

# Radiation Resistance and Reliability of the Stretched Lens Array (SLA) in Solar Electric Propulsion (SEP) Missions

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As space exploration continues to be the main focus of NASA, solar electric propulsion becomes a primary candidate for the means of reaching other planets. For solar electric propulsion missions to succeed a reliable solar array is essential. The array must be radiation resistant, able to operate at high voltages, withstand micrometeoroid impacts and changing space environments, not to mention, the array must be lightweight. This paper will present why the Stretched Lens Array is an optimal array for solar electric propulsion missions to the Moon, Mars, Jupiter, and beyond.

**Key Words:** Solar Array, Electric Propulsion, Radiation, Arcing, Resistance

## 1. Introduction

As space exploration continues to be the main focus of NASA, solar electric propulsion becomes a primary candidate for the means of reaching other planets. For solar electric propulsion missions to succeed a reliable solar array is essential. Several critical issues emerge as potential barriers to this approach: reducing solar array radiation damage, operating the array at high voltage (>300 V) for extended times for Hall or ion thrusters, designing an array that will be resistant to micrometeoroid impacts and the differing environmental conditions as the vehicle travels from LEO to GEO (or at Jupiter), producing 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. This paper will describe progress made to date on achieving an array that meets all these requirements. The stretched Lens Array is an optimal array for solar electric propulsion missions to the Moon, Mars, Jupiter, and beyond.

## 2. SLA Background

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 Fig. 1. From 1998-2001, NASA flew the Deep Space 1 mission that validated the use of solar-powered ion propulsion for extended space missions. This highly successful three-year mission used a concentrator array, known as SCARLET, that performed flawlessly and within 2% of its

projected performance over the entire mission. That design has evolved into the Stretched Lens Array. The primary difference between SCARLET and the SLA is that no additional glass cover is used over the silicone

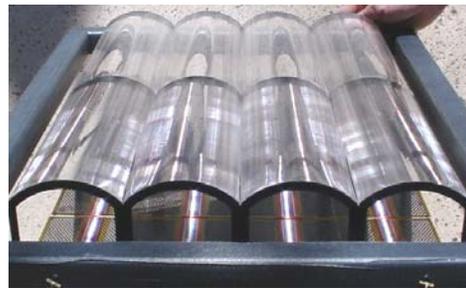


Figure 1: SLA in sunlight

lens. This has led to significant mass, cost and complexity reductions. The module shown in Fig. 2 is the latest version of the design using ATK Space Systems' SquareRigger Platform. This design leads to a specific



Fig. 2. Full scale SLASR panel

power exceeding 300 W/kg at voltages exceeding 300 V.

### 3. Advantages of SLA over a Planar Array

SLA's unique design offers advantages over a planar array in cost, radiation resistance, and weight. SLA offers unprecedented performance ( $>80 \text{ kW/m}^3$  stowed power,  $>300 \text{ W/m}^2$  areal power, and  $>300 \text{ W/kg}$  specific power), high voltage operation (300-600 V), and cost-effectiveness ( $>50\%$  savings in  $\$/\text{W}$  compared to planar arrays).

#### 3.1. Radiation Resistance

The SLA must survive seven round-trip 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 mission requires significant radiation shielding of the cells to keep power degradation in a reasonable range. Because of the concentrator design, the  $\sim 4 \text{ cm}^2$  cells, designed for 8x concentration can be shielded against radiation damage at about  $1/8^{\text{th}}$  the mass of a conventional planar array. This is of utmost importance for an electric propulsion mission transversing through the Van Allen Belts and possibly even to Jupiter's radiation belts. This paper will focus on the radiation resistance of the SLA for various SEP missions. The total mission radiation environment must be analyzed 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. The spreadsheet model estimates the spiral trajectories and the length of time the tug is in each altitude bin. This information can be used with ESA's Space Environmental Information System model (SPENVIS) to estimate the degradation of the solar array. The solar array degradation for a LEO to GEO tug mission and a lunar cargo tug has been calculated by SPENVIS simulations as seen in Fig. 3. The SLA uses more protective cover glass to reduce the radiation damage yet incurs only a small mass penalty.

