STRETCHED LENS ARRAY SQUARERIGGER (SLASR) TECHNOLOGY MATURATION

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ABSTRACT

Since April 2005, our team has been underway on a competitively awarded program sponsored by NASA's Exploration Systems Mission Directorate to develop, refine, and mature the unique solar array technology known as Stretched Lens Array SquareRigger (SLASR). SLASR offers an unprecedented portfolio of performance metrics, including the following:

- Areal Power Density = 300 W/m^2 (2005) - 400 W/m^2 (2008 Target)
- Specific Power = 300 W/kg (2005) - 500 W/kg (2008 Target) for a Full 100 kW Solar Array
- Stowed Power = 80 kW/m^3 (2005) - 120 kW/m^3 (2008 Target) for a Full 100 kW Solar Array
- Scalable Array Capacity = 100's of W's to 100's of kW's
- Super-Insulated Small Cell Circuit = High-Voltage (300-600 V) Operation at Low Mass Penalty
- Super-Shielded Small Cell Circuit = Excellent Radiation Hardness at Low Mass Penalty
- 85% Cell Area Savings = 75% Lower Array Cost per Watt than One-Sun Array
- Modular, Scalable, & Mass-Producible at MW's per Year Using Existing Processes and Capacities

Our team is currently developing improved components for SLASR, including the following:

- Mission-Tailorable-Thickness (0.2-10.0 microns) Protective Coating for the Silicone Stretched Lens
- Integral-Diode High-Efficiency Multi-Junction Photovoltaic Cell (Optimized for 8 Suns Irradiance)
- Fully Encapsulated High-Voltage (300-600 V) Cell Circuit (Photovoltaic Receiver)
- Thinner, Lighter Radiator for Waste Heat Rejection

Our team is also re-optimizing the SquareRigger platform, which was originally developed by ATK Space for thin-film solar cell deployment and support, to improve its compatibility with the stretched lens array concentrator blankets. In coming months, our team will also be performing space environmental effects testing of the new components for SLASR, and designing half-scale SLASR wing hardware, and full-scale bay hardware, for fabrication and testing in later phases of the multi-year program. At the

conclusion of the program, SLASR technology will be at NASA Technology Readiness Level (TRL) 6 by 2008.

In the following paragraphs, the heritage of SLASR technology is summarized, the latest SLASR technology is described, the benefits of SLASR to space exploration are presented, and all of the development activities mentioned above are discussed.

INTRODUCTION AND BACKGROUND

Since 1986, ENTECH and NASA have been developing and refining space photovoltaic arrays using refractive concentrator technology [1]. 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 greater slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators [2].

In the early 1990's, the first refractive concentrator array was developed and flown on the PASP Plus flight test, which included a number of small advanced arrays [3]. The refractive concentrator array used ENTECH mini-dome lenses over Boeing mechanically stacked multi-junction (MJ) cells (GaAs over GaSb). The mini-dome lenses were made by ENTECH from space-qualified silicone (DC 93-500), and coated by Boeing and OCLI to provide protection against space ultraviolet (UV) radiation and atomic oxygen (AO). Fig. 1 shows the mini-dome lens array which flew on PASP Plus.

This array performed extremely well throughout the year-long mission in a high-radiation, 70-degree inclination, 363 km by 2,550 km elliptical orbit, validating both the high performance and radiation hardness of the refractive concentrator approach [3]. Indeed, the mini-dome lens array provided the highest performance and the lowest degradation of all 12 advanced arrays on the PASP Plus flight test [3]. In addition, in high-voltage space plasma interaction experiments, the refractive concentrator array was able to withstand cell voltage excursions to 500 V relative to the plasma with minimal environmental interaction [3].

In the middle 1990's, ENTECH and NASA developed a new line-focus Fresnel lens concentrator, which is easier to make and more cost-effective than the mini-dome lens concentrator. Using a continuous roll-to-roll process, 3M can now rapidly mass-produce the line-focus silicone lens material in any desired quantity.

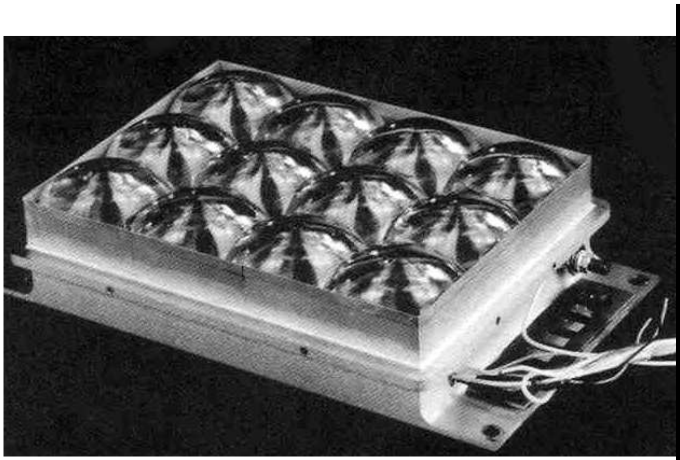
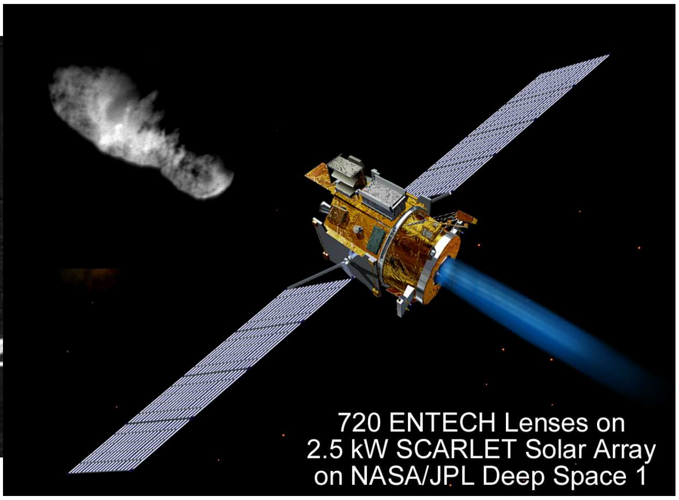


Fig. 1. Mini-Dome Lens Array for the PASP Plus Flight Test (1994-1995).



720 ENTECH Lenses on
2.5 kW SCARLET Solar Array
on NASA/JPL Deep Space 1

Fig. 2. SCARLET Array on NASA/JPL Deep Space 1 Probe (1998-2001).

In 1994, ABLE Engineering (now ATK Space) joined the refractive concentrator team and led the development of the SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array [4]. SCARLET used a small (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiatively cooled triple-junction cells. Launched in October 1998, a 2.5 kW SCARLET array powered both the spacecraft and the ion engine on the NASA/JPL Deep Space 1 probe, shown in Fig. 2.

SCARLET achieved over 200 W/m^2 areal power density and over 45 W/kg specific power, the best performance metrics up to that time [5]. The SCARLET array was the first solar array to fly using triple junction solar cells as the principal power source for a spacecraft. With SCARLET working flawlessly, Deep Space 1 had a spectacularly successful rendezvous with the comet, Borrelly, in September 2001, capturing the highest-resolution images of a comet to that date and other unprecedented comet data.

