

THE STRETCHED LENS ARRAY (SLA): AN ULTRA-LIGHT PHOTOVOLTAIC CONCENTRATOR ¹

Mark J. O'Neill
ENTECH, Inc.
Keller, Texas 76248 USA

Michael F. Piszczor
NASA Glenn
Cleveland, Ohio 44135 USA

Michael I. Eskenazi
AEC-ABLE
Goleta, CA 93117 USA

A. J. McDanal
ENTECH, Inc.
Keller, Texas 76248 USA

Patrick J. George
NASA Glenn
Cleveland, Ohio 44135 USA

Matthew M. Botke
AEC-ABLE
Goleta, CA 93117 USA

Henry W. Brandhorst
Space Power Institute
Auburn Univ., AL 36849 USA

David L. Edwards
NASA Marshall
Huntsville, Alabama 35812 USA

Paul A. Jaster
3M
St. Paul, MN 55144 USA

ABSTRACT

A high-performance, ultralight, photovoltaic concentrator array is being developed for space power. The stretched lens array (SLA) uses stretched-membrane, silicone Fresnel lenses to concentrate sunlight onto triple-junction photovoltaic cells. The cells are mounted to a composite radiator structure. The entire solar array wing, including lenses, photovoltaic cell flex circuits, composite panels, hinges, yoke, wiring harness, and deployment mechanisms, has a mass density of 1.6 kg/sq.m. NASA Glenn has measured 27.4% net SLA panel (Fig. 1) efficiency, or 375 W/sq.m. power density, at room temperature. At GEO operating cell temperature (80C), this power density will be 300 W/sq.m., resulting in more than 180 W/kg specific power at the full wing level. SLA is a direct ultralight descendent of the successful SCARLET array on NASA's Deep Space 1 spacecraft. This paper describes the evolution from SCARLET to SLA, summarizes the SLA's key features, and provides performance and mass data for this new concentrator array.

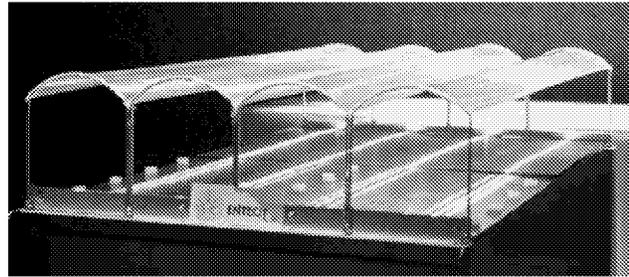


Fig. 1 – Stretched Lens Array (SLA) Prototype Panel

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 larger slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators [2].

1. This work has been conducted under several NASA-sponsored programs, including the Space Solar Power program, the Advanced Cross-Enterprise Technology Development program, and the New Millennium Space Technology 6 program.

In the early 1990's, the first refractive concentrator array was developed and flown on the PASP+ mission, 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 to provide protection against space ultraviolet (UV) radiation and atomic oxygen (AO). This array performed extremely well throughout the year-long mission in a high-radiation elliptical orbit, validating both the high performance and radiation hardness of the refractive concentrator approach [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, NASA, and 3M 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, AEC-ABLE joined the refractive concentrator team and led the development of the SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array [4]. SCARLET uses a small (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at about 8X concentration onto radiatively cooled multi-junction cells. Launched in October 1998, a 2.5 kW SCARLET array powers both the spacecraft and the ion engine on the NASA/JPL Deep Space 1 spacecraft, shown in Fig. 2. SCARLET achieved over 200 W/sq.m. areal power and over 45 W/kg specific power. With SCARLET working flawlessly, Deep Space 1 is currently about 150 million miles from earth, on its way to a comet rendezvous on September 22, 2001 [5].

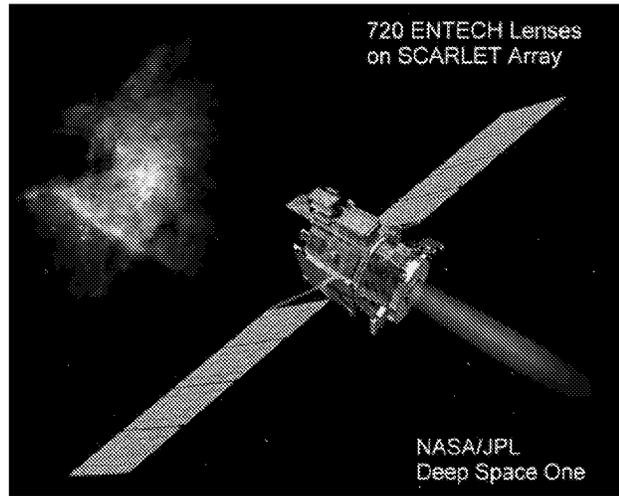


Fig. 2 - Deep Space 1 Probe Launched October 1998

Over the past three years, the team, now including Auburn's Space Power Institute, has developed a new space concentrator array technology, called the stretched lens array (SLA). SLA provides even higher performance than SCARLET at dramatically reduced mass and cost [6 and 7]. Both SCARLET and SLA use the same unique, patented, arched lens optical concentrator (Fig. 3), which provides outstanding optical performance and unparalleled tolerance of real world aberrations and errors [2]. The primary difference between the SCARLET lens and the SLA lens relates to their means of support: SCARLET used an arched glass superstrate to support the silicone lens, while SLA uses simple lengthwise tensioning of the silicone lens itself for support.

