ADVANCEMENTS IN DIRECT-DRIVING AN ELECTRIC THRUSTER WITH A STRETCHED LENS CONCENTRATING SOLAR ARRAY

Henry W. Brandhorst, Jr.[1], Julie A Rodiek[2], Steve R. Best[3], Mark J. O'Neill[4], and Michael F. Piszczor[5]
[1,2,3]Space Research Institute, Auburn University, AL 36849
[4]Entech Solar, Inc., Ft. Worth, TX 76177
[5]NASA Glenn Research Center, Cleveland, OH 44135

INTRODUCTION

As space exploration continues to be a primary focus of NASA, solar electric propulsion (SEP) becomes a forerunner in the mode of transportation to reach the moon and other planets in our solar system. The Stretched Lens Array (SLA) is a unique ultra-high-performance, ultra-light, cost-effective photovoltaic concentrator array using refractive concentrator technology. The SLA is capable of high voltage operation and sustainability in a high radiation environment which is essential for solar electric propulsion missions. The SLA can be specifically optimized for SEP by the ability to direct-drive Hall-effect thrusters. This technology sponsored 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. While this SLA array technology design has high efficiency, low mass, and radiation-hardness, the SLA must also tolerate plume interactions with the thruster. Terrestrial and space testing of the SLA will be documented showing its applicability to a SEP mission.

Auburn University in conjunction with Entech Solar Inc. has performed a "direct drive" experiment using a high-voltage (600 Voc) ENTECH SunLine concentrator array powered with multijunction solar cells coupled to a Russian T-100 Hall Effect Thruster (HET). This appears to be the first time a Hall thruster has been run directly from III-V-based multi-junction solar cells and at this high voltage. This paper discusses the set-up and testing results. Testing includes the inclusion of ENTECH's Stretched Lens Array hardware in a vacuum chamber to measure plume impingement effects at various positions relative to the exhaust axis of the thruster. The goal of this work was to define the most meaningful combined high voltage SLA concentrator array and Hall thruster demonstration tests relevant to solar electric propulsion, and to test SLA reliability and provide information to help advance the SLA's qualification. This is the next step under a Phase II STTR with NASA Glenn Research Center for the development of SLA hardware for SEP missions.

TESTING RATIONALE

Key issues relevant to the combined SLA and HET demonstration include planned testing for interactions between typical SLA test articles under bias potentials ranging 0V to 600V and exposure to the HET plasma effluents. Also, these tests evaluated the SLA's high array voltages application to directly drive SEP systems. The reason for this experiment can be understood by viewing the schematic of a typical SLA-SEP mission with the spacecraft in earth orbit as seen in Figure 1a. The array will point toward the sun while the spacecraft orbits the earth, and some interaction will take place between the array and the HET thruster plume, especially at the inner corners of the array as this move through the outer regions of the plume. While this SLA array technology design has high efficiency, low mass, and radiation-hardness, the SLA must also tolerate plume interactions with the thruster. The T-100 Russian HET on loan from NASA Glenn Research Center is capable of operating up to 1.3 kW. The results of dynamic testing with variable solar intensity and the full performance curve with the SunLine will be presented. The HET anode power and current plots revealed profiles similar to those previously collected of the SunLine's I-V characteristics. The testing schematic for the direct-driven HET and SLA is shown in Figure 1b.