At the end of the 38-month extended mission, in December 2001, SCARLET's power was still within + 2% of predictions. The SCARLET array won the Schreiber-Spence Technology Achievement Award in 1999 and the NASA Turning Goals into Reality (TGIR) Award in 2001.

Over the past four years, the team, now including Auburn University, EMCORE, Ion Beam Optics, and Texas A&M University, has developed an ultra-light version of the flight-proven SCARLET array, called the Stretched Lens Array (SLA), with much better performance metrics, as described in the following paragraphs [6].

STRETCHED LENS ARRAY (SLA)

The Stretched Lens Array (SLA) is an evolved version of SCARLET, retaining the essential power-generating elements (the silicone Fresnel lens, the multi-junction solar cells, and the composite radiator sheet) while discarding many of the non-power-generating elements (the lens glass arch superstrates, the lens support frames, the photovoltaic receiver support bars, and most of the honeycomb and back face sheet material in the panels). Fig. 3 shows the near-term, low-risk, rigid-panel version of SLA.

The defining feature of SLA that enables the elimination of so many elements of the SCARLET array is the stretched lens optical concentrator (Fig. 4). By using pop-up arches to stretch the silicone Fresnel lens in the lengthwise direction only, these lenses become self-supporting stressed membranes.

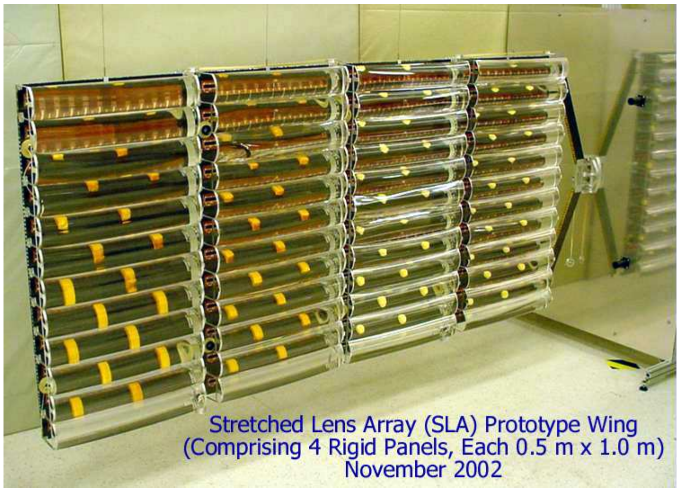


Fig. 3. Rigid-Panel Stretched Lens Array (SLA) Prototype Wing.

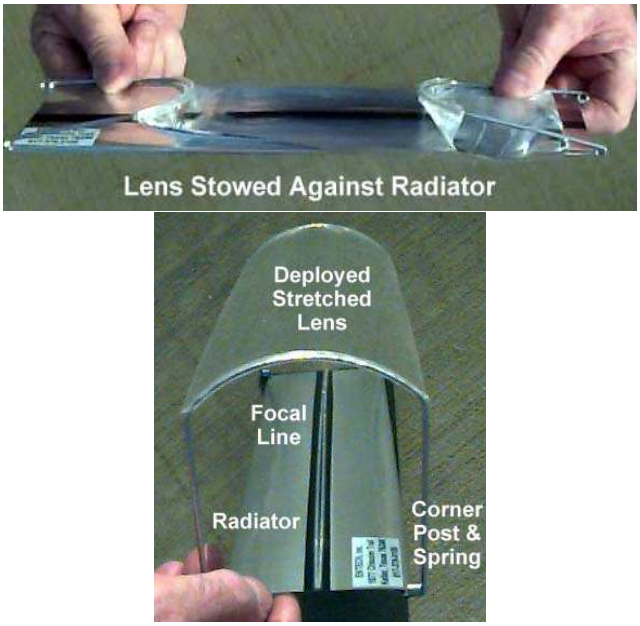


Fig. 4. Stretched Lens Approach.

SCARLET's glass arches are thus no longer needed, eliminating their complexity, fragility, expense, and mass in the new, patented SLA [7]. With this substantial lens-related mass reduction, the supporting panel structural loads are reduced, making ultra-light panels practical for SLA. This cascading mass-reducing effect of the stretched lenses continues throughout the SLA wing structure, resulting in unprecedented performance metrics.

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 per 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 (unmounted). 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.

All three refractive concentrator arrays discussed above, the mini-dome lens, SCARLET, and SLA, use Fresnel lens optical elements based on the same symmetrical refraction principle, shown schematically in Fig. 5. Solar rays intercept the smooth convex outer lens surface and are each refracted by the curved outer surface by one half the angular amount needed to focus these rays onto the solar cell. The other half of the required refraction is performed as the rays leave the inner prismatic lens surface. Thus, the solar ray incidence angle at the smooth outer surface equals the solar ray emergence angle at the prismatic inner surface for every ray, as shown in the enlarged view of the lens in Fig. 5.

This symmetrical refraction (angle in = angle out) condition minimizes reflection losses at the two lens surfaces, thereby providing maximal optical performance, while also offering unprecedented error tolerance for the mini-dome, SCARLET, and SLA lenses [2]. The mini-dome lens array uses a point-focus (3D) version of the symmetrical refraction lens, while both SCARLET and SLA use a line-focus (2D) version of the symmetrical refraction lens. The multitude of prisms in the symmetrical-refraction lens allows the individual prism angles to be tweaked to tailor the photon flux profile over the solar cell, both spatially and spectrally. For example, a patented optical innovation incorporated into the SCARLET and SLA lenses is an alternating-prism color-mixing feature that is critical to the optimal performance of monolithic multi-junction cells placed in the focus of such lenses [8].

Built and successfully tested in 2002, the rigid-panel SLA prototype wing in Fig. 3 included several complete photovoltaic receivers, each 0.5 m long and containing 14 series-connected triple-junction solar cells. The solar-to-electric conversion efficiency of each lens/receiver assembly was measured in a state-of-the-art solar simulator, using NASA Lear-Jet-flown reference cells for calibration. The net aperture area efficiency of the best lens/receiver assembly was 27.5% under simulated space sunlight (AM0 spectrum) at 28C cell temperature [9]. This net efficiency corresponds to 31% cell efficiency times 90% lens optical efficiency, and also matches separate NASA Lear Jet measurements on lens/cell units.

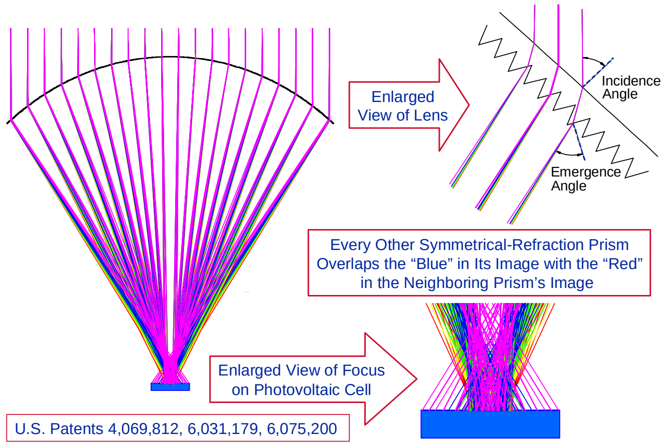


Fig 5. Symmetrical-Refraction Color-Mixing Fresnel Lens.

