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FROM IMAGINATION TOWARD REALITY: THE STRETCHED LENS ARRAY'S JOURNEY TO MISSION SUCCESS

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ABSTRACT

Going from a concept in one's imagination to mission success in today's conservative space industry is a long and tedious process requiring intensive design, testing, and analysis. This presentation will describe the hurdles that must be overcome in order to get a new technology from the drawing board, through the laboratory, and to mission success. It will chronicle this process by using the Stretched Lens Array (SLA) photovoltaic concentrator as an example. Terrestrial testing, experimental flight tests, potential missions, and missed opportunities will be discussed in an effort to show how to design a survivable space power system and get it flown. Reasons why new, more durable designs need to be flown for mission success will also be discussed. Satellite anomaly statistics will be shown documenting main failure modes. This presentation will follow the conference theme of "From Imagination to Reality." It will document the challenges, successes, and future potential of the Stretched Lens Array.

INTRODUCTION

Going from a concept in one's imagination to mission success in today's conservative space industry is a long and tedious process requiring intensive design, testing, and analysis. This presentation will describe the hurdles that must be overcome in order to get a new technology from the drawing board, through the laboratory, and to mission success. It will chronicle this process by using the Stretched Lens Array (SLA) photovoltaic concentrator as an example.

The SLA developed by ENTECH, Inc. is an array that uses refractive concentrator technology to collect and convert solar energy into useful electricity with efficiencies of greater than 27%. It is durable, lightweight, cost effective, radiation resistant, capable of reliable high voltage operation, and is inherently designed to withstand electrostatic discharge. The module shown in Fig. 1 is the latest version of the design using ATK Space Systems' SquareRigger Platform. This design leads to a specific power exceeding 300 W/kg at voltages exceeding 300 V.

Fig. 1: Full scale SLASR panel

Terrestrial testing, experimental flight tests, potential missions, and missed opportunities will be discussed in an effort to show how to design a survivable space power system and get it flown. Reasons why new, more durable designs need to be flown for mission success will also be discussed. Satellite anomaly statistics will be shown documenting main failure modes.

This presentation will follow the conferences' theme of "From Imagination to Reality." It will document the challenges, successes, and future potential of the Stretched Lens Array.

THE NEED FOR NEW DESIGNS

Solar Array Anomalies

Providing reliable power over the anticipated mission life is critical to all satellites; therefore solar arrays are one of the most vital links to satellite mission success. Furthermore, solar arrays are exposed to the harshest environment of virtually any satellite component. Over the last ten to eleven years Airclaims has documented 117 satellite solar array anomalies, 12 of which resulted in total satellite failure. Thus it is clear that solar array reliability is a serious, industry-wide and nation-wide issue. Past and current solar array failures on orbit increase the need for new more robust and reliable solar arrays.

To better face the challenge of solar array failures on orbit, more feedback is essential. A statistical analysis has been completed through the use of Ascend's Airclaims SpaceTrak database which is the space industry's leading events-based launch and satellite database.[1] The solar array anomalies that have occurred on orbit in the past ten years have been categorized by year and orbit showing that the number of satellite failures in GEO is significantly greater than any other orbit (see Fig. 2). This failure rate is not due to more satellites being sent to GEO, because, in fact, LEO has the highest launch rate. The LEO orbit is associated with much lower levels of anomalies. Information in this database allows manufacturers to focus on the issues in GEO that are causing failures and modify their solar array designs to withstand the environmental conditions present in this orbit. GEO failures are believed to be attributed to electrostatic discharge caused when an array comes out of an eclipse period into a solar storm. By analyzing the known anomalies it is possible to pinpoint key issues where focused attention is needed in order to find solutions. Unfortunately, little diagnostic measurements are available that would help isolate the root cause of the failure.