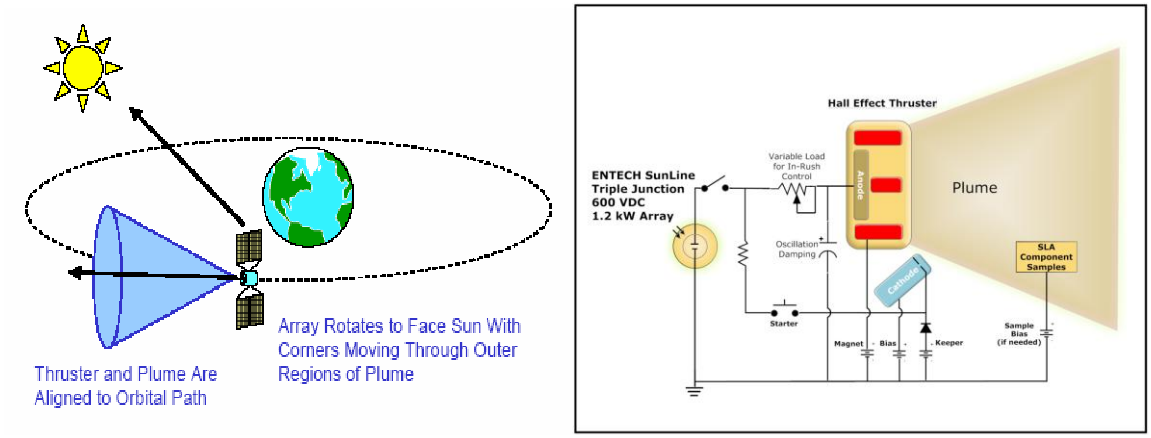

Fig. 1. (a) Typical solar electric propulsion mission (b) Schematic of planned direct-driven HET and SLA test configuration

SLA BACKGROUND

SLA is a unique ultra-high-performance, ultra-light, cost-effective photovoltaic concentrator array using refractive concentrator technology. (see Fig. 2a) 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]

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. 2b. That demonstration confirmed that the specific power goal of > 300W/kg is achievable.

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).

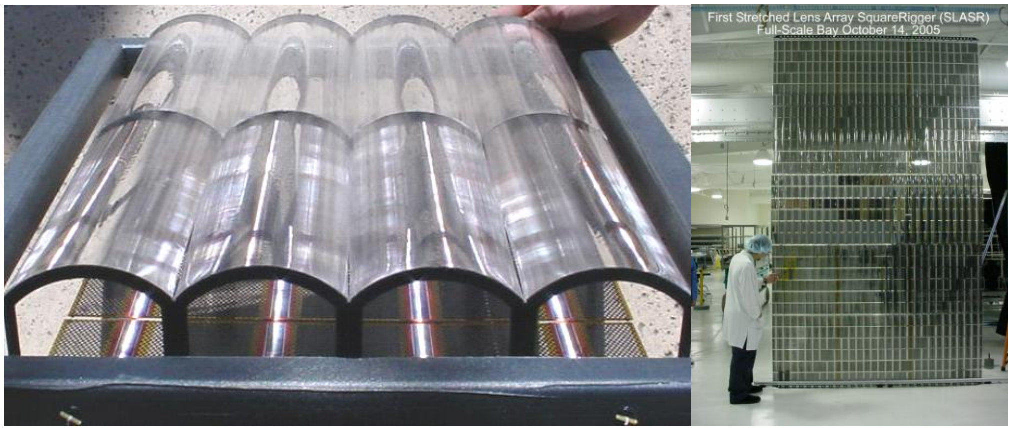

Fig. 2. (a) SLA demonstrator in sunlight (b) Full scale SLASR module

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 especially in high voltage, high radiation environments. SLA's unique attributes make it an optimal choice for SEP missions.

The Entech Solar SunLine triple-junction concentrator array, which will be used to power the thruster in this experiment, is very similar to the SLA design. Actual SLA test hardware will be used inside the vacuum chamber to test plume impingement effects at various positions relative to the exhaust axis of the thruster.

SLA HIGH VOLTAGE TESTING BACKGROUND

The SLA enables high voltage operation and sustainability in a high voltage environment which is especially dangerous for solar arrays. 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 Solar Inc. have performed testing based on guidelines for the terrestrial test from the European community, "Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges (IEC Standard 343, 1991). [2] The purpose of corona testing is to determine the lifetime of solar array designs under high voltage stress in the space environment.

This test will help prove 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. [3] 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.

Initial long-term ground tests of Stretched Lens Array photovoltaic circuit samples (see Figure 3) 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 6×10^{-5} torr. One sample underwent testing at 2,250 V for 289 days and showed no change. The SLA is also fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard.

Hypervelocity impact tests were performed on an Entech Solar, Inc. concentrator solar cell module and the silicone lens material at Auburn University demonstrating the SLA's resistance to micrometeoroid impacts and

