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STRETCHED LENS ARRAY SQUARERIGGER (SLASR): A UNIQUE HIGH-POWER SOLAR ARRAY FOR EXPLORATION MISSIONS

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ABSTRACT

Over the past two years, development has begun on a unique high-power solar concentrator array called Stretched Lens Array SquareRigger (SLASR). SLASR marries the high electrical performance and low mass of the ENTECH Stretched Lens Array (SLA) flexible blanket concentrator with the high structural performance and low mass of the ATK Space SquareRigger (SR) platform. SLASR offers unprecedented performance metrics for a space solar array of any type, including:

- High Power Capacity (100 kW to multi-MW Class)
- Compact Launch Stowage (80-120 kW/m³)
- State of the Art Areal Power Density (300 to 400 W/m²)
- Outstanding Array-Level Specific Power (300 to 1,000 W/kg)
- High-Voltage Operation at Low Insulation Mass Penalty (300 to 600 V)
- Excellent Manufacturability Using Proven Processes (Cells and Lenses at MWs/year)
- Improved Radiation Hardness at Low Shielding Mass Penalty (Enabling Solar Electric Propulsion Space Tugs Through the Radiation Belts)
- Exceptional Cost Effectiveness (50 to 75 Percent Less than High-Efficiency Planar Arrays)

This paper describes SLASR technology, discusses SLASR developments to date, and outlines plans for SLASR technology maturation. The advantages of SLASR over other high-power solar array technologies are presented, including a comparison of key performance parameters for large-scale solar electric propulsion space tug missions.

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].

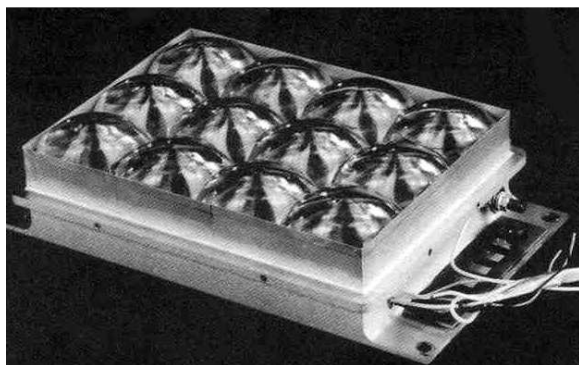


Fig. 1. Mini-Dome Lens Array for the PASP Plus Flight Test (1994-1995).

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.

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/m² areal power density and over 45 W/kg specific power, the best performance metrics up to



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

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

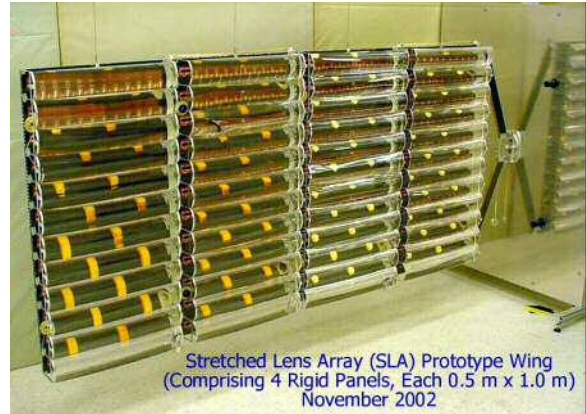


Fig. 3. Rigid-Panel Stretched Lens Array (SLA) Prototype Wing.

become self-supporting stressed membranes. 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.

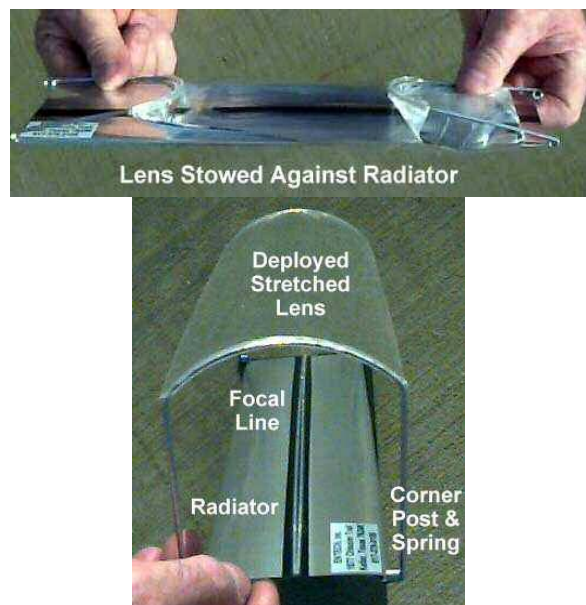


Fig. 4. Stretched Lens Approach.