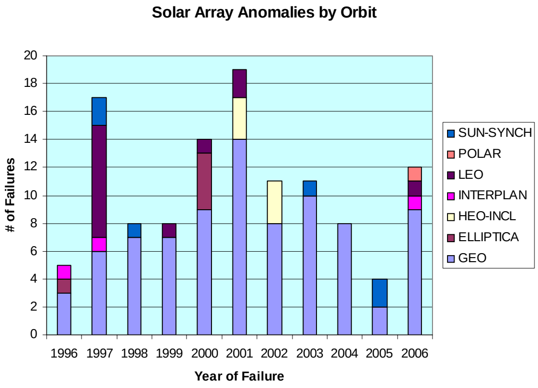

Fig. 2: Satellite failures by orbit

In addition, the number of solar array anomalies on satellites in GEO coincides quite well with the classic infant mortality trend as shown in figure 3. This generally indicates that the design is poor and/or there are defects in array construction. This observation raises fundamental questions about present day solar array designs, their construction and their testing (or over-testing) prior to launch. Ways to solve the cause for these anomalies prior to flight and creation of new designs that prevent these anomalies must be found. Unfortunately, new solar array designs are usually not considered for flight due to the conservative belief that flight heritage is the best proof of performance and that requiring more pre-launch testing will resolve the problems. Most stringent testing will not correct an inherent design flaw.

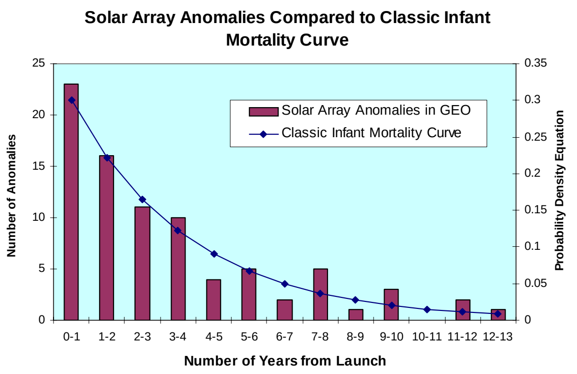

Fig. 3: Years b/w launch and solar array anomaly in GEO

In our opinion, an example of a new technology that should be embraced is the Stretched Lens Array developed by ENTECH Inc. in Ft. Worth, TX. The SLA is a refractive concentrator with efficiencies greater than 27%. It can be super-insulated and super-shielded with minimal mass penalty because of its 8X concentration level. Ground testing has shown that it is resistance to electrostatic discharge and micrometeoroid bombardment. This makes it an optimal candidate for GEO missions which have previously been shown to be the most susceptible to anomalies. The reduced mass of the SLA also allows for the potential of more transponders. Better designs, such as the SLA, need to be tested and flown because they provide a way to improve the reliability of solar arrays and eliminate the present anomalies at lower cost.

Increased performance

Solar array power levels will continue to increase as lunar bases, solar electric propulsion missions, and higher power communication satellites are developed. As power levels continue to increase, more durable arrays that can operate at high voltage and in high radiation environments must be incorporated. The higher power levels make high voltage operation desirable in order to lower resistive losses. SLA's small cell size (85% smaller than the cells in planar high-efficiency arrays), allows the cell circuit to be super-insulated and super-shielded without a significant mass penalty. Lower mass, lower cost and higher efficiencies will combine to enable future missions.

Overcoming the idea of "stick with what you know"

Going from the lab to mission success is a long and tedious process requiring extreme testing and analysis. It is important to find a niche where the new technology can fill a void or fix a problem; otherwise the known industry standard is "stick with what you know" (i.e. "heritage"). The space sector is extremely conservative and past failures make it difficult to get a new design built and flown despite demonstrated advantages. The best way to fit into the tight market is to invent something that fill a specific need along with increasing the performance and lowering the cost of current options. The SLA can overcome the electrostatic discharge problem that is currently occurring in GEO satellites and it is lighter and cheaper.

FUNDING EFFORTS

Funding for the development of new inventions is always a factor in enabling a technology to go from the conceptual stage to production. Two main sources of funding are provided by Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs through NASA or other U.S. government agencies. ENTECH Inc. began developing space concentrators in the late 1980's under SBIR programs from NASA and the Strategic Defence Initiative Organization (SDIO). This funding covered the initial cost of research and prototype testing and even some flight experiments. Once an innovation proves its functionality and reliability in space, it will enter the marketplace with potential customers covering the remaining costs. Other sources of funding are available through grants and research cooperatives.

EXPERIMENTAL FLIGHT TESTS

A new innovation must prove itself through experimental flight tests. Ground testing is rarely persuasive or sufficient. Past flight experiments with comparable SLA hardware include PASP+, SCARLET, and MISSE.

