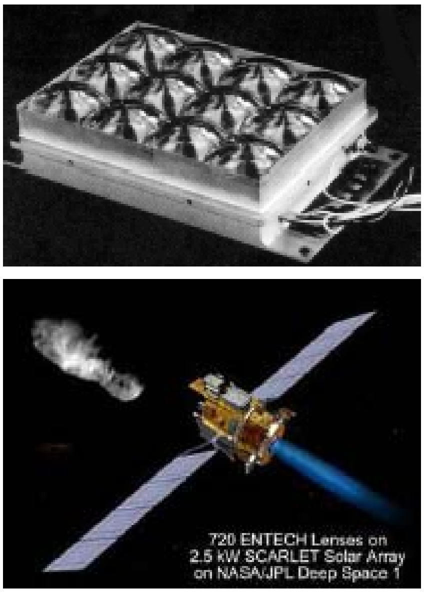


Figure 1: Top photo is the PASP+ module, bottom photo is the SCARLET Deep Space 1 array

Figure 2: Full scale SLASR panel

2.2 SLA performance parameters

Because of its 8.5X geometric concentration ratio, SLA saves over 85% of the required area, mass and cost of the multi-junction solar cells per watt of power produced. Significantly, the total combined areal mass density (kg/m^2 of sun-collecting aperture area) of the lens material, the radiator sheet material, and the fully assembled photovoltaic receiver is much less (about 50%) than for a one-sun multi-junction cell assembly alone. Thus, SLA has a substantial inherent mass advantage over planar, one-sun multi-junction-cell solar arrays. Similarly, due to its 85% cell area and cost savings, SLA has a substantial inherent power cost advantage ($/W) over such planar multi-junction-cell arrays. The Stretched Lens Array offers unprecedented performance (>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).

SLA's small cell size also allows super-insulation and super-shielding of the solar cells to enable high-voltage operation and radiation hardness in the space environment. SLA's demonstrated high performance and radiation tolerance, coupled with its substantial mass and cost advantages, will lead to many applications especailly in high voltage, high radiation environments. SLA's unique attributes make it an optimal choice for Solar Electric Propulsion (SEP) missions.

3 SLA HARDWARE TESTING

Some obstacles to SEP include the use of high voltage operation to reduce cable mass and permit direct drive thruster operation along with durability and resilience to the space environment. Ground testing of the array is essential to help prove the reliability of space operation.

3.1 Lens material tests

Ground testing consisting of combined electron and proton testing and UV/VUV testing have confirmed the durability of the SLA lens material and coating to space 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. The current lens coating blocks the VUV wavelengths below 200nm which are known to be the damaging wavelengths that cause yellowing of the silicone lens material. Space lens material tests were performed on the MISSE 1 and MISSE 5 flight experiments that spent 48 months and 12 months, respectively, on the ISS exposed to sunlight. There is no available data yet for the MISSE 5 experiments, but for MISSE 1 the UVR-coated silicone lens material held up very well with very little degradation. The coated silicone samples showed only slight yellowing after four years in orbit and spectral transmittance measurements taken at NASA Marshall

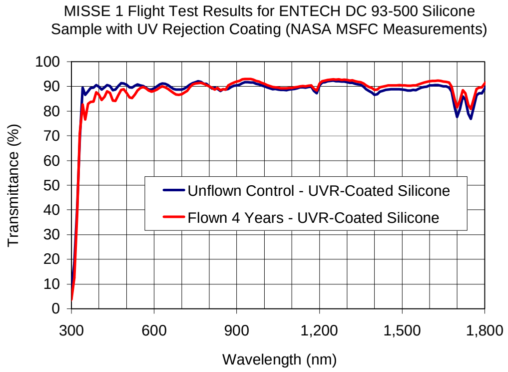


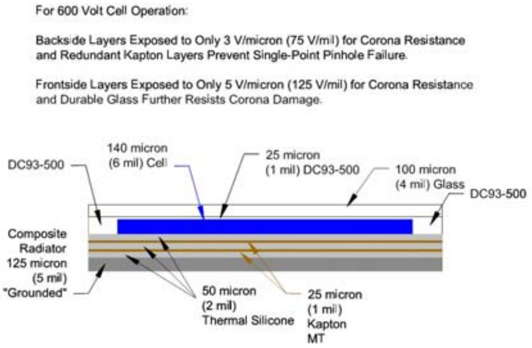
Figure 3: Spectral transmittance measurements of MISSE 1 samples

Space Flight Center matched results from the unflown control proving minimal degradation. Results can be seen in Fig. 3. The MISSE 5 experiment sample had a newer, more robust coating.