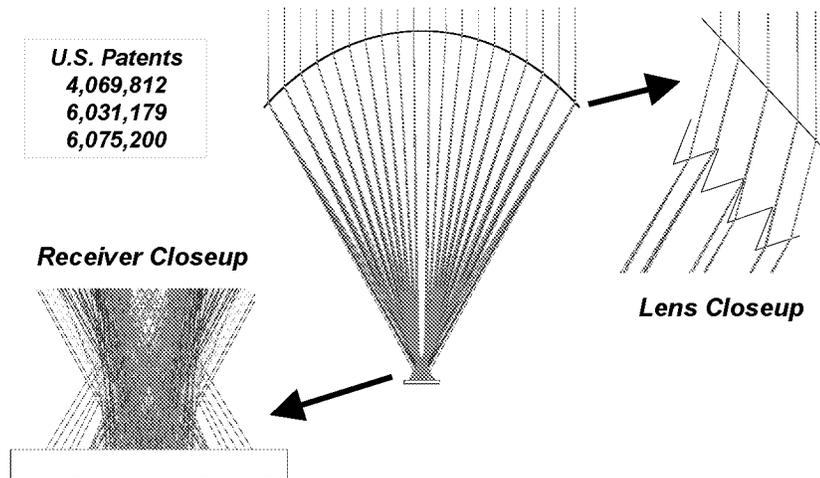


Fig. 3 - Unique Fresnel Lens Used in Both SCARLET and SLA Arrays

In 1999-2000, under NASA's Space Solar Power program, the SLA team designed, developed, fabricated, and tested a fully functional prototype SLA panel (Fig. 1). This panel achieved unprecedented performance, characterized by a net solar-to-electrical conversion efficiency of 27.4% under simulated space sunlight at room temperature [7]. Furthermore, the same SLA technology provided unprecedented performance under outdoor terrestrial sunlight, characterized by 25-29% net conversion efficiency at operating temperature [8].

In 2001-2002, under NASA's Advanced Cross-Enterprise Technology Development program, the SLA team is developing an optimized, near-term, robust, SLA solar array wing. This SLA wing builds upon the 15 year heritage of refractive concentrators for space power, including the successful flight heritage of the PASP+ and SCARLET arrays referenced above. The SLA team is also working on a NASA/JPL New Millennium Program Space Technology 6 study which could lead to a near-term flight test for SLA.

EVOLUTION FROM THE SCARLET ARRAY TO THE STRETCHED LENS ARRAY (SLA)

The patented SLA [6 and 9] is an ultralight descendent of SCARLET as shown by comparing Figs. 4 and 5, and as discussed in the following paragraphs. Both SCARLET and SLA use the same small, arch-shaped, line-focus Fresnel lenses (8.5 cm aperture width) to focus sunlight onto high-efficiency multi-junction solar cells (1.0 cm active width). This concentration ratio (8.5X) provides ± 2 degree sun-pointing tolerance about the critical axis, and can be adjusted for specific mission requirements. 3M makes the continuous web of thin lensfilm material (about 150 microns thick) from space-qualified DC93-500 silicone.



Fig. 4 - Deep Space 1 *SCARLET* Panel Assembly

Fig. 4 shows a SCARLET panel during assembly at ABL. To support and UV-protect the 200-micron-thick silicone lens material, each lens was laminated to a 75-micron-thick, thermally shaped, ceria-doped glass arch. The laminated lenses were then inserted into a protective frame, made from composite material. The lens-populated lens frame is the upper deck in Fig. 4. The photovoltaic receivers were attached to a high thermal conductivity composite honeycomb panel, which is the lower deck in Fig. 4. For launch, the lens frames were stowed against the honeycomb panels, which were folded together in the same fashion as for a planar solar array. Once on orbit, the SCARLET panels unfolded to form a wing, and the lens frames deployed to their proper position [5].

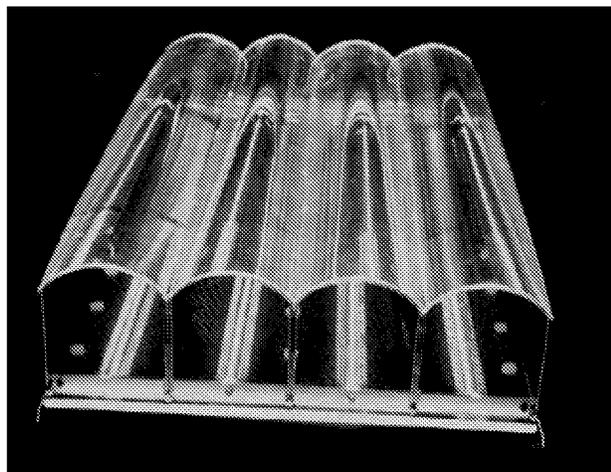


Fig. 5 - Stretched Lens Array (SLA) Prototype Panel

Fig. 5 shows a prototype SLA panel. The thin silicone lens material is now supported as a stretched membrane between end arches, so both the glass arches and the lens frame have been eliminated. The composite radiator is now a thin composite sheet, which is more than adequate for excellent thermal performance. Like the silicone lens, the radiator sheet is now supported as a stretched membrane between edge elements, so the honeycomb panel has been eliminated. Without any sacrifice in optical, thermal, or electrical functionality, the SLA panel in Fig. 5 is approximately four times lighter (per square meter of lens aperture) than the SCARLET panel in Fig. 4. Indeed, the SLA performance is

significantly higher than SCARLET because the optical losses caused by the glass arches and the lens frame have been eliminated. A UV-rejection coating is used on the outer surface of the lens.