On geostationary earth orbit (GEO), the operating cell temperature for SLA cells of this efficiency will be about 80C, resulting in a cell efficiency reduction factor of 87%. Combining this factor with the geometrical packing loss factor (95%), the net SLA efficiency at operating temperature on GEO at beginning of life (BOL) will be about 23%, corresponding to a wing-level areal power density well above 300 W/m^2. At a 7 kW wing size, which is typical of current GEO communication satellites, the corresponding specific power is over 180 W/kg (BOL) at operating temperature.

In addition, the well insulated photovoltaic receivers in the prototype SLA wing of Fig. 3 were wet hi-pot tested for possible leakage current with a 500 V potential applied between the cell circuits and the panel, and the measured leakage current was less than 1 micro-Amp for each receiver [9]. SLA's high-voltage capability is facilitated by the small size of the photovoltaic cells, which allows super-encapsulation of the cell circuits at low mass penalty.

In addition to the near-term, low-risk rigid-panel version of SLA, an advanced version of SLA is also under development. The advanced version is a flexible-blanket SLA, similar to the small prototype array shown in Fig. 6.

For this SLA version, the lenses form one flexible blanket while the radiator elements, containing the photovoltaic receivers, form a second flexible blanket. Both blankets fold up into a very compact stow volume for launch, and automatically deploy on orbit. One of the most efficient platforms for deploying and supporting the flexible-blanket version of SLA is the SquareRigger platform, developed by ABLE Engineering (now ATK Space) [10], as further discussed in the following paragraphs.

STRETCHED LENS ARRAY SQUARERIGGER (SLASR)

The SquareRigger platform was originally developed by ABLE Engineering (now ATK Space) under funding from the Air Force Research Laboratory for use with thin-film photovoltaic blankets in space. However, with the much higher efficiencies achievable with SLA compared to thin-film photovoltaics, the marriage of SLA and SquareRigger provides unprecedented performance metrics, summarized in Table 1 [11].

Initial development of the SLA SquareRigger (SLASR) technology, including a small prototype demonstrator (Fig. 7), has recently been completed by ABLE Engineering (ATK Space), with ENTECH subcontract support [10]. Currently, additional development, including much larger scale hardware development, is being done. All of this development work is directed toward the SLASR array

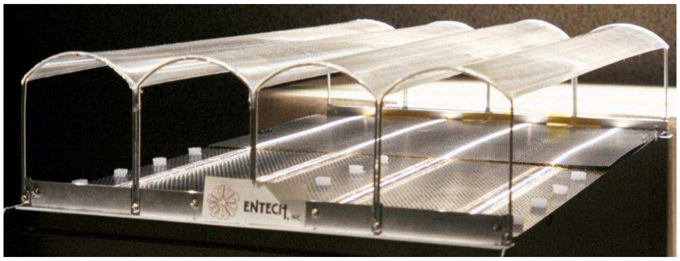


Fig. 6. Flexible-Blanket Stretched Lens Array (SLA) Prototype.

Time Frame	< 5 Years	5-10 Years
Power Capability (kW)	100	1,000
BOL Specific Power (W/kg)	330	500
Stowed Power (kW/m^3)	80	120
Voltage	1,000	TBD

Table 1. Estimated Performance Attributes of SLA on ABLE's (ATK Space's) SquareRigger Platform.

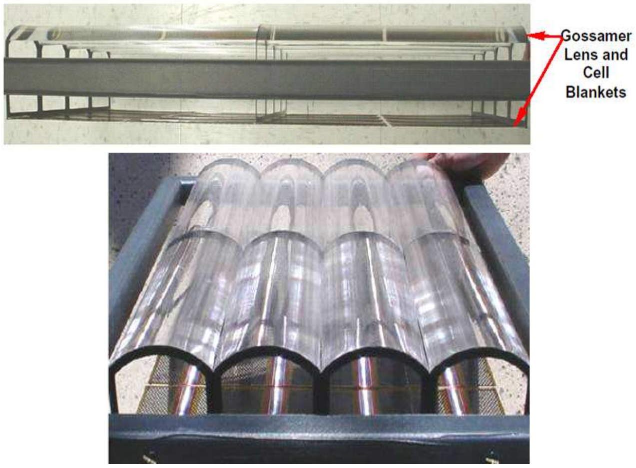


Fig. 7. SLA SquareRigger Prototype Demonstrator.