Significantly, the total combined areal mass density (kg per m² 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

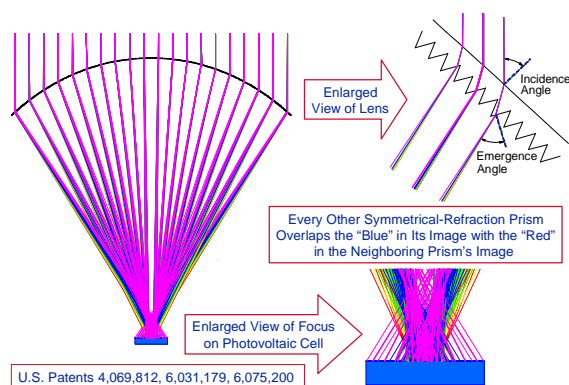


Fig 5. Symmetrical-Refraction Color-Mixing Fresnel Lens.

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.

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/m². 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.

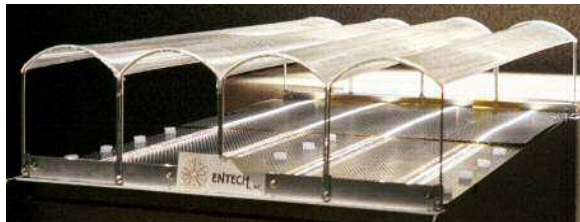


Fig. 6. Flexible-Blanket Stretched Lens Array (SLA) Prototype.

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].

| 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.

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 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/m³ stowed power, and operational voltages above 1,000 V) in the near-term (2010) to mid-term (2015).

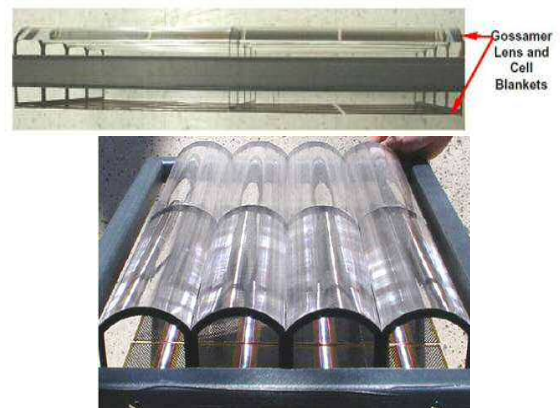


Fig. 7. SLA SquareRigger Prototype Demonstrator.