3.2 High voltage corona testing

Corona testing had proven the SLA can operate at high voltage (>300 V) for extended times for Hall or ion thrusters. The SLA can be specifically optimized for SEP by the ability to direct-drive Hall-effect thrusters. This technology designed by NASA Glenn can minimize the inefficiency, mass, cost and complexity of the power management and distribution interface between the solar array and electric thruster [5]. The initial drawback is that the solar array must be able to operate at the voltage level needed to drive the electric thruster. This voltage is much higher than the present operation voltage of space solar arrays of 100 V. Serious discharge, arcing, and ground-fault problems have occurred on orbit with even the present operating voltage. SLA overcomes this challenge by fully encapsulating the entire cell circuit to create a sealed environment. This can be accomplished without a huge mass penalty due to the 8X concentration and fewer cells needed to provide the same amount of power.

To test the sustainability of SLA in high voltage operations, array segments, seen in Fig. 4, are under test for corona breakdown. 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. Auburn University has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. These tests are being conducted using the guidelines found in ESA's IEC International Standard #343 (1991): "Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges [6]." The samples underwent testing at 2,250 V for ten and a half months and showed no change. Due to the SLA's inherent protection against electrostatic discharge it is especially well suited for electric propulsion missions. The SLA is also fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard.


For 600 Volt Cell Operation:

Backside Layers Exposed to Only 3 V/micron (75 V/mil) for Corona Resistance and Redundant Kapton Layers Prevent Single-Point Pinhole Failure.

Frontside Layers Exposed to Only 5 V/micron (125 V/mil) for Corona Resistance and Durable Glass Further Resists Corona Damage.

Figure 4: Test sample configuration

3.3 Hypervelocity impact testing

Hypervelocity testing at Auburn University showed the SLA's resistance to micrometeoroid impacts and electrostatic discharge even at voltages as high as 1000V. 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 test sample in the last test is shown in Fig. 5. No surface arcs occurred over the sample despite visible particle impact penetrations of the covers. Additional tests were performed with the stretched lens in place over the samples, and the lens provided excellent shielding of the cell circuits. 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.

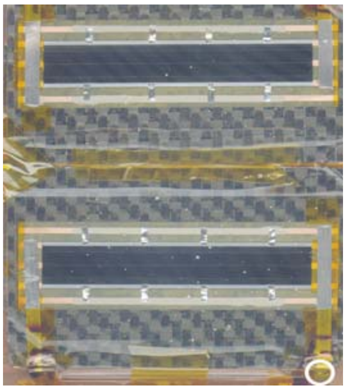


Figure 5: Stretched lens array module after testing

4 RADIATION ANALYSIS

For a solar array to be considered for SEP it must survive slow spiraling transits through the Earth's radiation belts with the requirement that the loss in solar array power is not excessive and still enables the 15 to 20 year mission life. Even for today's advanced triple-junction solar cells, the radiation dose for this type of mission requires significant radiation shielding of the cells to keep power degradation in a reasonable range. Because of the concentrator design of the SLA, the ~4 cm^2 cells, designed for 8x concentration can be shielded against radiation damage at about 1/8th the mass of a conventional planar array. This is of utmost importance for all electric propulsion missions transversing through the Van Allen Belts and for missions in high radiation orbets such as MEO. To determine the SLA's radiation resistance, various SEP missions and high radiation orbits have been analyized. The total mission radiation environment must be computed to determine the optimal amount of shielding needed to withstand the radiation dose. A trajectory must first be determined because the electron and proton radiation fluences vary widely with orbital altitude and inclination. 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 as shown in Fig. 6. 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 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. Figure 7 shows the SLA advantage over a planar array by displaying the areal power density variation for the heaviest SLA analyzed versus the lightest one-sun array analyzed. 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.