Fig. 5 shows the SLA prototype panel under terrestrial sunlight illumination. Note the focal lines on each of the four photovoltaic receivers, which utilize conventional copper-clad polyimide flex circuit construction. Performance measurements for this SLA prototype panel are discussed below.

PROTOTYPE SLA PANEL PERFORMANCE TESTING

Under the NASA Space Solar Power program, the prototype SLA panel shown in Figs. 1 and 5 was designed, developed, fabricated, and tested by the refractive concentrator team. Both Spectrolab and TECSTAR developed monolithic triple junction (GaInP/GaAs/Ge) concentrator cells for the prototype panel. These cells were equipped with ENTECH prism covers to eliminate the normal gridline shadowing loss. Cells were assembled into photovoltaic receivers using polyimide flex circuits, which were attached to the graphite sheet radiator with space-qualified silicone pressure sensitive adhesive (PSA).

The prototype SLA panel was first tested under terrestrial sunlight by ENTECH, then tested in a large area pulsed solar simulator (LAPSS) by ABLE, and finally LAPSS-tested by NASA Glenn. To ensure accuracy, NASA Glenn flew cells from the same production run on the NASA Lear Jet to determine their AM0 short-circuit currents, and then used one of these cells to set the intensity of the LAPSS lamp to maintain 1 AM0 sun irradiance at the lens aperture. Fig. 6 shows the measured IV curve for the best of the four lens/receiver modules in the prototype panel. These results were measured at room temperature (about 20C), and correspond to 27.4% net module efficiency and 375 W/sq.m. output power density, based on the module aperture area (8.5 cm lens aperture width x 24.0 cm photovoltaic receiver active length = 204 sq.cm.).

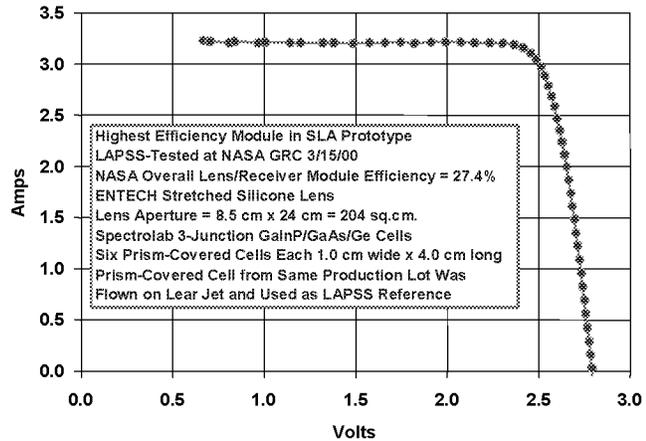


Fig. 6 – NASA-Measured 27.4% Module Efficiency (AM0)

OTHER SLA TESTING

A number of other important tests have been performed for the key elements of the stretched lens array (SLA), as summarized in the following paragraphs.

Stretched Lens Optical Efficiency

Numerous stretched membrane lenses have been tested under outdoor terrestrial sunlight by ENTECH, to determine the net optical efficiency. Since the top cell (GaInP) limits the current of the triple-junction stack, the short-circuit current output of a reference GaInP cell is used to determine the lens efficiency. Under a variety of test conditions, the optical efficiency of the stretched silicone lens has typically been measured at 92-93%. Knowing this lens efficiency value, the corresponding cell efficiency for the prototype panel discussed in the previous paragraph is seen to be 30% (27.4% module/92% lens). This cell efficiency value is in very close agreement with Spectrolab's in-house cell efficiency measurement.

Stretched Lens Thermal Cycling

To verify the thermal durability of the new stretched membrane lens, multiple samples were exposed to GEO thermal cycling by ABLE, and all passed the equivalent of more than 20 years in GEO (over 1,830 thermal cycles from -180C to +90C).

Lens Material Space Ultraviolet Exposure Testing

Like the silicone mini-dome lenses on the PASP+ mission, the SLA lenses will be equipped with a thin-film ultraviolet rejection (UVR) coating to protect the silicone. To verify the durability of the coated lens material, NASA Marshall has completed 7,000 equivalent sun hours (ESH) of near ultraviolet (NUV) exposure testing on both coated and uncoated lens material samples made by ENTECH [10 and 11]. Figs. 7 and 8 show the NASA Marshall spectral transmittance measurements for coated and uncoated samples, respectively. Interestingly, the NUV-exposed uncoated lens material still has a 93% transmittance, for the current-limiting top cell (GaInP) response spectrum, after 7,000 ESH of NUV. The coated material has degraded to 89% transmittance for the top cell response spectrum after 7,000 ESH of NUV. NASA Marshall is currently running combined vacuum ultraviolet (VUV) and NUV testing of lens material samples. Initial results of these tests indicate that a UVR coating may be needed to block damaging wavelengths in the VUV range below 200 nm, instead of all wavelengths below 300 nm as previously anticipated.