PASP+

The first refractive concentrator array was developed and flown on the PASP-Plus mission in 1994-95, which included eleven small advanced arrays plus a mini-dome lens concentrator. 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 coated to provide protection against space ultraviolet radiation and atomic oxygen. The mini-dome lens array which flew on PASP Plus can be seen in Fig. 4.

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. This validated the high performance and radiation hardness of the refractive concentrator approach.[2] In fact, the mini-dome lens array provided the highest performance and the lowest degradation of all 12 advanced arrays on the PASP Plus flight test.[2] It is also noteworthy to mention the refractive concentrator array was able to withstand cell voltage excursions to 500 V relative to the plasma with minimal environmental interaction in high-voltage space plasma interaction experiments.[2]

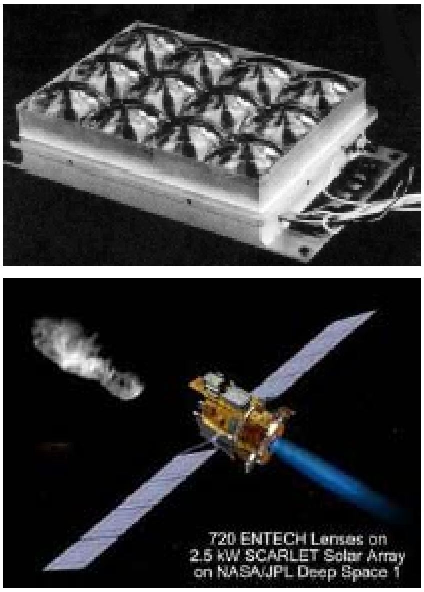

Fig. 4: Top photo is the PASP+ module, bottom photo is the SCARLET Deep Space 1 array

SCARLET

In the late 1990's, a new line-focus Fresnel lens concentrator, which is easier to make and more cost-effective than the mini-dome lens concentrator, was developed. The SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array was flown on the Deep Space 1 NASA mission between 1998-2001 (see Fig. 4).[3] SCARLET used an (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiatively cooled triple-junction cells. The solar array was the first to fly using triple-junction solar cells as the principal power source for a spacecraft. The 2.7 kW SCARLET array powered both the spacecraft's electronics and the ion engine. 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. At the end of the 38-month extended mission, in December 2001, SCARLET's power was still within + 2% of predictions.[4] The Stretched Lens Array is an evolved version of SCARLET, retaining the essential power-generating elements.

DEVELOPMENTAL STAGES

Initial Concept

For the last 30 years, ENTECH has designed patented concentrating systems to produce useful energy from sunlight for both space and terrestrial applications. SLA uses a unique color-mixing stretched Fresnel lens to focus sunlight onto unique integral-diode multijunction cells. The lens provides over 90% net optical efficiency combined with an amazing tolerance for shape error.[5] The concentration ratio of SLA can be tailored to meet mission sun-pointing requirements. For example, to provide ±2 degrees of sun-pointing tolerance about the critical axis, a geometric concentration ratio of 8.5X is used, corresponding to a lens aperture width of 8.5 cm and a cell active width of 1.0 cm. The small aperture size of SLA enables excellent radiator thermal performance, maintaining the SLA cell temperature within about 10ºC of competing one-sun array cell temperatures for any type of mission.