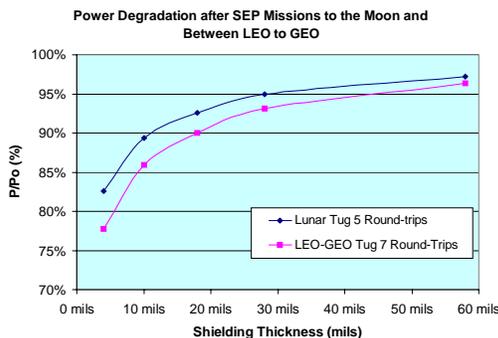


Fig. 3. Power degradation of two SEP tug missions

#### 3.2. Cost

One study showed SLA with SEP could save NASA  $>\$10$  billion for lunar exploration cargo transportation.<sup>1,2</sup> A SLA-powered SEP approach for delivering 110 metric tons of cargo to the lunar surface over a five-year period will save about 350 metric tons of launch mass compared to a conventional chemical approach, comprising  $\$3.5$  Billion in launch cost savings alone.

#### 3.3. Mass and Power Advantages

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. 4. A 100 kWe SLA, adequately shielded with a 20 mil coverglass, will still have a specific power of 260 W/kg after 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. These calculations do not take into account that a heavier planar array would need more fuel for the round trip, which would increase the overall weight and trip time. Thereby, increasing the radiation damage and lowering the specific power. Several variations in tug mass and trip time were analyzed and results stayed relatively the same. 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 Solar Electric Propulsion (SEP) applications.

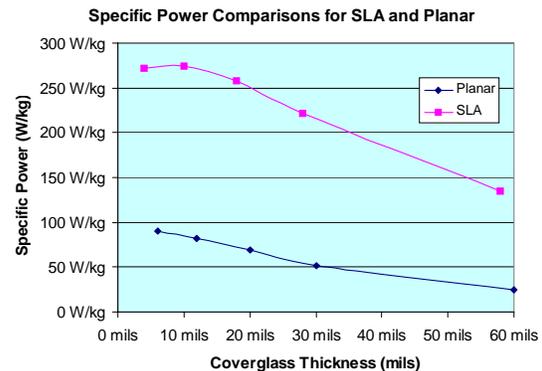


Fig. 4. Specific power comparison for SLA and Planar Arrays

### 4. Ground Testing of the SLA

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.

#### 4.1. High Voltage Testing

Corona testing had proven the SLA can operate at high voltage ( $>300 \text{ V}$ ) 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.<sup>3</sup> 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 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."<sup>4</sup> 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.

#### 4.2. Material Testing

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  $5 \times 10^{10}$  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 Space Flight Center matched results from the unflown control proving minimal degradation. Results can be seen in Fig. 5. The MISSE 5 experiment sample had a newer, more robust coating.

#### 4.3 Micrometeoroid Testing

Hypervelocity testing at Auburn University showed the

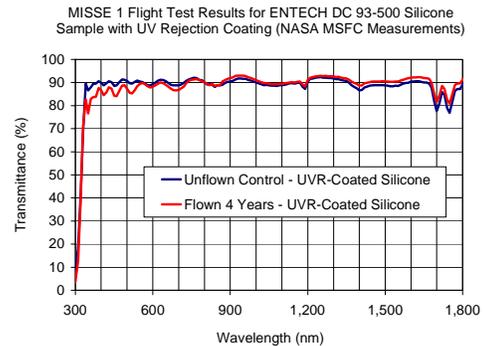


Fig. 5. Spectral transmittance measurements of MISSE 1 samples

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. 6. No surface arcs occurred over the sample



Fig. 6. Stretched lens array module after testing

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  $-1027\text{V}$ . Although there were many impacts no arcing was observed.

## 5. 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. In conclusion, the SLA is reliable, radiation resistant, scalable, cost-effective, durable, and efficient. It is an optimal candidate for SEP missions to GEO, the moon, Mars, and beyond.

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