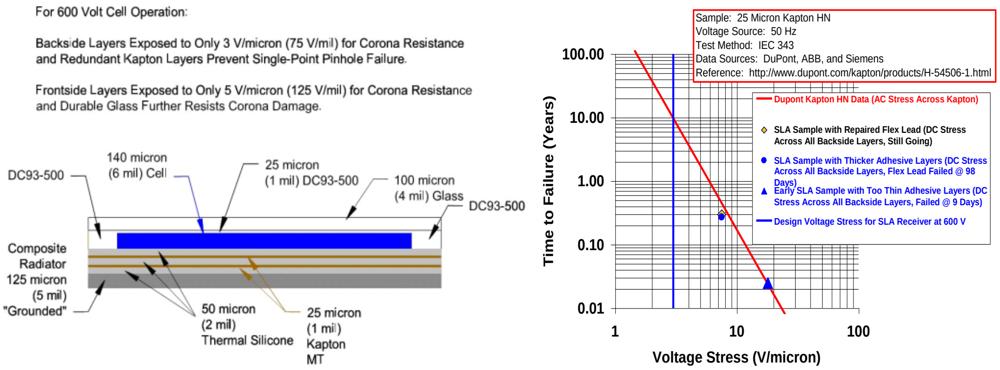

Fig. 3. (a) Test sample configuration (b) ENTECH Inc. underwater Hi-Pot testing results

electrostatic discharge even at voltages as high as 600 V. Micrometeoroid impacts on solar arrays can lead to arcing if the spacecraft is at an elevated potential. No surface arcs occurred despite 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. In addition, the SLA lens acts as a meteoroid bumper and thus provides additional protection.

CURRENT TEST SET-UP

The high-voltage solar array used for testing was transported from Entech Solar to Auburn University (Figure 4a and 4b) where it has been interfaced with the Hall-effect thruster in the large vacuum chamber (Figure 4c). The array uses two of Entech Solar's color-mixing lenses to focus sunlight onto two photovoltaic receivers each using 240 series-connected triple-junction Spectrolab cells to provide 600 Voc output at open-circuit conditions. The peak power point is around 500 V, and the total power output of the array is approximately 1.2 kW under clear sky conditions. The Russian thruster is a Model T-100 SPT, designed and constructed by the Keldysh Research Center (KeRC), and capable of operating up to 1.3 kW.[4] This thruster is on loan to Auburn from the NASA Glenn Research Center.

Auburn's Electric Propulsion (EP) test facility has a 9.2 m^3 stainless-steel vacuum chamber, 1.8 m diameter by 3.6 m length. Modifications funded previously as a NASA commercialization program center, Center for Space Exploration Power Systems (CSEPS), improved the vacuum system quality for use in electric propulsion applications. For research applications like the Hall direct-drive demonstration, the use of a cryogenic pumping capability consisting of cryopanels in the chamber interior and externally mounted cryopumps provides a low contamination environment free of oil back streaming issues problematic when using oil diffusion pumps. Cryogenic temperature sensors monitor chamber component temperatures during tests.

Fig. 4. (a),(b) Entech Solar SunLine installed at Auburn Univ. (c) T-100 Hall Thruster and cathode

TEST RESULTS

Figure 5a shows multiple views of the T-100 HET plasma discharge while under direct drive power from the Entech Solar SunLine PV array. Many other settings during several of the parameter sweeps provided additional information. Visual effects are the discharge confinement during Xe flow reduction and increase in anode fall voltage (e.g. Figure 5b), and variability thought to be related to the passing of thin, high altitude cirrus cloud lines dropping the power (Figure 5c) temporarily, then recovered. Testing, data reduction and analysis is ongoing and data charts will be presented to illustrate trends and dynamic behaviors.

Figure 5e illustrates one set of data from these SunLine-HET direct-drive runs. The HET anode power and current are plotted revealing profiles similar to those previously collected of the SunLine's I-V characteristic. The HET's nominal operational voltage is typically 300 V but by reducing the xenon flow to the anode, the anode voltage drop was increased allowing operations more closely aligned with the SunLine's maximum power point. The HET's magnetic coil was adjusted for minimum anode current.