Proton and Electron Testing of Stretched Lens Sample

A stretched lens sample (Fig. 9) was recently fabricated by ENTECH and exposed to proton and electron radiation by NASA Marshall. First, the lens optical efficiency was measured outdoors by ENTECH, using a single-junction GaInP

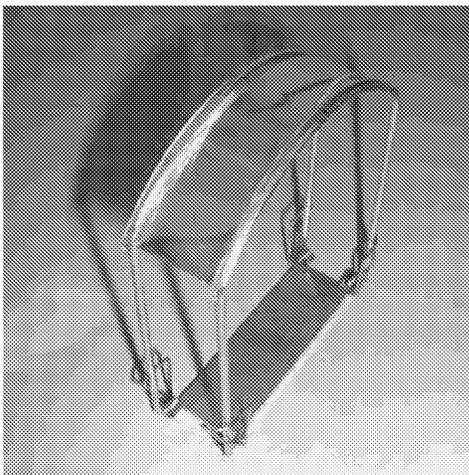


Fig. 9 – Stretched Lens Sample for Proton and Electron Exposure Testing

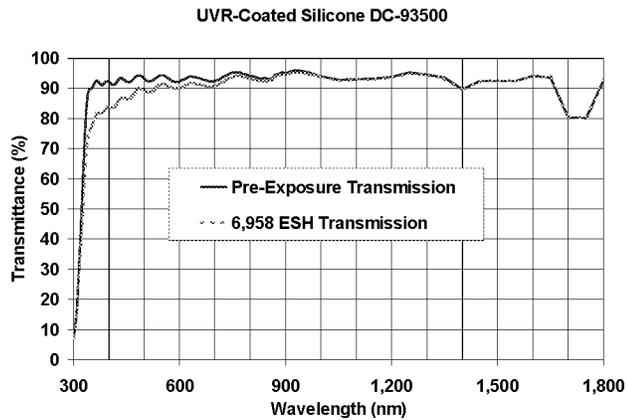


Fig. 7 – NASA Marshall NUV Exposure Test Results for UVR-Coated DC93-500 Lens Material Sample

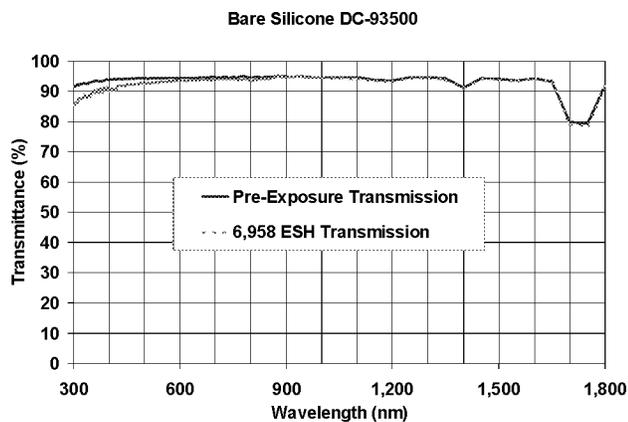


Fig. 8 – NASA Marshall NUV Exposure Test Results for Uncoated DC93-500 Lens Material Sample

reference cell at 9.3X geometric concentration. The cell was provided by the National Renewable Energy Laboratory (NREL). Next, NASA Marshall exposed the sample to protons equivalent to 15 years on GEO, based on a detailed dose-depth profile analysis resulting in this test exposure combination:

- ◆ 4.3×10^{12} protons/sq.cm. at 700 keV
- ◆ 9.0×10^{11} protons/sq.cm. at 525 keV
- ◆ 5.7×10^{13} protons/sq.cm. at 225 keV

Then the lens optical efficiency was re-measured outdoors by ENTECH with no measurable degradation. Next, NASA Marshall exposed the sample to electrons:

- ◆ 1×10^{15} electrons/sq.cm. at 1 MeV

The lens optical efficiency was once again re-measured outdoors by ENTECH with no measurable degradation (optical efficiency still 90-92%).

Micrometeoroid Impact Testing of Lenses and Photovoltaic Receivers at High Voltage in Plasma

Auburn University's Space Power Institute has conducted numerous simulated micrometeoroid impact tests (at 10-12 km/sec) of both lens and photovoltaic receiver samples in a plasma chamber. These tests included:

- ◆ Stretched Lenses Alone
- ◆ Receivers Alone
- ◆ Combined Lenses over Receivers
- ◆ Front and Back Impact
- ◆ Cells Biased at -400 V and -1,000 V Relative to Plasma During Tests

The lens impact tests showed clean penetrations with no peripheral damage such as tearing (Fig. 10).