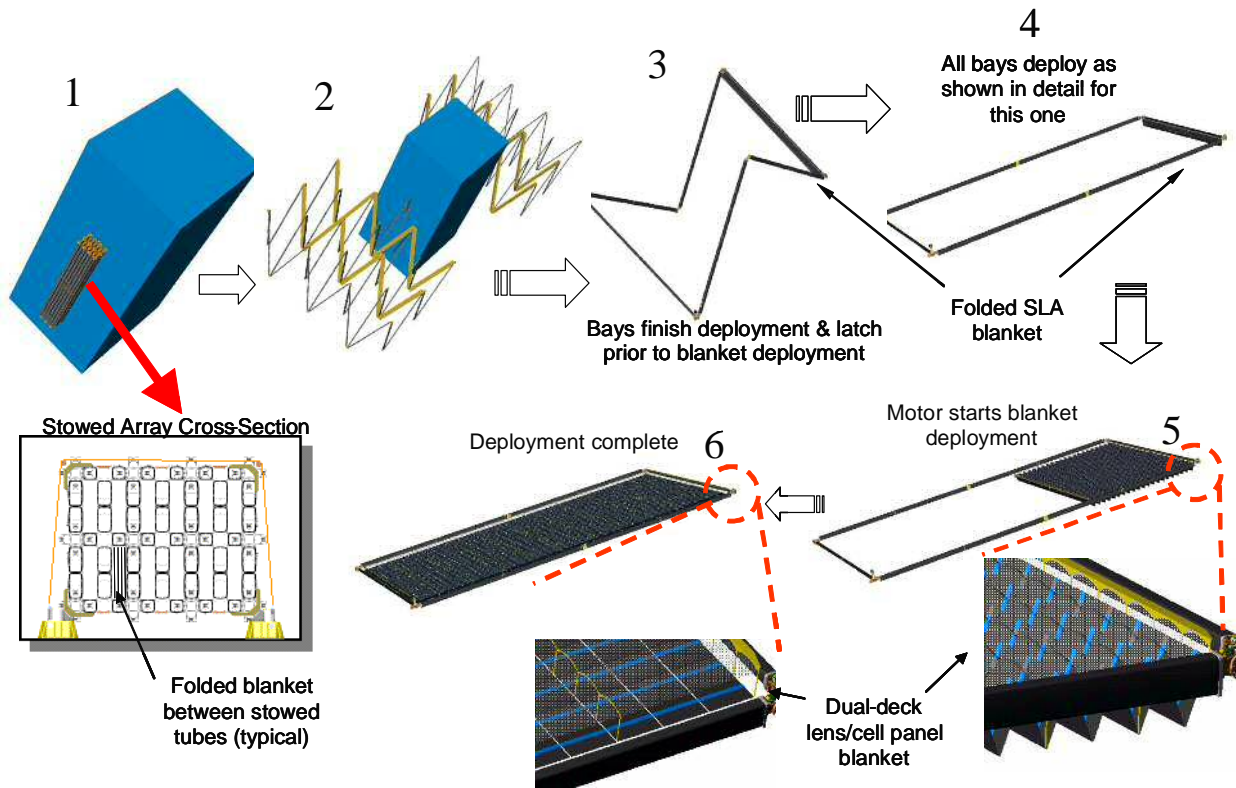


Fig. 8. Stretched Lens Array SquareRigger (SLASR) Schematic.

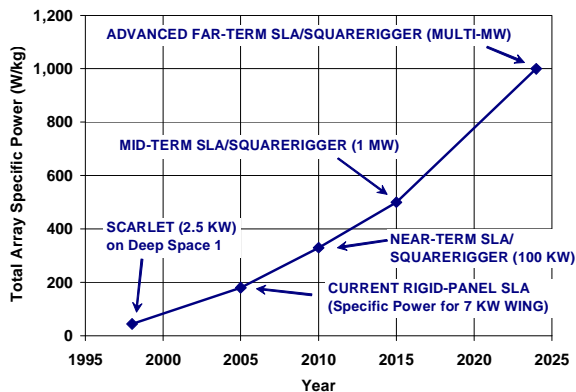


Fig. 9. Long-Term Technology Roadmap for the Stretched Lens Array (SLA).

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/m²), ultra-light mass density (low kg/m²), spectacular stowed power density (kW/m³), 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.

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

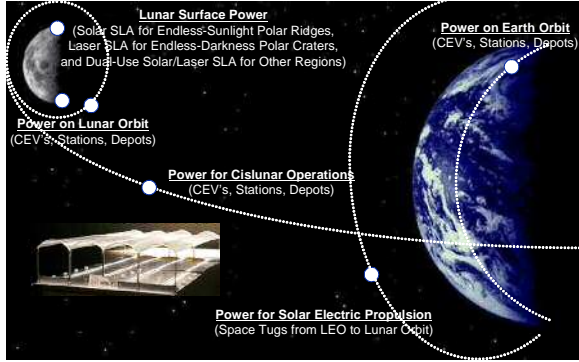


Fig. 10. Near-Term SLASR Applications for Space Exploration in the Earth-Moon Neighborhood.

applications also include power for cislunar operations and for solar electric propulsion (SEP) space tugs to deliver cargo from Earth orbit to the lunar orbit 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 sample for a 600 V version of SLASR for such an SEP mission [14]. This test sample has been subjected to underwater hi-pot tests with more than 2,200 V bias applied between the solar cell and the composite radiator, which was surrounded by water to crudely simulate space plasma. The leakage current was less than 1 micro-amp, indicating the excellent resistance for the encapsulation above and below the cell. The top surface of the cell can be

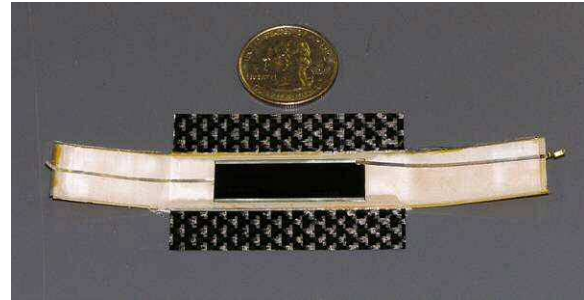


Fig. 11. Fully Encapsulated SLASR Receiver Sample.

encapsulated with either a thin cover glass or with a silicone prismatic cell cover. The thickness of either type of cell cover is optimized by trading off radiation degradation and array mass for the specific mission.