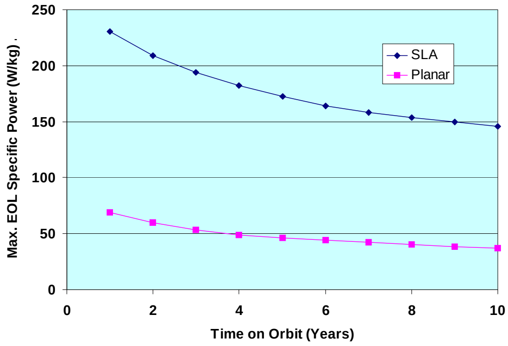


Figure 6: EOL specific power with optimal shielding

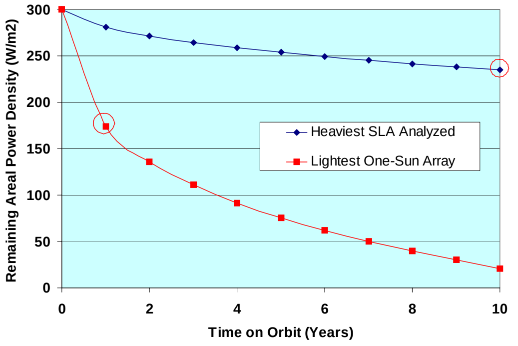


Figure 7: SLA/planar areal power density comparison

The solar array degradation for a LEO to GEO tug mission and a lunar cargo tug has also been calculated by SPENVIS simulations as seen in Fig. 8. The SLA uses more protective cover glass to reduce the radiation damage yet incurs only a small mass penalty. Comparisons of the end-of-life specific power between a SLA and a planar array are presented for an orbital transfer mission from LEO to GEO in Fig. 9. A 100 kWe SLA, adequately shielded with a 20 mil coverglass, will still have a specific power of 260 W/kg <u>after</u> seven round-trip LEO-GEO missions. A conventional planar one-sun array with the same amount of shielding would only have 70 W/kg after such a mission. This incorporates satellites being transferred in both directions with a tug mass of 1000 kg

The SLA has a huge mass advantage, a 3-4X advantage over competing arrays, especially in high radiation environments making it an optimal candidate for SEP missions through the Van Allen Belts or even to Jupiter. The SLA is ideally matched to high radiation and Solar Electric Propulsion applications.

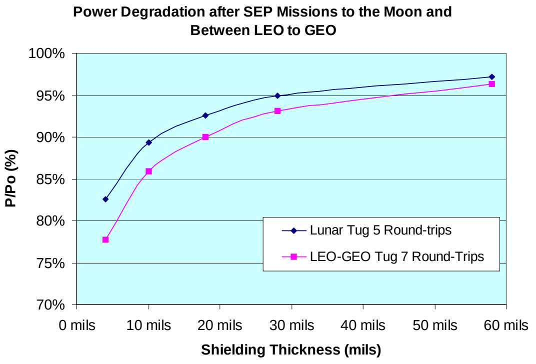


Figure 8: Power degradation of two SEP tug missions

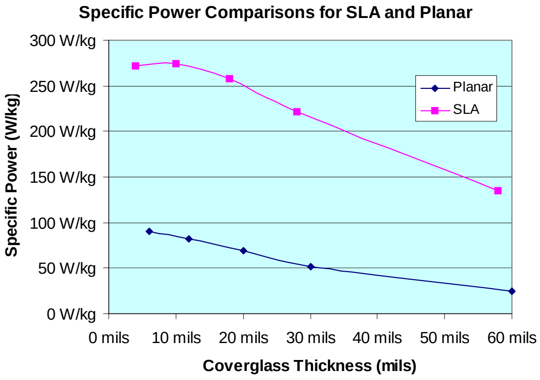


Figure 9: Specific power comparison for SLA and Planar Arrays

5 FUTURE TEST AND FLIGHT OPPORTUNITIES

5.1 TacSat IV

The first fully functional SLA flight experiment will fly in 2009 on the DOD TacSat IV spacecraft. TacSat IV 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. 10) 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.