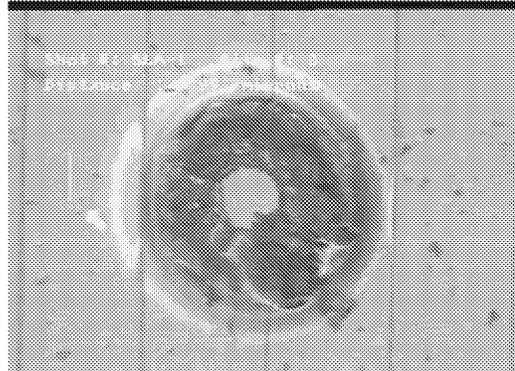


Fig. 10 – Stretched Lens Sample Showing Micrometeoroid Puncture

ENTECH mounted the single-cell photovoltaic receivers to composite radiator sheet, and fully encapsulated the receivers to enable high-voltage operation. Two of the receivers were tested multiple times (Fig. 11). Auburn first tested these receiver samples in a simulated LEO plasma, with the cells biased to more than 400 volts (negative) relative to the plasma. Micrometeoroids were then shot at the samples, causing minor damage to the cover glass over each cell, but no electrical discharge or current leakage problems were observed. After this successful test, the receiver samples were re-tested, with the cells biased to more than 1,000 volts (negative) relative to the plasma. Micrometeoroids were then shot again at the samples, and the only discharge which occurred was a transient event due to a puncture of the polyimide tape over the lead wire located inside the white circle in Fig. 11. This event was self-healing, with no lasting leakage current to the plasma.

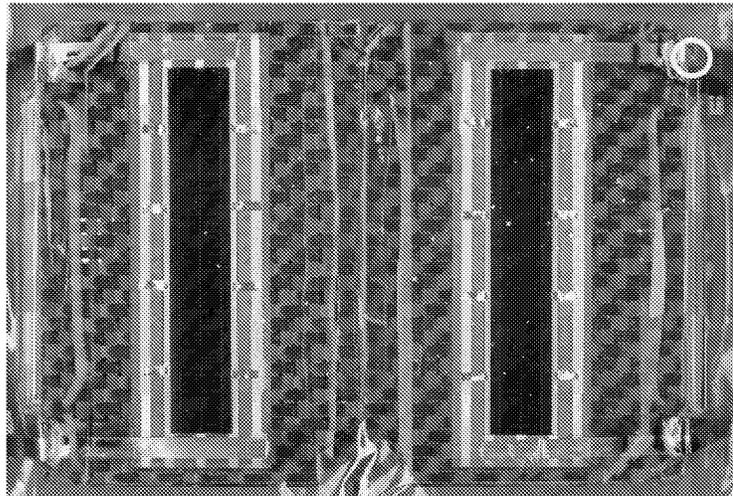


Fig. 11 – Photovoltaic Receiver Samples After Micrometeoroid Impact

Despite many impacts over the photovoltaic receivers, as evidenced by the many pockmarks in the photo in Fig. 11, the receivers had no discharge events during or after these tests.

A final set of tests was conducted with the lens stretched in front of the receivers to simulate the flight-like configuration. The receivers were once again held at 1,000 V (negative) relative to the plasma. Micrometeoroids were first shot at the front (lens side) of the units, and the lens proved to be an excellent natural micrometeoroid shield for the receivers, preventing any direct impact on the receivers. Micrometeoroids were then shot from the back (radiator side) of the units. No discharge problems of any kind occurred during or after these combined lens/receiver tests.

This high-voltage capability, with very little mass penalty, is one of the key advantages of the SLA approach over conventional planar arrays. The small cells can be super-insulated without adding much mass to the array, due to the small size of the solar cells. For high-power arrays (e.g., 20 kW and larger), this high-voltage capability provides significant savings in wiring mass and cost compared to conventional lower-voltage planar arrays. The added encapsulation can also be designed to provide excellent radiation tolerance for high-radiation missions.

SLA RIGID PANEL WING APPROACH

In 1999-2000, the SLA team thoroughly investigated a flexible blanket platform for the stretched lens array (SLA) [7]. While this blanket approach has an advantage in stowage volume over more conventional rigid panel platforms, it lacks the maturity and flight heritage of the rigid panel wing. This year, under the new NASA Advanced Cross-Enterprise Technology Development program, the SLA team is developing a new ultralight rigid panel wing as the platform of choice for SLA. Figs. 12-14 show the basic rigid panel SLA wing approach in schematic form. The flexible lenses fold down flat against the rigid panels for compact stowing during launch (Fig. 12). On orbit, as the panels unfold, spring driven end arches deploy and tension the individual stretched lenses across the panel's length (Fig. 13). The wing continues to deploy until the panels are all co-planar in their final locked wing position (Fig. 14).

This unfolding rigid panel solar array approach has been widely used for many years for NASA, DOD, and commercial spacecraft. One unique feature in the new SLA rigid panel array relates to the panels themselves, which use only a single face sheet and no honeycomb, except as a support frame around each panel. The use of very lightweight "picture-frame" panels is enabled by the very low mass of the supported cells and lenses, and by snubbing during launch to the inboard and outboard panels which are reinforced honeycomb panels. The thin composite face sheet forms the photovoltaic receiver mounting surface and the waste heat radiator, and is stretched in drum-like fashion over the peripheral honeycomb picture-frame structure. The individual pop-up lenses use the same basic deployment and support approach that has been used successfully on numerous SLA prototypes (Fig. 15).