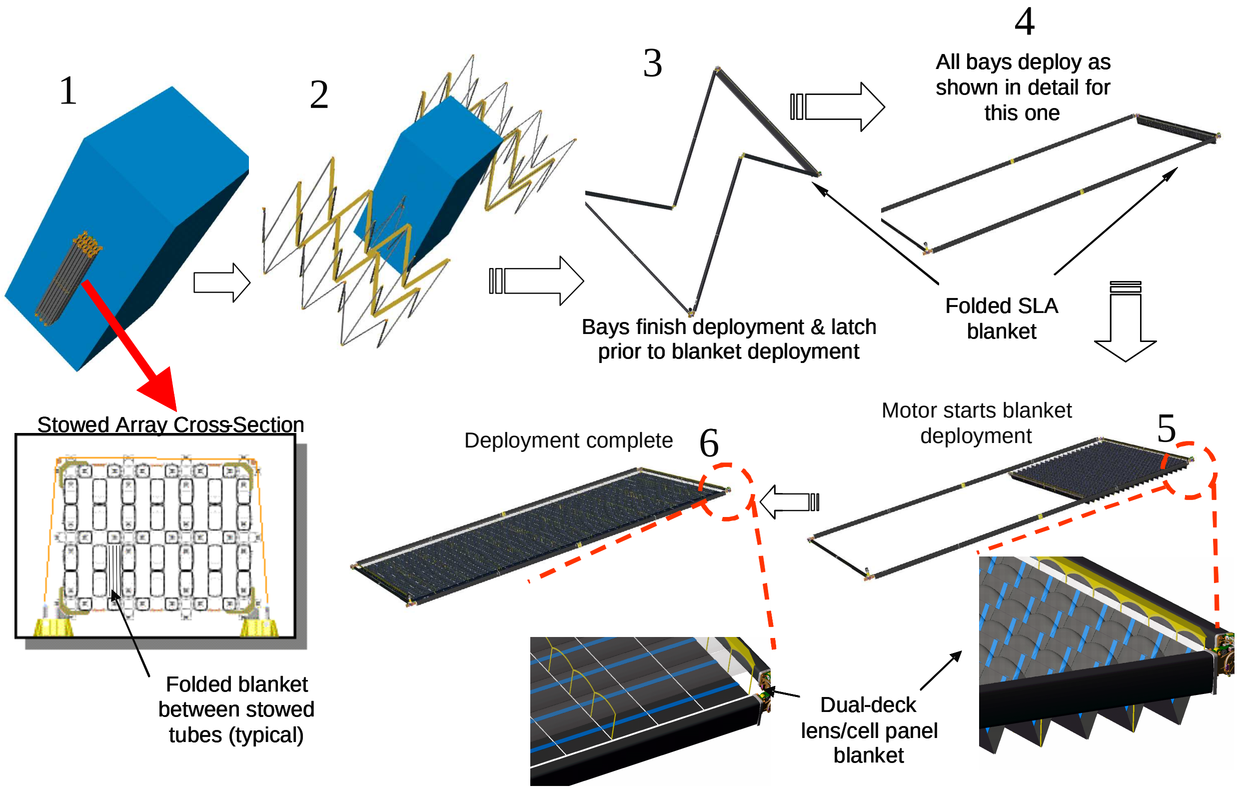


Fig. 8. Stretched Lens Array SquareRigger (SLASR) Schematic.

approach shown schematically in Fig. 8. Analysis of this type of SLASR system led to the near-term and mid-term performance metric estimates of Table 1. Note that SLASR enables giant space solar arrays in the 100 kW to 1 MW class, with spectacular performance metrics (300 to 500 W/kg specific power, 80 to 120 kW/m^3 stowed power, and operational voltages above 1,000 V) in the near-term (2010) to mid-term (2015).

In the longer term (2020-2025), with constantly improving solar cell efficiencies and incorporation of new nanotechnology materials into the lens and radiator elements, SLA's technology roadmap leads to 1,000 W/kg solar arrays, as shown in Fig. 9 [12]. Indeed, SLA is unique among all solar array technologies in its portfolio of attributes, which include world-record-level solar-to-electric conversion efficiency (high W/m^2), ultra-light mass density (low kg/m^2), spectacular stowed power density (kW/m^3), highly scalable power (kW to multi-MW), high-voltage capability (kV), modularity (individual lens/cell building blocks), mass-producibility, and cost effectiveness [13]. SLA's unique portfolio of attributes matches the critical requirements for space power systems for many planned NASA Exploration missions, as discussed in the following paragraphs.

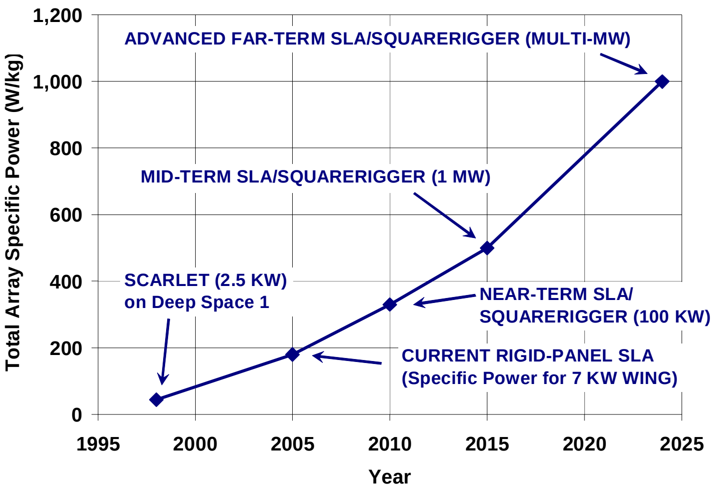


Fig. 9. Long-Term Technology Roadmap for the Stretched Lens Array (SLA).

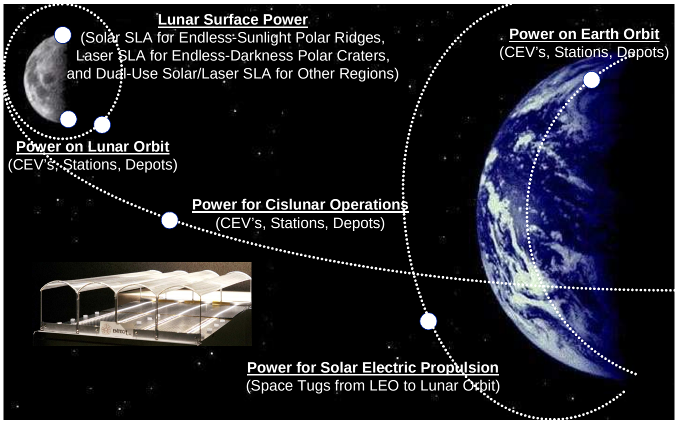
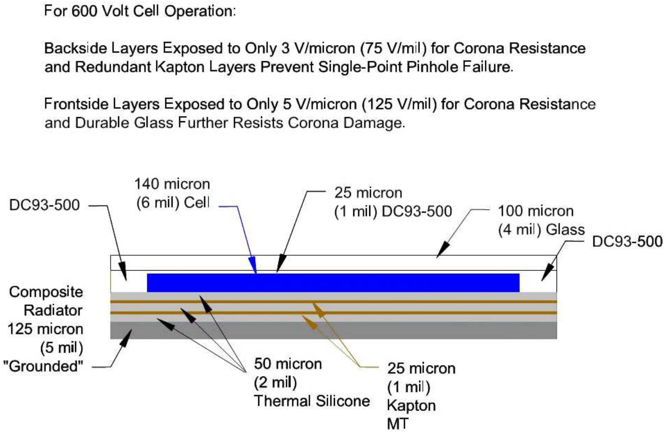


Fig. 10. Near-Term SLASR Applications for Space Exploration in the Earth-Moon Neighborhood.


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.

Fig. 11. Fully Encapsulated 600 Volt SLASR Receiver.

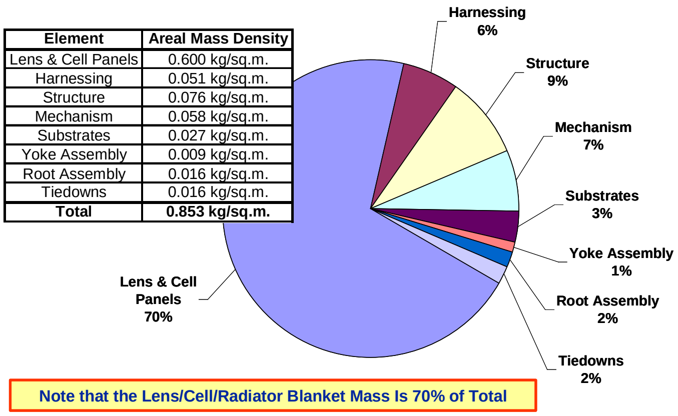
SLASR FOR EXPLORATION MISSIONS

Electrical power is a critical need for all space exploration missions, and the SLASR's unique portfolio of attributes enables it to meet the needs of many exploration missions. Fig. 10 shows some of SLASR's applications to near-term space exploration missions in the Earth-Moon neighborhood. These include power on Earth orbit to support NASA's planned Crew Exploration Vehicle (CEV), and earth-orbiting depots and stations. SLASR applications also include power for cislunar operations and for solar electric propulsion (SEP) space tugs to deliver cargo from low Earth orbit (LEO) to the low lunar orbit (LLO) in support of robotic and human exploration missions to the Moon. SLASR applications at the Moon include power for orbiting spacecraft and surface power.

