

## ON THE PERFORMANCE AND SPACE RELIABILITY OF THE STRETCHED LENS ARRAY

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**ABSTRACT:** Over the past decade, substantial advances have been made in the technology for the concentrator system known as the Stretched Lens Array. Continued developments have included space lens material tests, hypervelocity impact tests, and corona discharge tests which have confirmed the durability of this array design for high voltage operation making it well suited for electric propulsion missions. In addition, 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 confirming that the specific power goal of > 300W/kg is achievable. Radiation shielding can be increased 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. Finally, a space flight experiment is being developed to compare the results of the SLA with conventional one-sun triple junction and thin film cells in a high radiation environment. The status and results of these programs will be presented that show the SLA is ready for flight for missions with array sizes from 1 to 100 kW at substantial cost savings.

**Keywords:** concentrators, reliability, high-efficiency

### 1 INTRODUCTION

Over the past decade, substantial advances have been made in the technology for the concentrator system known as the Stretched Lens Array (SLA). Continued developments have included space lens material tests on the MISSE 1 and MISSE 5 flight experiments on the ISS exposed to sunlight. Hypervelocity impact tests with 1,000 V cell bias and corona discharge tests have confirmed the durability of this array design for high voltage operation. Thus it is especially well suited for electric propulsion missions. In addition, 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 confirming that the specific power goal of > 300W/kg is achievable.

In addition radiation shielding can be increased 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. Finally, a space flight experiment is being proposed to compare the results of the SLA with conventional one-sun triple junction and thin film cells in a high radiation environment. This experiment would be self-powered and could be designed to fly on many platforms. The status and results of these programs will be presented that show the SLA is ready for flight for missions with array sizes from 1 to 100 kW at substantial cost savings.

### 2 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). The refractive concentrators minimize the effects of shape errors and provide more than 100X larger slope error tolerance than reflective or flat concentrators [1]. SLA's unique, lightweight, and efficient design leads to outstanding performance ratings in areal power density (W/m<sup>2</sup>), stowed power density (kW/m<sup>3</sup>), specific power (W/kg) and overall cost-effectiveness. It currently offers the following measures of performance:

- ❖ Areal Power Density: > 300 W/m<sup>2</sup>
- ❖ Specific Power: > 300 W/kg for a 100 kW Solar Array
- ❖ Stowed Power: > 80 kW/m<sup>3</sup> 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 [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]. 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. 1. That demonstration confirmed that the specific power goal of > 300W/kg is achievable.

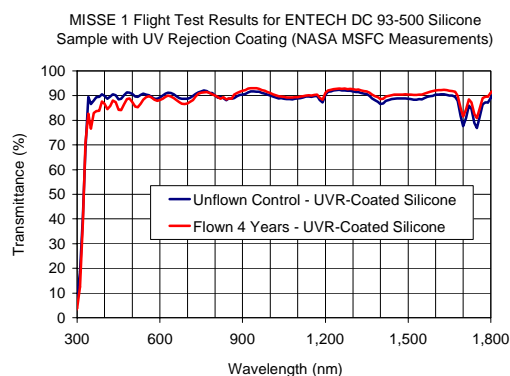


**Figure 1:** Full scale SLASR panel

### 3 SLA TESTING

#### 3.1 Lens Material Testing

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 Space Flight Center matched results from the unflown control proving minimal degradation. Results can be seen in Fig. 2. The MISSE 5 experiment sample had a newer, more robust coating.

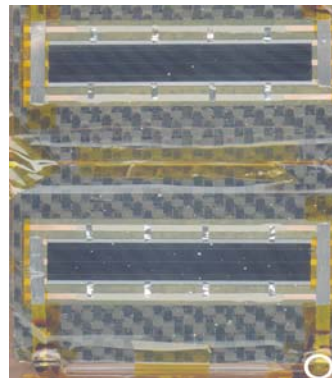


**Figure 2:** Spectral transmittance measurements of MISSE 1 samples

#### 3.2 Hypervelocity Testing

Hypervelocity impact tests were performed on an ENTECH, Inc. concentrator solar cell module and the

silicone lens material. Multijunction solar cells were placed in series and were completely covered with cover glass and boundaries were also fully encapsulated with silicone. A Tesla coil provided the background plasma. Maximum particle velocities 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 [5]. The test sample in the last test is shown in Fig. 3. No surface arcs occurred despite



**Figure 3:** Stretched lens array module after testing

particle impact penetrations of the covers. The SLA lens acts as a meteoroid bumper and thus provides additional protection. Figure 4 shows a typical impact site on the DC 93-500 silicone lens material held in tension as would be the case in space [6]. No tearing of the lens was seen.



**Figure 4:** Lens sample after hypervelocity shot

Rear impact shots were also performed on the cell sample and no arcing was observed.