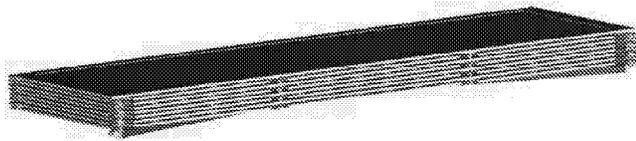


Fig. 12 – Stowed Rigid Panel SLA Wing

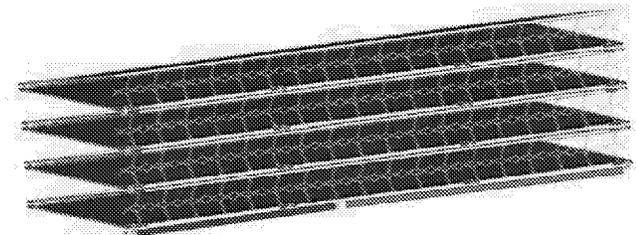


Fig. 13 – Lenses Deploying on Rigid Panel SLA Wing

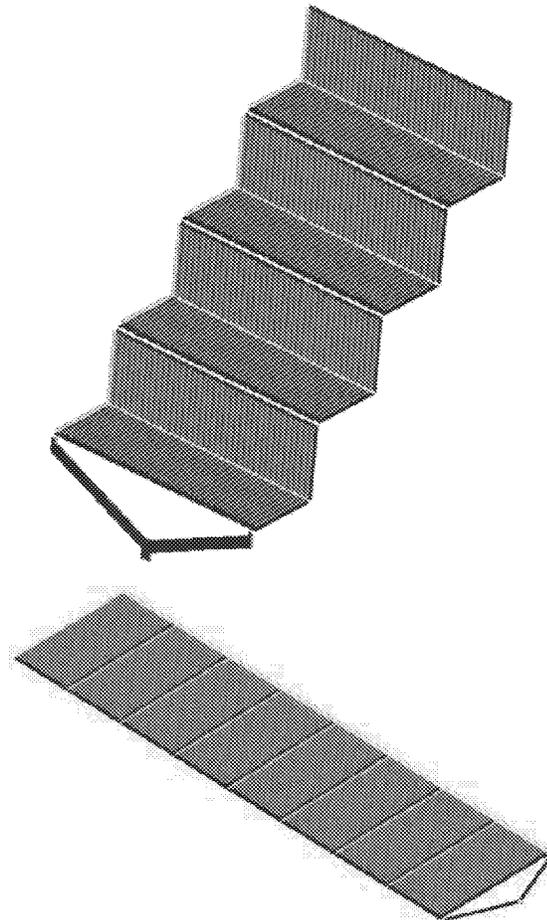


Fig. 14 – Panels Deploying on Rigid Panel SLA Wing

PROTOTYPE FOUR-PANEL SLA WING

Recently, the SLA team has fabricated a prototype four-panel SLA wing to demonstrate the mechanical functionality of the rigid-panel SLA wing approach (Fig. 16). Two of the four panels have been equipped with pop-up lenses, as shown in the photo of Fig. 16. Each panel is about 0.5 m long by 1.0 m wide, with 12 side-by-side pop-up lenses, each 0.5 m long. Flight-like hinges and other mechanical hardware are also incorporated into the prototype SLA wing. The prototype wing has already validated the expected robustness and mechanical functionality of the rigid-panel SLA approach.

Next fiscal year, all four prototype panels will be equipped with lenses, and one of the panels will be equipped with several "live" photovoltaic receivers. This final SLA wing will be the key deliverable under the NASA Advanced Cross-Enterprise Technology Development program.