One important class of missions mentioned above relates to SLASR-powered SEP tugs. These tugs are envisioned as reusable cargo carriers from low earth orbit to lunar orbit, transporting materials needed for sustained exploration of the Moon. The most efficient and lowest mass approach to SEP tugs involves the direct-driving of electric thrusters by high-voltage solar arrays, operating around 600 V.

To operate reliably for many years at high voltage, the photovoltaic cell circuit must be extremely well insulated, to prevent electrical interaction with the space plasma or with the "grounded" solar array structures. Figure 11 shows a fully encapsulated photovoltaic receiver for a 600 V version of SLASR for such an SEP mission [14]. The multi-junction cell uses an integral bypass diode and end tabs to enable this compact configuration. The voltage gradients through the insulating layers above (5 V/micron) and below (3 V/micron) the cell circuit were selected to ensure reliable long-term high-voltage endurance of the insulating layers. The cover glass thickness above the cell can be increased for additional radiation shielding if needed for the specific mission, with trade studies required to determine the optimal cover thickness.

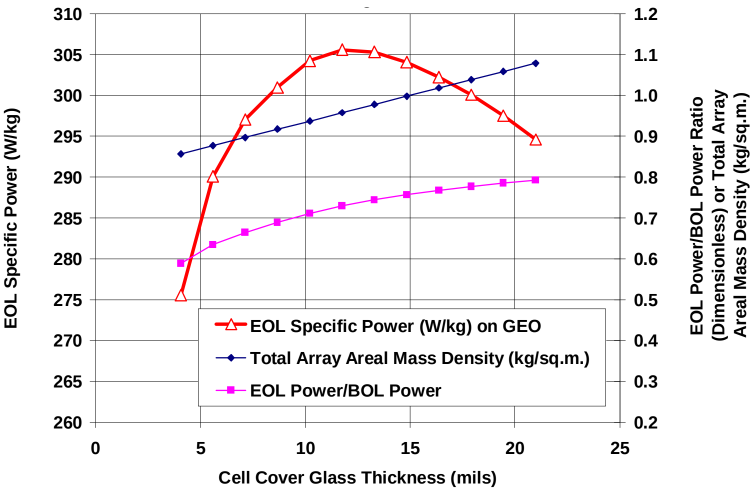
For the baseline receiver design shown in Fig. 11, the total Stretched Lens Array SquareRigger (SLASR) array mass breakdown for a 100 kW array is summarized in Fig. 12 [10]. Note that the total areal mass density for the full SLASR array



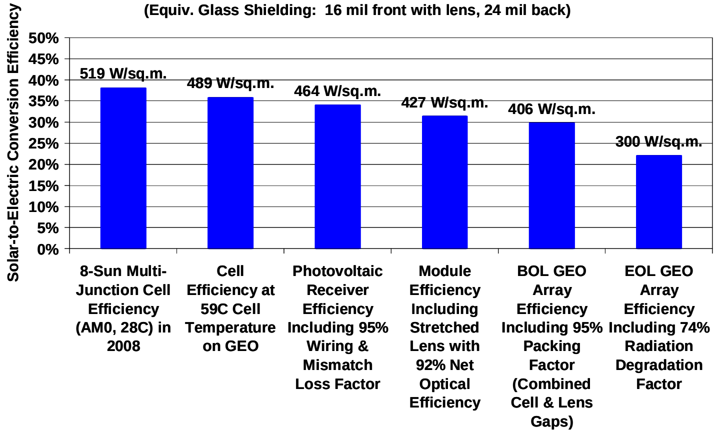
Element	Areal Mass Density
Lens & Cell Panels	0.600 kg/sq.m.
Harnessing	0.051 kg/sq.m.
Structure	0.076 kg/sq.m.
Mechanism	0.058 kg/sq.m.
Substrates	0.027 kg/sq.m.
Yoke Assembly	0.009 kg/sq.m.
Root Assembly	0.016 kg/sq.m.
Tiedowns	0.016 kg/sq.m.
Total	**0.853 kg/sq.m.**

Fig. 12. Mass Breakdown for 100 kW Stretched Lens Array SquareRigger (SLASR) System.

is only 0.85 kg/m^2, with 70% of this mass in the lens and cell/radiator blanket elements. This mass breakdown is for a SLASR optimized for a typical geostationary orbit (GEO) mission. For a higher radiation mission, more shielding of the solar cell will generally be needed, as discussed below.



SLA on GEO with 2008 Cell Technology and 2008 Mass Breakdown
Optimal EOL Specific Power Occurs with 13 mil Cover Glass
(Equiv. Glass Shielding: 16 mil front with lens, 24 mil back)



SLASR Wing-Level Areal Mass Density = 0.98 kg/sq.m.
SLASR EOL Specific Power = 300 W/sq.m./0.98 kg/sq.m. = 305 W/kg

Fig. 13. Results of SEP Mission Study for Space Tug with 5 Annual Trips from Low Earth Orbit to Lunar Orbit.

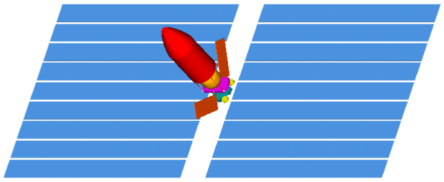
A number of recent trade studies have been performed related to reusable SEP lunar tugs using SLASR to power the Hall-Effect thrusters which propel the tug. One typical mission is discussed in the following paragraphs. This mission involves five annual round trips from LEO to LLO, with each trip comprising a slow series of spirals through the Earth's radiation belts at an inclination angle of 28 degrees. The complete mission radiation environment for the solar array is calculated using the European Space Agency's excellent online tool known as the Space Environment Information System, or by the acronym, SPENVIS, at www.spenvis.oma.be. This tool is used to integrate the effects of all the electron and proton exposures over all portions of all the outbound and inbound trajectories. This radiation environment is then used in a cell shielding optimization, with key SLASR results shown in Fig. 13.

This SLASR-powered SEP tug mission study is further described in later paragraphs, and assumed a 2008 technology freeze. In 2008, the expected one-sun solar cell efficiency is 34%, which equates to an 8-sun solar cell efficiency of 38%, based on the measured performance gain with concentration for SLA cells from both Spectrolab and EMCORE, the two leading suppliers of multi-junction solar cells. The key parameter plotted in the upper graph of Fig. 13 is the end-of-life (EOL) specific power, after radiation degradation of the solar cells due to the 10 slow spiraling transits of the earth's radiation belts (five outbound trips with cargo and five return trips without cargo). The peak point of the SLA curve (about 305 W/kg) corresponds to the optimal amount of cell radiation shielding (about a 13 mil cover glass). More shielding adds to array mass (linear curve) more quickly than it reduces array power degradation (bottom curve), resulting in a falloff in EOL specific power (curve with peak). The cell degradation curve (bottom curve) in Fig. 13 includes the effects of backside radiation, which are mitigated by the shielding of the radiator, dielectric layers, and Ge wafer behind the triple-junction solar cell layers.