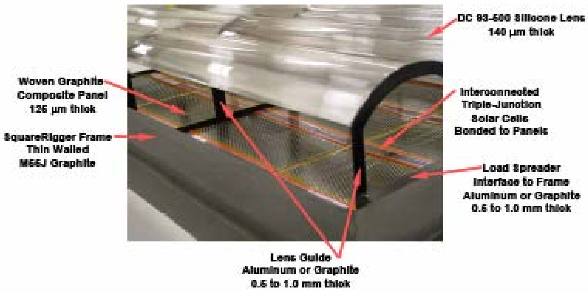

Fig. 5: SLA prototype

Modifications for improvement

The defining feature of SLA that enables the elimination of many elements of the SCARLET array is the stretched lens optical concentrator shown in figure 5. By using pop-up arches to stretch the silicone Fresnel lens in the lengthwise direction only, these lenses become self-supporting stressed membranes. SCARLET's glass arches are thus no longer needed, eliminating their complexity, fragility, expense, and mass in the new SLA.[5] With this substantial lens-related mass reduction, the supporting panel structural loads are reduced, making ultra-light panels practical for SLA. Because of its 8.5X geometric concentration ratio, SLA saves over 85% of the required area, mass and cost of the multi-junction solar cells per watt of power produced. Significantly, the total combined areal mass density (kg/m^2 of sun-collecting aperture area) of the lens material, the radiator sheet material, and the fully assembled photovoltaic receiver is much less (about 50%) than for a one-sun multi-junction cell assembly alone. Thus, SLA has a substantial inherent mass advantage over planar, one-sun multi-junction-cell solar arrays. Similarly, due to its 85% cell area and cost savings, SLA has at least a two-fold inherent power cost advantage ($/W) over such planar multi-junction-cell arrays. The SLA offers unprecedented performance (>80 kW/m^3 stowed power, >300 W/m^2 areal power, and >300 W/kg specific power) and cost-effectiveness (50-75% savings in $/W compared to conventional solar arrays).

Versatility of design

The solar array must have the ability to operate in with various structural elements and deployment mechanisms. Fig. 6 shows the near-term, low-risk, rigid-panel version of SLA. The SLA on the SquareRigger Platform (SLASR) was previously shown in Fig. 1 and its unique deployment of this structure is shown in Fig. 7. This array design spans the range in power from 4 kW to above 100 kW.

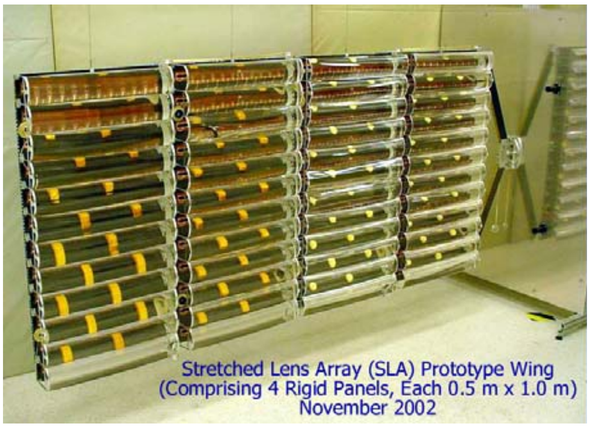

Fig. 6: Rigid-Panel Stretched Lens Array (SLA) Prototype Wing.

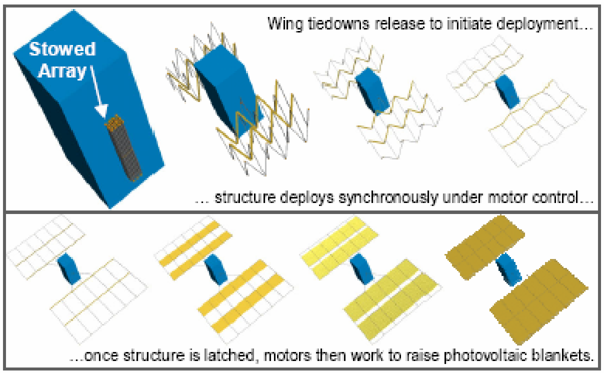

Fig. 7: Deployment of SLASR

Increasing Power, lowering mass

As technologies continue to improve it is possible to increase the efficiency and decrease the mass of the solar array. Currently the majority of the mass, 70%, is made up of the lens and cell panels. With the use of the new IMM cell and changes to the adhesives it is possible to lower this to 54% as seen in Fig. 8.