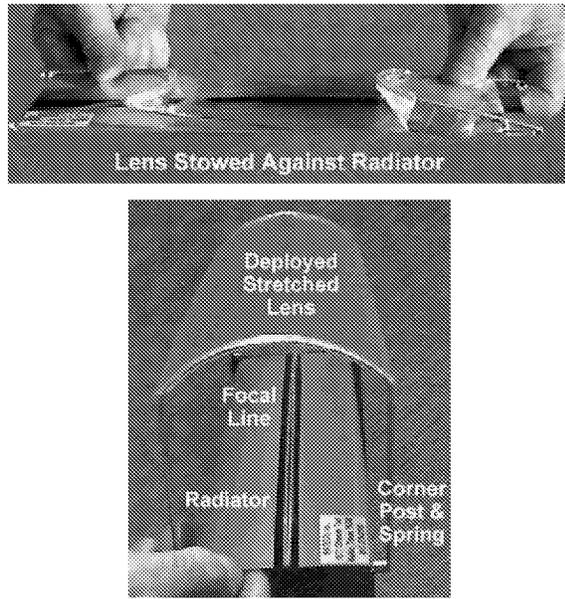


Fig. 15 – Prototype SLA Model with Pop-Up Lens

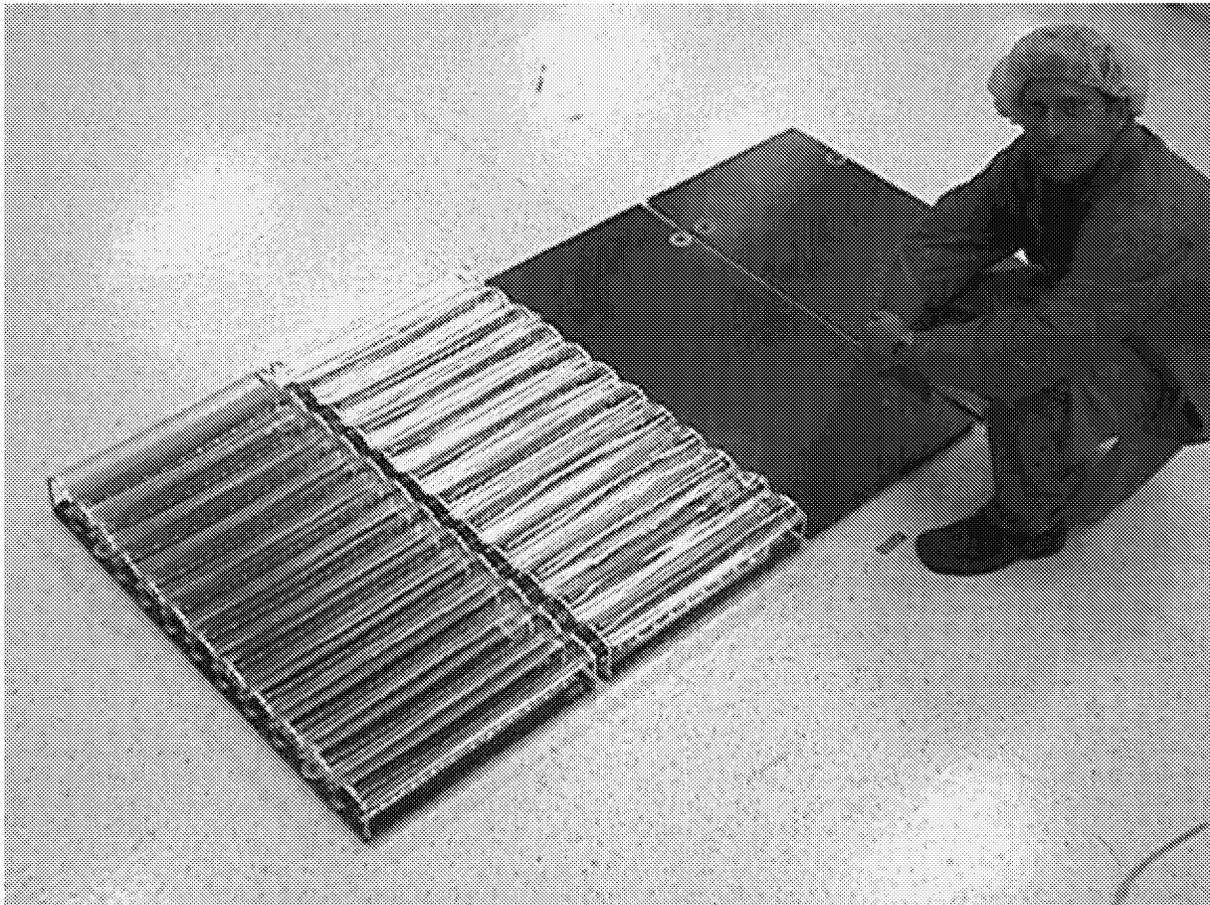


Fig. 16 – Prototype SLA Wing with Pop-Up Lenses

SLA WING-LEVEL MASS AND PERFORMANCE

A detailed mass and performance analysis has been done for the rigid panel SLA wing point design shown in Fig. 17. This wing has a total mass of 39 kg and provides a total lens aperture area of 24 sq.m. At beginning of life (BOL), this wing provides over 7 kW of output power and over 180 W/kg of specific power. These values are based on the use of existing cells with a demonstrated efficiency of 30% at 8 suns and 28C. With improved 32%-efficient cells, wing-level BOL specific power should exceed 190 W/kg in 2002.

Key features of the rigid-panel SLA wing are summarized in Table 1. In addition to excellent performance, mass, and stiffness characteristics, the rigid panel SLA wing approach also enables the outermost panel to be populated with planar cells for pre-deployment power generation (e.g., during LEO to GEO orbit transfer), if a specific mission needs this capability. Furthermore, many mission planners and spacecraft program managers prefer the low-risk, rigid panel deployment approach over flexible blanket approaches.

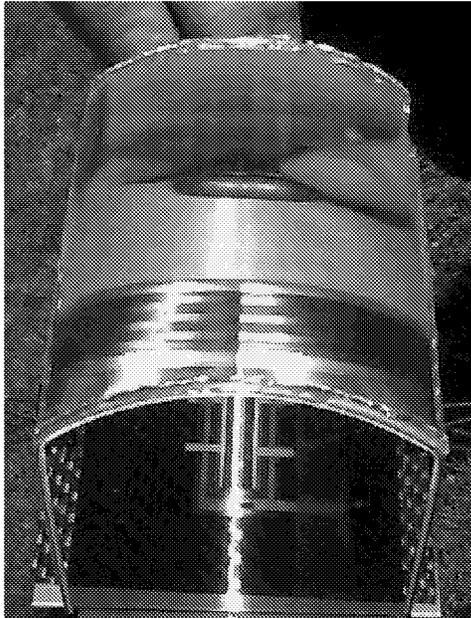


Fig. 18 – Outdoor Test of World-Record-Performance SLA Mini-Module

Fig. 18 is currently the performance world record holder at 27% net efficiency at operating temperature, confirmed by NREL in outdoor testing. Recently, ENTECH has measured over 27% net efficiency for similar mini-concentrator modules using cells from three different suppliers: Spectrolab, EMCORE, and JX Crystals (using