A "waterfall diagram" of SLASR performance for this SEP tug mission is shown at the bottom of Fig. 13, beginning with a 38% BOL cell efficiency (equivalent to 519 W/m^2 of areal power density) and going down to a 22% EOL array-level efficiency (equivalent to 300 W/m^2 of areal power density), after all loss mechanisms are treated. While not included in Fig. 13, similar optimization analyses for the same SEP tug mission have been performed for one-sun planar arrays (using either high-efficiency triple-junction cells or lower efficiency thin-film cells). When the same electrical insulation approach and the same array support platform approach are used for the planar arrays as for SLASR, SLASR consistently offers an advantage over the planar arrays of more than 3X in end-of-life specific power. Furthermore, SLA offers substantial advantages in cost effectiveness, due to its use of much less expensive solar cell material than the planar arrays.

The key assumptions and key system-level results for this SLASR-powered SEP tug mission are shown in Fig. 14. A 600 kW class SLASR-powered tug was analyzed for this mission involving five round trips from low earth orbit (LEO) to low lunar orbit (LLO), with one round trip being made each year. For each trip, 22 metric tons (MT) of cargo was delivered to the lunar surface, as shown in Fig. 14. Chemical thrusters were assumed for delivering the cargo from LLO to the lunar surface, and the mass of the required chemical fuel was included in the analysis.

- **SLASR-Powered SEP Tug**
    - **Nominal 600 kW SLASR Array (Approx. 2,000 sq.m. Total)**
    - **Aerojet Hall-Effect Thrusters**
    - **600 Volt Direct Drive System**
    - **22 MT to Lunar Surface Each Trip**
    - **1 Year Max Round-Trip Time**
    - **Reusable Tug (5 Round Trips)**



- **Reusable Lunar SEP Tug Mission**
    - **Five Round-Trips (One per Year) from LEO (400 km) to LLO, with On-Board Chemically Fueled Lander Delivering Cargo to Lunar Surface**
    - **First LEO Launch Contains Tug, Xenon, Lander with Chemical Fuel, and Cargo**
    - **Subsequent LEO Launches Provide New Xenon, Lander with Fuel, and Cargo, Which Dock with Tug in LEO for Next Trip**
    - **28 Degree Inclination Near Earth with Plane Changes Near Moon**

Conventional Chemical Cargo Transport		Reusable SLA-Powered SEP Cargo Transport	
Item	**Mass**	**Item**	**Mass**
LEO-to-LLO Vehicle (Expendable)	10 MT	LEO-to-LLO Vehicle (Reusable)	10 MT
Cargo (Including Lander)	22 MT	Cargo (Including Lander)	22 MT
LLO-to-Lunar Surface Fuel	15 MT	LLO-to-Lunar Surface Fuel	15 MT
LEO-to-LLO Fuel	80 MT	LEO-to-LLO Propellant (Xenon)	23 MT
Total Launch Mass	127 MT	Total Launch Mass (First Launch w/Vehicle)	70 MT
		Total Launch Mass (Subsequent Launches)	60 MT
Total LEO Launch Mass for Five Deliveries Over Five Years (110 MT Total Cargo)	635 MT	Total LEO Launch Mass for Five Deliveries Over Five Years (110 MT Total Cargo)	310 MT
Launch Costs Using Shuttle-Derived Heavy ($10 M/MT from ATK: safesimplesoon.com)	**$6,350 Million**	Launch Costs Using Shuttle-Derived Heavy ($10 M/MT from ATK: safesimplesoon.com)	**$3,100 Million**

- **SEP Offers Over $3 Billion in Savings Just in Launch Costs per Tug**
- **SEP Offers Additional Savings of 4 Fewer LEO-to-LLO Vehicles**
- **More than 5 Round-Trips May Be Practical for SEP Tug (More Savings)**
- **For 70-MT-Class Shuttle-Derived Launch Vehicles, SEP Approach Will Require Half as Many Launches as Chemical Approach, and, as ATK Accurately States, "Fewer Launches + Fewer Payloads + Fewer In-Space Assemblies = Higher Mission Reliability"**

Fig. 14. Exploration Mission Study of a SLASR-Powered SEP Lunar Cargo Tug, Making 5 Annual Round Trips from Low Earth Orbit to Lunar Orbit, Providing Billions of Dollars in Launch Cost Savings Compared to Chemical Propulsion.

A comparison was made between the SLASR-powered SEP cargo delivery versus conventional chemical propulsion cargo delivery, and the results are summarized in Fig. 14. Note that the SLASR-powered SEP tug offers a savings of more than 300 MT for initial mass delivered to LEO, which corresponds to about $3 Billion in launch cost savings alone. Additional savings are offered by the need for fewer space vehicles. Higher mission reliability is also offered by reducing the number of needed launches substantially.

SLASR offers similar substantial advantages for a variety of other space exploration missions, including those shown in Fig. 10 for near-term lunar robotic and human exploration missions. SLASR's advantages for space exploration missions include a set of unprecedented performance metrics and features:

- Areal Power Density = 300-400 W/m^2
- Specific Power = 300-500 W/kg for Full 100 kW Solar Array
- Stowed Power = 80-120 kW/m^3 for 100 kW Solar Array
- Scalable Array Capacity = 100's of W's to 100's of kW's
- Super-Insulated Small Cell Circuit = High-Voltage Operation
- Super-Shielded Small Cell Circuit = Radiation Hardness
- 85% Cell Area Savings = 75% Lower Array Cost per Watt
- Modular, Scalable, & Mass-Producible at MW's per Year Using Existing Processes and Capabilities

With this unique portfolio of attributes, SLASR will be able to contribute not only to the exploration missions in the Earth-Moon neighborhood shown in Fig. 10, but also to later exploration missions to Mars, other planets, and asteroids in the solar system.