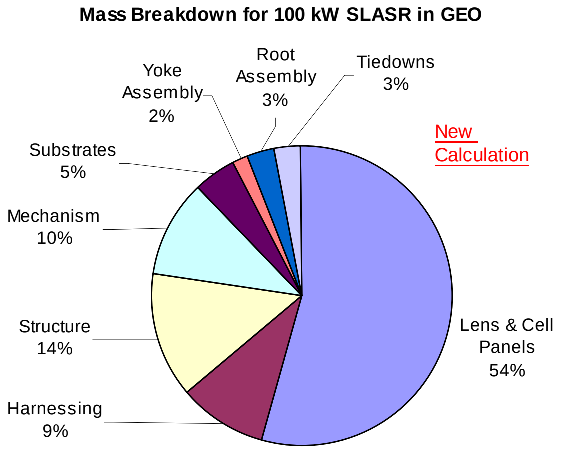

Fig. 8: Mass breakdown for a 100 kW SLASR

ENVIRONMENTAL TESTING

SLA system testing includes micrometeoroid bombardment, space environmental effects, extreme temperature cycling, radiation exposure on the lens material, and corona testing. All aspects of the SLA have tested durable to the space environment and the results will be presented.

High Voltage Operation

The SLA design is suited for high voltage operation because the entire cell and cell edges are fully encapsulated by a cover glass that overhangs the perimeter and the silicone adhesive covers the cell edges, thus it provides a sealed environment which limits the possibility of electrostatic discharge. Similarly, any exposed interconnection will also be sealed. To test the survivability of the SLA in high voltage operations, array segments underwent testing for corona breakdown. ENTECH has fabricated and tested a number of such single-cell SLA receiver samples at very high voltage levels (2,250 to 4,500 V) in an underwater hi-pot test for very long periods of time. Auburn University has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. These tests are being conducted using the guidelines found in ESA's IEC International Standard #343 (1991): "Recommended Test Methods for Determining the Relative Resistance of Insulating Materials to Breakdown by Surface Discharges."[6] The samples underwent testing at 2,250 V for ten and a half months and showed no change. Due to the SLA's inherent protection against electrostatic discharge it is especially well-suited for electric propulsion missions. The SLA is also fully compliant with the new NASA-STD-4005: "Low Earth Orbit Spacecraft Charging Design Standard".

Hypervelocity Impact Testing

Micrometeoroid impacts on solar arrays can lead to array arcing if the spacecraft is at an elevated potential in a conductive plasma field. Therefore, hypervelocity testing of the solar array is necessary. A concentrator solar cell module supplied by ENTECH, Inc was tested at Auburn University's Hypervelocity Impact Facility. The module was tested at voltages over 1000 V and was impacted by soda lime glass particles moving at 10-12 km/sec while in a simulated LEO plasma environment.[7] The module consisted of a string of concentrator multijunction solar cells in series that were completely covered with cover glass. The cover glass extended well beyond the cell boundaries and was also filled with silicone adhesive providing a sealed environment. No arcing occurred over the sample despite visible particle impact penetrations of the covers. Additional tests were performed with the stretched lens in place over the samples, and the lens was not torn and provided excellent additional shielding of the cell circuits. In effect, it acted as a micrometeoroid bumper and shattered the particles. The sample was also exposed to rear-side impact test shot with bias voltage at –1027V.[7] Although there were many impacts no arcing was observed.

Radiation Exposure

Testing has also shown that the silicone lens material can tolerate $5x10^{10}$ rads of combined electron and proton exposure with only minor degradation. The energy distribution of the particles was chosen to simulate the GEO spectrum. The dose was equivalent to 10 years on GEO using the current AE8/AP8 environments. Spectral transmittance data from NASA MSFC testing of lens material with UV-rejection coatings shows no damage after more than 1000 equivalent sun hours of combined vacuum ultraviolet (VUV) and near ultraviolet (NUV) exposure.

Thus all aspects of the SLA have tested and shown durable to the space environment.

OBSTACLES

Conservative beliefs of "heritage"

The first hurdle in getting a new technology flown in the space sector is overcoming the conservative belief that heritage is best. Better designs that will improve solar arrays and eliminate present failures need to be tested and flown. New technology is usually not embraced due to the increased fear of failure. Satellite owners and manufactures would rather "stick with what they know" than to take any additional risks. This limits the opportunities to make major increases in solar array reliability. Newer designs are often engineered and built to withstand known anomalies, yet "heritage" is deemed more worthy. However, in retrospect, oftentimes sufficient changes have been made in the design to eliminate its heritage status.