For a typical LEO or GEO mission, 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 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

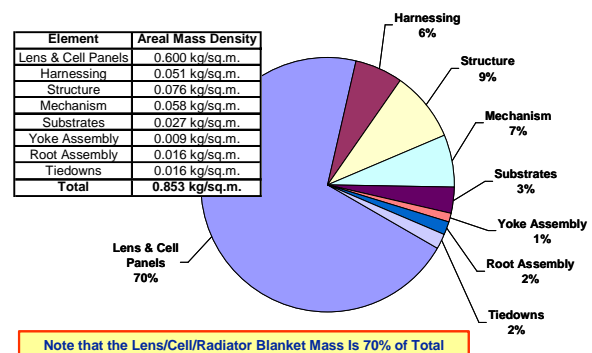


Fig. 12. Mass Breakdown for 100 kW Stretched Lens Array SquareRigger (SLASR) System.

needed, as discussed below.

A number of recent trade studies of SEP tug missions have been performed, with typical results for one such mission shown in Fig. 13. This mission study was based on a 2008 technology freeze, including an

expected one-sun solar cell efficiency of 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 Fig. 13 is the end-of-life specific power, after radiation degradation of the solar cells due to the 13 slow spiraling transits of the earth's radiation belts. The peak point of the SLA curve (about 280 W/kg) corresponds to the optimal amount of cell radiation shielding. (More shielding adds to array mass more quickly than it reduces array power degradation.) The same is true for a planar multi-junction cell array, which is also shown in Fig. 13. Note that the planar array peaks at approximately 80 W/kg. Note also that the peaks occur at wing-level areal mass

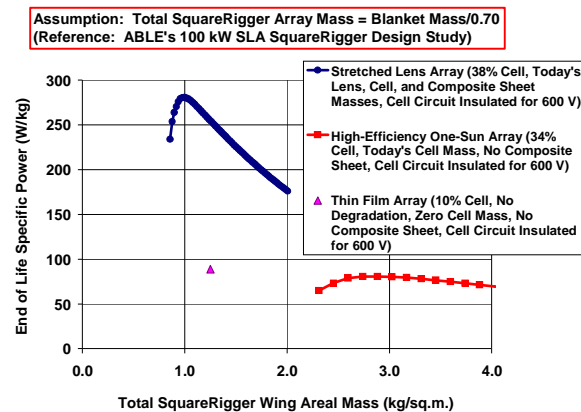


Fig. 13. Results of SEP Mission Study for Space Tug with 7 Annual Trips from Low Earth Orbit to Lunar Orbit, Including 6 Return Trips (13 Total Transits of the Earth's Radiation Belts).

densities of about 1 kg/m² for SLA and about 3 kg/m² for the planar array.

For comparison, a highly idealized thin-film solar cell array is shown by a single triangular data point in Fig. 13. For this idealized array, a cell efficiency of 10%, with zero cell mass and zero radiation degradation, was assumed. Note that this idealized thin-film array provides about 90 W/kg at about 1.3 kg/m² areal mass density. All three array types were assumed to utilize the same SquareRigger platform and the

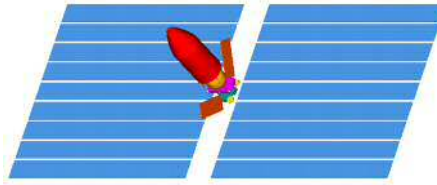
same fully encapsulated high-voltage insulation system of Fig. 11, with an optimal amount of added cover glass shielding for the SLA and high-efficiency planar array. In summary, for this important exploration application, SLA offers an advantage over planar arrays of more than 3X in end-of-life specific power. Furthermore, SLA offers substantial advantages in cost effectiveness, due to its use of much less expensive solar cell material than the planar arrays.

More recently, another SLASR-powered SEP mission has also been analyzed, with key assumptions and results shown in Fig. 14. A 600 kW class SLASR-powered tug was analyzed for a 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.

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-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.

SLASR’s advantages for space exploration missions include a set of unprecedented performance metrics and features:

- Areal Power Density = 300-400 W/m²
- Specific Power = 300-500 W/kg for Full 100 kW Solar Array
- Stowed Power = 80-120 kW/m³ 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-Produced 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 NASA's Exploration Systems Research & Technology (ESR&T) program. This work includes the development of several improved key components of SLASR:

- 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

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. 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.

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