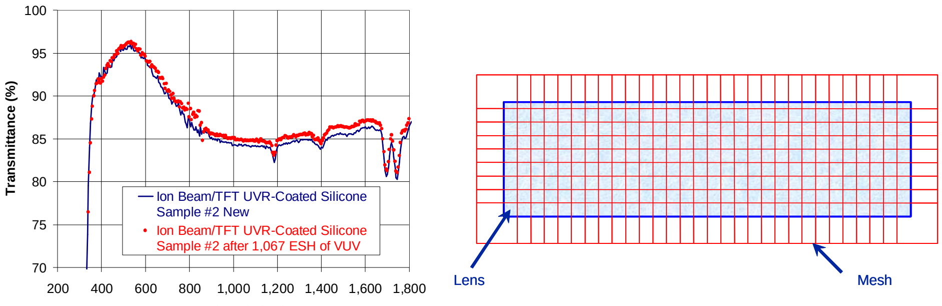
SLASR TECHNOLOGY MATURATION

SLASR technology maturation work is currently proceeding well under the NASA Exploration Systems Research & Technology (ESR&T) program. This work includes the development of several improved key components of SLASR:

- Mission-Tailorable-Thickness (0.2-5.0 microns) Protective Coating for the Silicone Stretched Lens
- Integral-Diode High-Efficiency Multi-Junction Photovoltaic Cell (Optimized for 8 Suns Irradiance)
- Fully Encapsulated High-Voltage (300-600 V) Cell Circuit (Photovoltaic Receiver)
- Thinner, Lighter Radiator for Waste Heat Rejection

The new lens coating work is based on the latest protective coating from SLASR team member, Ion Beam Optics, which very effectively blocks vacuum ultraviolet (VUV) wavelengths in space sunlight from reaching and possibly damaging the silicone lens material beneath the coating. The graph in Fig. 15 shows the spectral transmittance of a coated silicone samples before and after more than 1,000 equivalent sun hours (ESH) of space sunlight VUV exposure by SLASR team member, NASA Marshall. This thin lens coating will provide adequate lens protection for many missions (e.g., LEO, GEO, or Deep Space). For very high radiation missions (e.g., belt flyers or space tugs flying between LEO and lunar orbit), a thicker coating would be desirable to reduce the charged particle radiation dose reaching the silicone. Dose-depth profile calculations show that a coating thickness up to 5 microns could be desirable for such missions. Such a thick coating will be relatively rigid, making it seem to be incompatible with the stretched lens approach. However, by using a parquet approach to the coating application, the thick coating can be separated into small regions, allowing the lens as a whole to remain flexible enough to stow and deploy as a stretched lens, as shown by the model in Fig. 15.

The new process being developed under the present technology maturation program uses a mesh screen during coating application to provide the patterned parquet geometry, as also shown in Fig. 15. Results to date indicate that this approach will indeed be practical for the SLASR lenses.



Latest Ion Beam Optics Thin Lens Coating Blocks UV Very Well

For High-Radiation Missions, a Thick (1-5 Microns) Parquet Coating Should Offer Additional Lens Radiation Hardness While Maintaining Lens Flexibility

To Prove the Concept, ENTECH Built This Model Last Year Using a SCARLET Lens “Coated” with a 75-Micron-Thick Glass Arch, Broken into Small Pieces to Simulate the Parquet

Fig. 15. Mission-Tailorable Thick Parquet Lens Coating for High-Radiation Missions.

Under previous Stretched Lens Array (SLA) development programs, the photovoltaic receiver used discrete bypass diodes to protect the multi-junction cells from reverse-bias damage. These discrete diodes were relatively large, and were positioned alongside the solar cells, making the overall circuit about 2.0 cm wide, although the cells were only 1.2 cm wide, including busbars. The whole photovoltaic circuit (cells and diodes) must be well insulated, both above and below the circuit, to operate reliably at high voltage in space. To reduce the mass and complexity of the SLASR photovoltaic receiver, SLASR team member, EMCORE, is developing an integral-diode concentrator cell as shown in Fig. 16. To increase reliability and to minimize diode temperature excursions under bypass operation, redundant diodes are being used on the new cell. Two end tabs will be used to connect the back of the neighboring cell to both top busbars of the SLASR concentrator cell, as well as closing the circuit between the tops of the diodes and the busbars on the SLASR concentrator cell. The total photovoltaic receiver width is about 40% narrower for this approach than for prior SLA receiver approaches, reducing mass proportionally. New cells have already started being processed by EMCORE, as shown in the photo in Fig. 16. In addition to

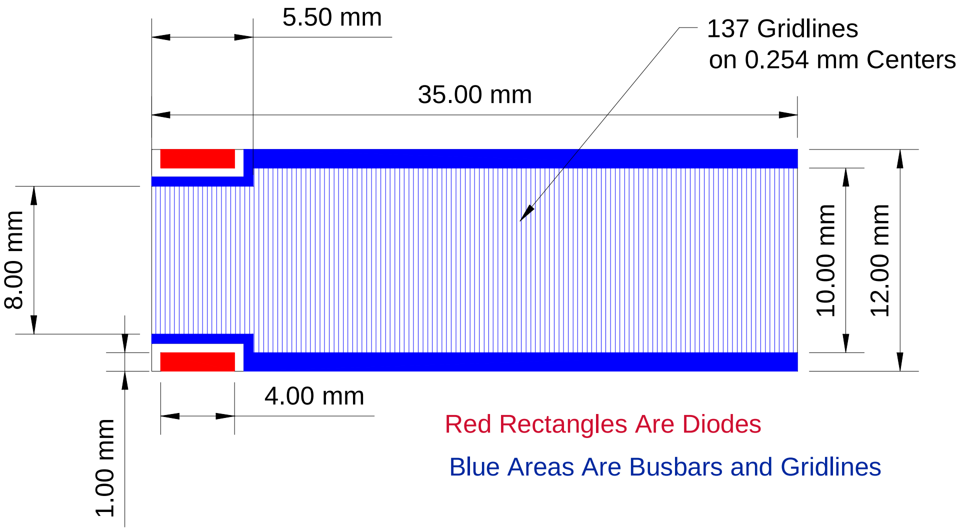


Photo of Actual EMCORE SLASR Cell

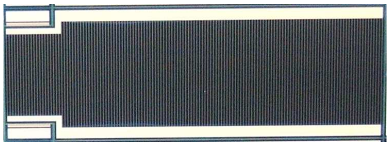
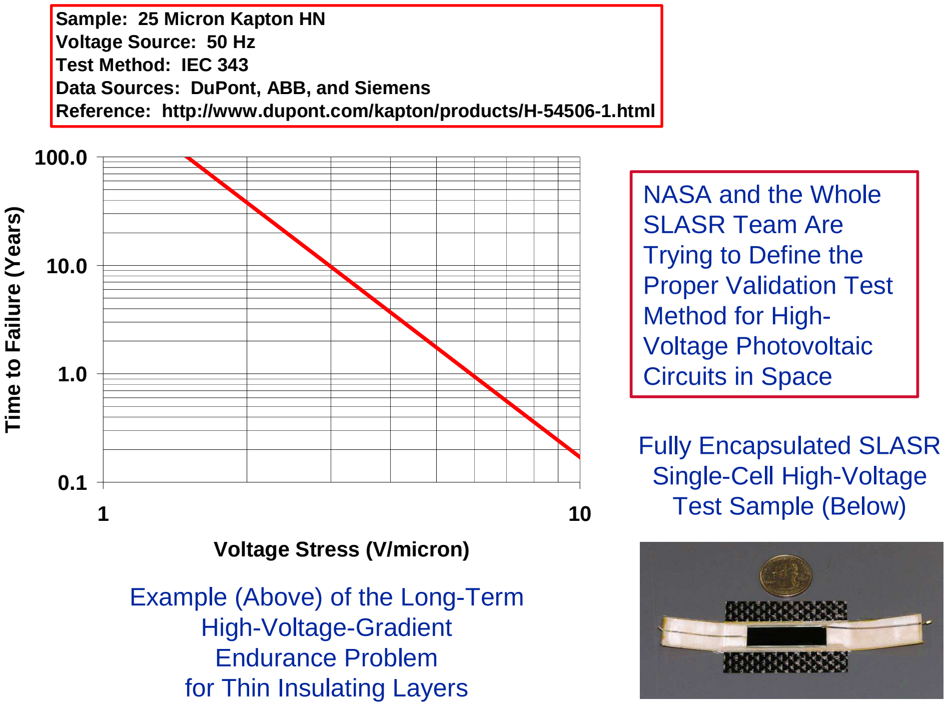


Fig. 16. Integral-Diode Concentrator Cell Development.

adding the integral diodes to the SLASR cells, higher efficiency cells will be developed over the course of the technology maturation program, with a goal of 2% absolute increase per year compared to the current 30% efficient SLASR cells.