Lost Opportunities

Satellite and space mission failures leave devastating and far reaching consequences. Millions of dollars will be lost along with years of work on the prototype elements. ENTECH and ABLE Engineering (now ATK Space) looked for a near-term flight opportunity early in the SLA development and found the COMET/METEOR spacecraft that was set to be launched in 1995. They worked hard to put together the first flight test, using 4-cm-wide glass/silicone lenses over tiny strips of GaAs solar cells from Spectrolab, with thick silicone secondary optics for radiation hardness. The whole assembly was attached to the spacecraft in time for the launch on a Conestoga rocket from Wallops Island, VA. Unfortunately, the launch vehicle failed less than a minute after launch, and was lost in the Atlantic Ocean. Thus one validation opportunity was lost.

Failures of designs deemed “similar” by design

Today concentrator arrays have a bad name because of the very expensive and serious miscalculations in the past. However, not all concentrators are same and therefore not all types should be disregarded without serious consideration. The publicized concentrator failures dealt with reflective concentrator systems. The major problem with reflective concentrator systems is their lack of shape error tolerance. Refractive concentrators minimize the effects of shape errors and provide more than 100X larger slope error tolerance than do the reflective or flat concentrators.[5] These effects are shown in Figs. 9 and 10.

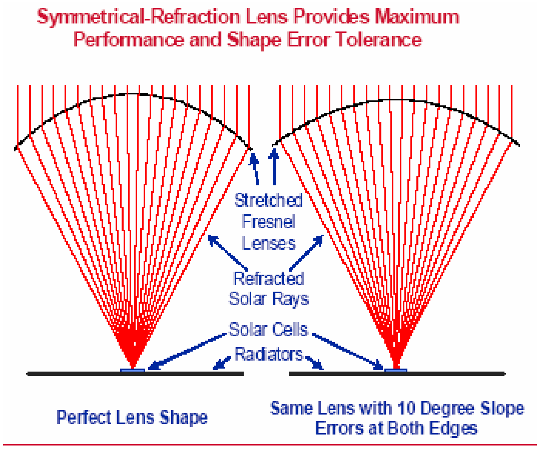

Fig. 9: Shape error tolerance for a refraction system.

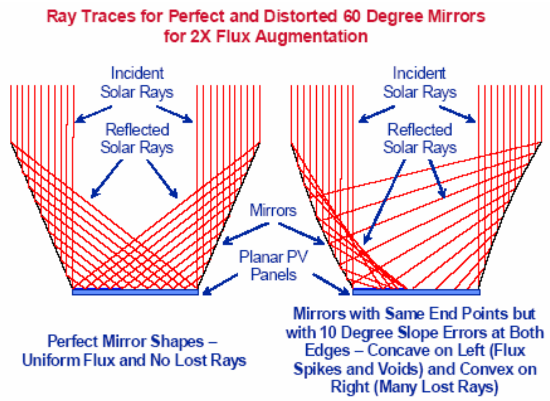

Fig. 10: Distortion of a reflection system

Another shortcoming of reflector concentrator systems is due to non-uniform irradiance. This problem arises because the cell with the least illumination limits the current of the cells that are connected in series with it. This has a significant dampening effect on the power output of the solar array. The SLA avoids these problems entirely by having the same focal line on every cell in every series string thus making the current output essentially identical in every string.

The thermal challenge of removing heat from the photovoltaic panel is another shortcoming of the reflector system. The radiator area needs to be the same size as the aperture area of the optics in order to maintain a temperature near that of a planar one sun array. Providing the extra area can be quite costly due the increased weight and was not implemented on the well-known concentrator array failures. High temperatures can cause outgassing leading to damage to the array and severe power degradation as was seen in previous flights. In the SLA design, the radiator spans the entire width of the lens aperture – 8.5 cm. This allows the radiator to be rather thin yet still conduct the necessary heat away from the narrow cells. The SCARLET array, a predecessor of SLA, remained at the predicted temperature (~70 ºC at GEO conditions) throughout its mission and had no outgassing.

A query of the Airclaims’ Ascend SpaceTrak database on concentrator failures showed the only claims were associated with the fleet of Boeing 702/GEM satellites. Degradation in power in these satellites occurred at a faster rate than expected causing satellite life expectancy to be downgraded from 15 years to 6.75 years. This was believed to be caused by a 'fogging' effect caused by outgassing.[1] The fogging was believed due to the increased operating temperature of these reflective concentrator arrays (>125 ºC). As shown in Fig. 10, the geometry of these concentrators created a heat trough which caused higher temperatures and outgassing of sealants leading to a ‘fogging’ effect that then led to reduced power production. This problem is NOT seen in refractive systems such as the SLA. The SLA concentrator system provides reliable power and should not be impugned by its predecessors.