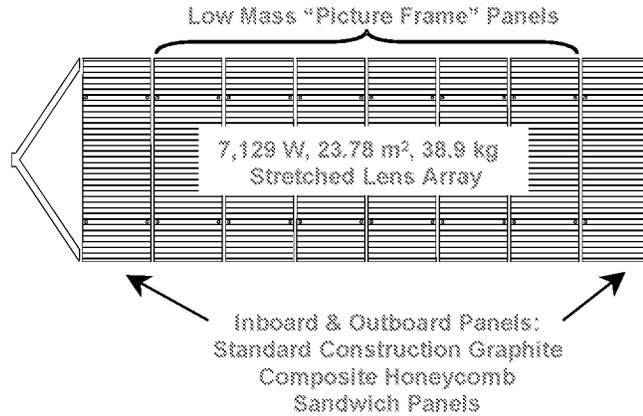


Fig. 17 – Point Design Parameters for SLA Wing

Feature	Value or Characteristic
Point Design Basis	7,129 Watts (BOL)
SLA Implementation	Pop-up lenses
Base Platform Design Maturity	Most components flight proven on DS1
Specific Power	183 W/kg
Stowed Volume	0.11 m³/kW
Stowed Stiffness	40 Hz
Deployed Stiffness	0.1 Hz
Stowed Power	Easily implemented on outer panel
Ease of Adding Planar Panel	Easily implemented on outer panel
Flatness & Warping	Well understood flat stable platform
Deployment Testing	Can use existing off-loaders
Power Testing	Pop-up lenses allow each panel to be tested as a complete assembly before wing integration
Commercial Appeal	Easier to integrate on commercial spacecraft. Readily accepted configuration.
Self Shadowing	No self shadowing

Table 1 – Key Features of the Rigid Panel SLA Wing

SYNERGY WITH TERRESTRIAL PHOTOVOLTAIC CONCENTRATORS

Many aspects of the SLA technology are directly applicable to future terrestrial photovoltaic systems, including the color-mixing lens optical concentrator and the multi-junction cells operating under multi-sun concentration. Indeed, ENTECH is working with NREL on the development of a 27% efficient terrestrial concentrator system using color-mixing lenses and multi-junction cells. The feasibility of this combination has already been demonstrated in mini-module tests at both ENTECH and NREL. The SLA mini-concentrator shown in

TECSTAR top cells). High-concentration (400X) terrestrial concentrator modules are now under development by ENTECH.

SLA ADVANTAGES OVER OTHER SPACE ARRAYS

The Stretched Lens Array (SLA) offers outstanding wing-level performance:

- Operational Power Density: > 300 W/sq.m.
- Specific Power: > 180 W/kg
- Compact Stowage for Launch: > 9 kW/cu.m.
- High-Voltage Operation: > 400 V.

SLA is inherently lower in cost than planar high-efficiency arrays:

- 80% Savings in Most Expensive Cost Element, the Solar Cells
- Silicone Lensfilm Is Mass-Produced by Continuous Process by 3M.

Panel structure and wing deployment are conventional and simple.

SLA appears to be durable for the space environment:

- Protons, Electrons, UV, Thermal Cycling, Micrometeoroids.

SLA is the ultralight descendent of the SCARLET array on Deep Space 1, and builds on that successful flight heritage.

CONCLUSIONS

A new lightweight rigid-panel concentrator array is under development for future space power applications. SLA provides a substantial cost advantage over planar arrays by using only one-eighth as much expensive solar cell material for the same power output. In addition, the thin silicone lensfilm and the thin composite sheet radiator provide a substantial mass/area advantage over conventional planar cell assemblies. The new rigid-panel SLA wing employs a conventional, conservative, well-proven approach to array deployment and support on orbit, while offering outstanding performance, high-voltage capability, and radiation tolerance.

REFERENCES

1. M.F. Piszczor and M.J. O'Neill, "Development of a Dome Fresnel Lens/GaAs Photovoltaic Concentrator for Space Applications," 19th IEEE-PVSC, 1987.
2. M.J. O'Neill, "Silicon Low-Concentration, Line-Focus, Terrestrial Modules," Chapter 10 in **Solar Cells and Their Applications**, John Wiley & Sons, 1995.
3. H. Curtis and D. Marvin, "Final Results from the PASP Plus Flight Experiment," 25th IEEE-PVSC, 1996.
4. P.A. Jones et al., "The SCARLET Light Concentrating Solar Array," 25th IEEE-PVSC, 1996.
5. D.M. Murphy, "The SCARLET Solar Array: Technology Validation and Flight Results," Deep Space 1 Technology Validation Symposium, Pasadena, 2000.
6. M.J. O'Neill, "Stretched Fresnel Lens Solar Concentrator for Space Power," U.S. Patent 6,075,200, 2000.
7. M.J. O'Neill et al., "The Stretched Lens Ultralight Concentrator Array," 28th IEEE-PVSC, 2000.
8. M.J. O'Neill et al., "Development Of Terrestrial Concentrator Modules Incorporating High-Efficiency Multi-Junction Cells," 28th IEEE-PVSC, 2000.
9. M.J. O'Neill, "Color-Mixing Lens for Solar Concentrator System and Methods of Manufacture and Operation Thereof," U.S. Patent 6,031,179, 2000.
10. D.L. Edwards et al., "Optical Analysis of Transparent Polymeric Material Exposed to Ultraviolet Radiation," with 8th International Symposium on Materials in a Space Environment, Arcachon, France, 2000.
11. M.J. O'Neill et al., "The Stretched Lens Array (SLA), an Ultralight Concentrator for Space Power," 36th IECEC, Savannah, 2001.