Sample: 25 Micron Kapton HN
Voltage Source: 50 Hz
Test Method: IEC 343
Data Sources: DuPont, ABB, and Siemens
Reference: http://www.dupont.com/kapton/products/H-54506-1.html

NASA and the Whole SLASR Team Are Trying to Define the Proper Validation Test Method for High-Voltage Photovoltaic Circuits in Space

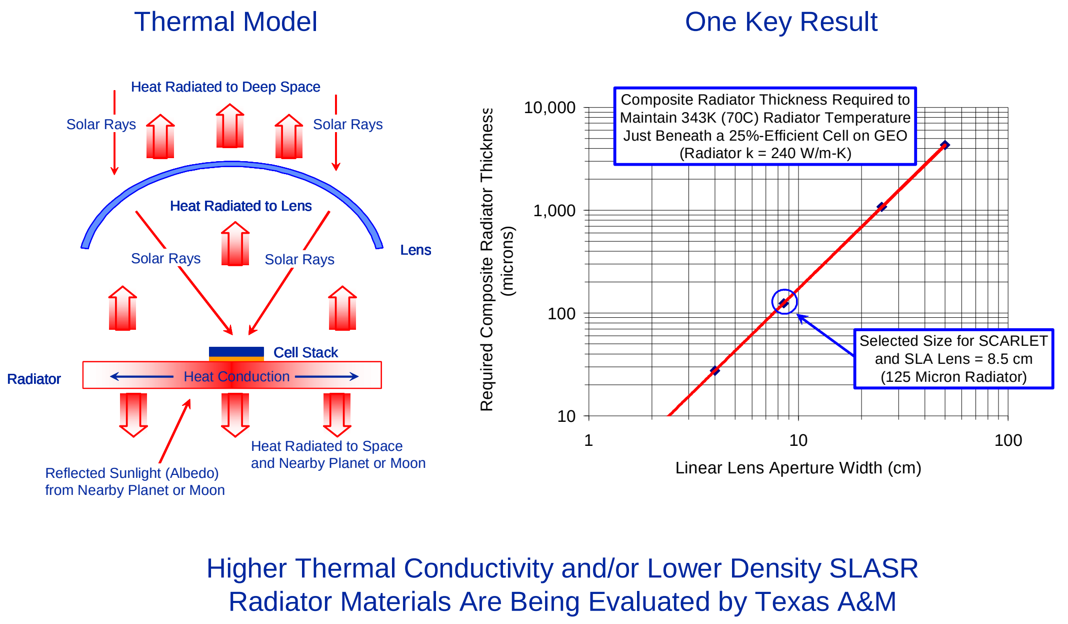
Example (Above) of the Long-Term High-Voltage-Gradient Endurance Problem for Thin Insulating Layers

Fully Encapsulated SLASR Single-Cell High-Voltage Test Sample (Below)

Fig. 17. High-Voltage Photovoltaic Receiver Development.

High-voltage photovoltaic arrays for space applications will be needed for high-power requirements, such as solar electric propulsion (SEP) space tugs or lunar surface power plants for robotic and human exploration missions. With the exception of the International Space Station (ISS) array, which operates in the 150-200 V range, space solar arrays typically operate at relatively low voltages of about 100 V or less. To move this operating voltage level to much higher values (300-600 V), additional insulation will be needed above and below the cell circuit, and new test methods will be needed to validate high-voltage designs for long-term reliable operation in space. An example of the high-voltage test problem is shown in the graph of Fig. 17. Normal DuPont Kapton is an excellent insulator, but long-term high-voltage-gradient exposure leads to failures at much lower V/micron gradients than short-term exposure, which might correspond to a validation test. SLASR team members at NASA Glenn and NASA Marshall are studying this problem to help define the appropriate validation test method to ensure reliable long-term operation at high voltage in space. ENTECH is fabricating fully encapsulated photovoltaic receiver samples to test using various approaches, as shown by the small photo in Fig. 17. For example, this sample has been successfully tested for 24 hours with 2,250 V applied to the cell circuit relative to the composite radiator in an underwater hi-pot test. The water is in intimate contact with the radiator in this test, and simulates (crudely) the space plasma which can surround a space solar array. The 2,250 V was selected based on terrestrial photovoltaic test standards, which require such tests to be performed at twice the rated voltage plus 1,000 V. Thus a 600 V application would require a 2,200 V short-term hi-pot test. For space applications, this test will clearly need to be substantially modified or replaced entirely, but it does show the potential of the fully encapsulated SLASR photovoltaic receiver approach.

Development of a thinner, lighter radiator for SLASR is also underway, led by SLASR team member, Texas A&M. Fig. 18 summarizes the SLASR radiator thermal problem. The current size of the lens aperture was dictated by the radiator thickness requirement shown in the graph. Wider apertures lead to much thicker radiators to provide for the same operating cell temperature in space. Higher thermal conductivity materials and lower density materials are both under investigation, with a goal of reducing the radiator mass per unit area by 40% over the course of the technology maturation program.


Thermal Model

One Key Result

Higher Thermal Conductivity and/or Lower Density SLASR Radiator Materials Are Being Evaluated by Texas A&M

Fig. 18. SLASR Radiator Thermal Model and One Key Result.

The SLASR team is also re-optimizing the SquareRigger platform, which was originally developed by ATK Space for thin-film solar cell deployment and support, to improve its compatibility with the Stretched Lens Array (SLA) concentrator blankets.

In coming months, our team will also be performing space environmental effects testing of the new components for SLASR, and designing half-scale SLASR wing hardware, and full-scale bay hardware, for fabrication and testing in later phases of the multi-year program.

CONCLUSIONS

Development of a new solar array technology called Stretched Lens Array SquareRigger (SLASR) is proceeding well under a NASA-sponsored technology maturation program. SLASR offers unprecedented performance metrics and other attributes that make it applicable to a wide range of space exploration activities, including near-term missions in the Earth-Moon neighborhood, and longer term missions to Mars and beyond.

ACKNOWLEDGMENT

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