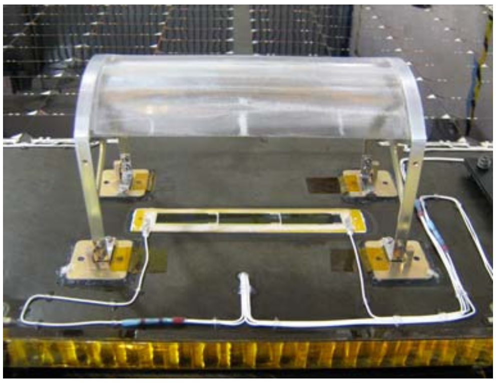


Figure 10: SLATE-T4 Parquet-Coated Lens and Three-Cell Photovoltaic Receiver Mounted on TacSat IV Solar Array Panel

5.2 Direct drive experiment

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 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. 11).

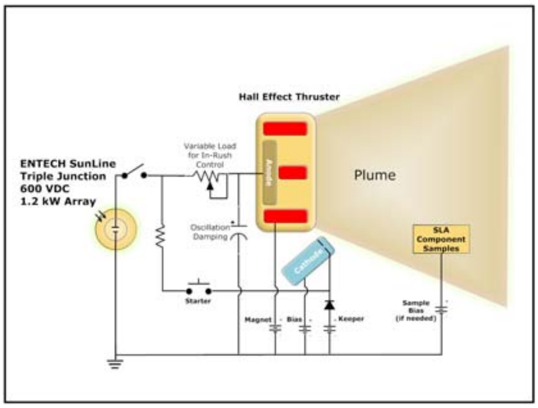


Figure 11: Schematic of planned direct-driven HET and SLA test configuration.

The high-voltage array shown in Fig. 12 was transported from ENTECH to Auburn where it is being interfaced with the Hall-effect thruster in the large vacuum chamber shown in Fig 13. The array uses two of ENTECH's color-mixing lenses to focus sunlight onto two photovoltaic receivers each using 240 series-connected triple-junction Spectrolab cells to provide 600 V output at open-circuit conditions. The peak power point is around 500 V, and the total power output of the array is over 1 kW under clear sky conditions [7]. The Russian thruster shown in Fig. 13, is a Model T-100 SPT, designed and constructed by the Keldish Research Center (KeRC), and capable of operating up to 1.3 kW [7]. This thruster is on loan to Auburn from NASA Glenn. Testing is on-going at Auburn University.

Figure 12: SunLine Concentrator array

Figure 13: Auburn student inspects Russian T-100 thruster

6 CONCLUSION

The SLA is an array that can withstand the differing environmental conditions as the vehicle travels from LEO to GEO, the moon, or Jupiter. It is also an array that is light weight to preserve payload mass fraction – and to do this at a cost that is lower than today's arrays. The SLA is fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard. The Stretched Lens Array is a superior solar array for all orbital applications. Analytical modeling and terrestrial test results of the SLA have been examined to demonstrate its ability to withstand the hazards of the space environment in all orbits. SPENVIS simulations predicting the degradation, EOL specific power, and EOL areal power density have shown the SLA's benefits and huge advantage over a planar array. Ground testing consisting of combined electron and proton testing and UV/VUV testing have confirmed the durability of the lens material and coating to space hazards. Corona testing had proven the SLA can operate at high voltage (>300 V) for extended times without arcing. Hypervelocity testing at Auburn University showed the SLA's resistance to micrometeoroid impacts and electrostatic discharge even at voltages as high as 1000V. In conclusion, the SLA is a practical and affordable, not to mention reliable solution to solar array power needs in high radiation, high voltage missions.

7 REFERENCES

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