#### 3.3 Corona Testing

Corona discharge tests have confirmed the durability of this array design for high voltage operation. The SLA design is suited for high voltage operation because the entire cell and cell edges are fully encapsulated by a cover glasses that overhangs the perimeter and the silicone adhesive covers the cell edges, Thus it provides a sealed environment which limits the possibility of electrostatic discharge. 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. 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. 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  $6 \times 10^{-5}$  torr. The samples have been undergoing testing at 2,250 V since January 5, 2007 and have shown no change. Due to the SLA's inherent protection against electrostatic discharge it is especially well suited for electric propulsion missions and high power geosynchronous orbits.

#### 4 RADIATION SHIELDING

Radiation shielding can be increased 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. To understand and compare the various radiation environments for these orbits, simulations have been run using The European Space Environment Information System (SPENVIS) and the data has been graphed. The natural radiation environment in space is defined by existing models, such as AE-8 for trapped electrons and AP-8 for trapped protons in Earth's radiation belts, and JPL models for solar protons. SPENVIS incorporates these models in an online analysis program package. The SPENVIS model provides the 1 MeV equivalent electron radiation doses for given orbits and durations. Losses in maximum power ( $P_{max}$ ), short circuit current ( $I_{sc}$ ) and open circuit voltage ( $V_{oc}$ ) are calculated as a function of protective layer thickness. 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 as shown in Fig. 5 for a high radiation orbit of 5000 km with a 28 degree inclination angle.

Next the mass of the cover glass material must be

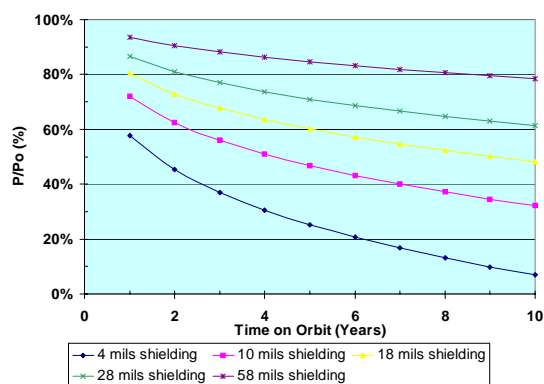


Figure 5: SLA performance in high radiation orbit

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  $300 \text{ W/m}^2$  which is comparable to today's SLA. Note that

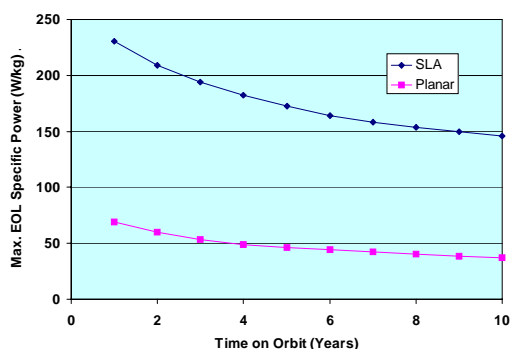


Figure 6: EOL specific power with optimal shielding

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.

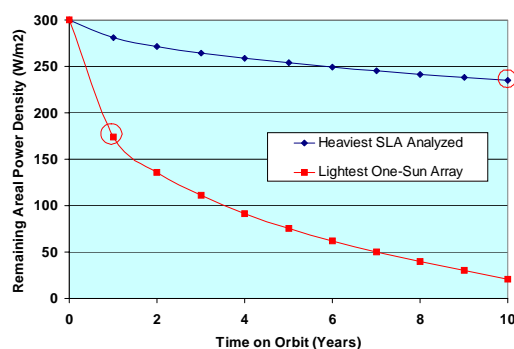


Figure 7: SLA/planar areal power density comparison

#### 5 FUTURE FLIGHT EXPERIMENT

A space flight experiment is being proposed that would compare the results of the SLA module with conventional one-sun triple junction and thin film cells in a high radiation environment. This experiment would be self-powered and could fly on many platforms. The experiment is being designed with two panels that unfold. Part of each panel would be devoted to the SLA experiment and the other half of each panel would be devoted to one-sun cells, half of which provide power and the other half of which are one-sun cell experiments, including both crystalline cells and thin-film cells with different types and amounts of shielding. Cell degradation would be determined by measuring full I-V curves. The data acquisition system would be mounted under one of these panels to provide additional shielding and will use radiation-hardened components due to the high radiation environment of the Van Allen belts. This technology experiment would provide valuable solar cell

degradation information due to the natural radiation of space along with providing flight validation for the Stretched Lens Array.

## 6 SUMMARY

The ENTECH Stretched Lens Array has been shown to be capable of reliable operation at high voltage and in high radiation environments. It has undergone and survived space environment material tests, corona discharge tests, and hypervelocity impact testing. Its 8X concentration ratio and 85% cell area savings allows for up to 75% savings in array dollars per watt versus one-sun arrays. SLA's small cell size allows the cell circuit to be super-insulated and super-shielded without incurring a significant mass penalty. 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 that protects against electrostatic discharge making it well suited for electric propulsion missions. The SLA is ready for flight for missions with array sizes from 1 to 100 kW at substantial cost savings.

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