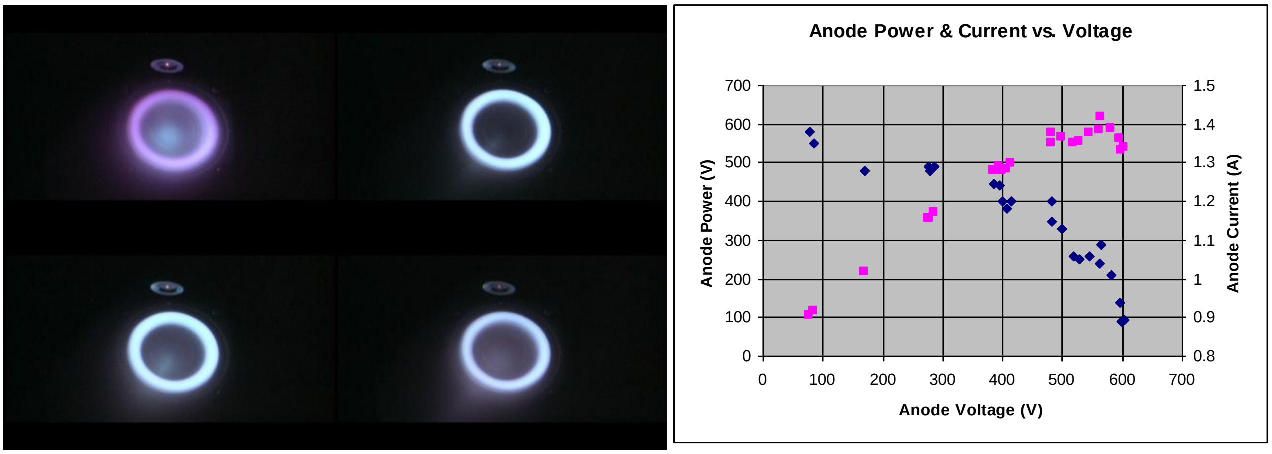

Fig. 5. HET under direct-drive by SunLine PV array; (a) Magnet coil current 5 A, (b) Xe flow rate reduction increasing anode fall voltage, 369W, 286V,1.29A, Xe @17 sccm, Coil 5 A, (c) effect of thin, high-altitude cirrus clouds slightly obscuring sunlight, 218W, 170V,1.28A, Xe @17 sccm, Coil 5 A, (d) 478W, 384V,1.246A, Xe @12.2 sccm, Coil 5 A. (e) SunLine direct-drive of T-100 HET

For the portion of tests relating to the exposure of the SLA sample modules, especially the lens, to the HET's ion plume impingement, the SLA sample modules were installed in close proximity of the HET thruster exhaust, as shown in Fig. 6. The SLA test modules were located approximately 50 degrees from the thruster's exhaust axis, and approximately 1 meter away. Here tests have been run to compare the ion plume's outer flux erosion effects on first, an uncoated-lens version of the SLA assembly. Tests are currently underway with a coated-lens version of the SLA assembly. Results are pending conclusion of tests and review.

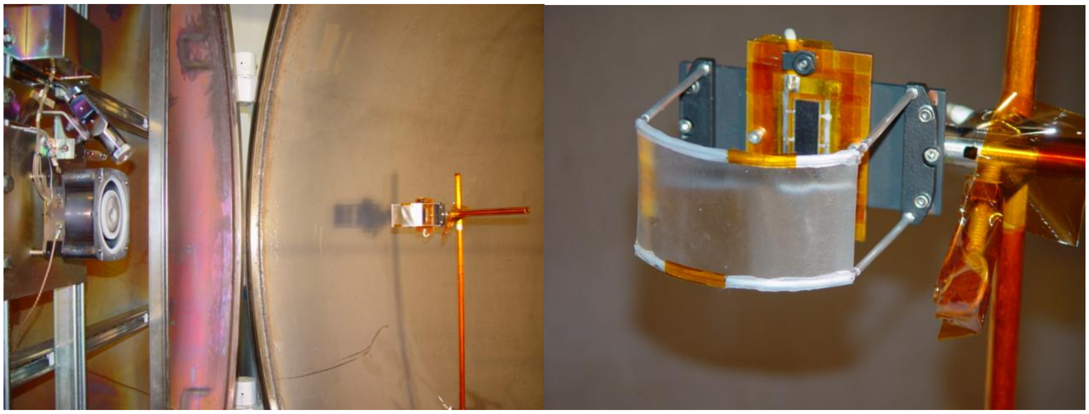

Fig. 6. (a) SLA test article in vacuum chamber with Hall thruster (b) SLA sample module in chamber

CONCLUSION

This may well be the first time a Hall thruster has been run directly from III-V-based multi-junction solar cells and at this high voltage. The T-100 HET operated very stably throughout the variations of anode voltage, current, and Xe flow rate even with variable solar conditions including thin clouds passage. This test demonstrates a level of compatibility of Hall thrusters powered under direct-drive from a high voltage array. Furthermore, the 'squareness' of the PV I-V curve did not seem to cause any major operational problems. There is a need to re-tune the magnet current and adjust Xe flow rate for most efficient operation. The III-V multi-junction SunLine concentrator array was very compatible with the T-100 HET operation. SLA sample exposure effects to ion plume impingement are ongoing and will be reported later.

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