THE NEXT STEPS TOWARD FLIGHT

Upcoming Flight Test

Under an MDA-sponsored Phase II STTR program, ENTECH and Auburn University have fabricated and delivered a near term flight experiment for integration onto the main solar array for the Naval Research Laboratory's TacSat IV spacecraft, scheduled for launch in 2009. This flight experiment is known as the Stretched Lens Array Technology Experiment on TacSat IV (SLATE-T4). SLATE-T4 is shown in Fig. 11. TacSat IV is intended to fly in a high radiation orbit, thus providing valuable solar cell degradation information along with proving flight validation for the Stretched Lens Array. The SLA receiver includes a 0.5 mm-thick ceria-doped cover glass (made by QioptiQ) and the lens incorporates ENTECH's proprietary thick parquet coating, applied by Ion Beam Optics. These will provide protection from degradation due to the effects of solar ultraviolet radiation, atomic oxygen, and low-energy charged particles.

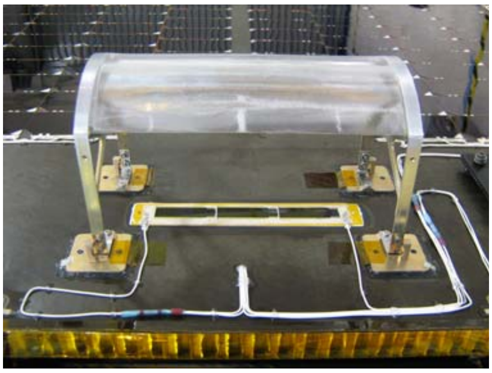

Fig. 11: SLATE-T4 Parquet-Coated Lens and Three-Cell Photovoltaic Receiver Mounted on TacSat IV Solar Array Panel

On-going Testing Opportunity

Fig. 12 shows a schematic of a typical SLA-SEP mission with the spacecraft in earth orbit.[4] The array will point toward the sun while the spacecraft orbits the earth, and some interaction will take place between the array and the thruster plume, especially at the inner corners of the array as these move through the outer regions of the plume. Thus, in addition to providing high efficiency, low mass, and radiation-hardness, the SLA must also tolerate plume interactions with the thruster.

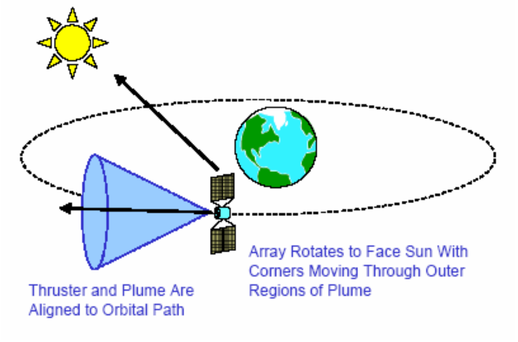

Fig. 12: Typical Solar Electric Propulsion Mission Schematic.[4]

Future SLA testing will consist of a "direct drive" experiment using a high-voltage (600 V open-circuit) SunLine concentrator array that has multijunction solar cells coupled to a Russian T-100 Hall thruster. This is the next step under a Phase II STTR with NASA Glenn for the development of SLA hardware for SEP missions and will be performed at Auburn University. The goal of this demonstration is to prove reliable operation of a Hall thruster powered directly from a high voltage concentrator array. Testing will include the addition of Stretched Lens Array hardware in a vacuum chamber at the Space Research Institute at Auburn University to measure plume impingement effects at various positions relative to the exhaust axis of the thruster. A schematic of planned testing can be seen in Fig. 13.

The high-voltage array shown in Fig. 14 was transported from ENTECH to Auburn where it is being interfaced with the Hall-effect thruster in the large vacuum chamber shown in Fig 15. The array uses two of ENTECH's color-mixing lenses to focus sunlight onto two photovoltaic receivers each using 240 series-connected triple-junction Spectrolab cells to

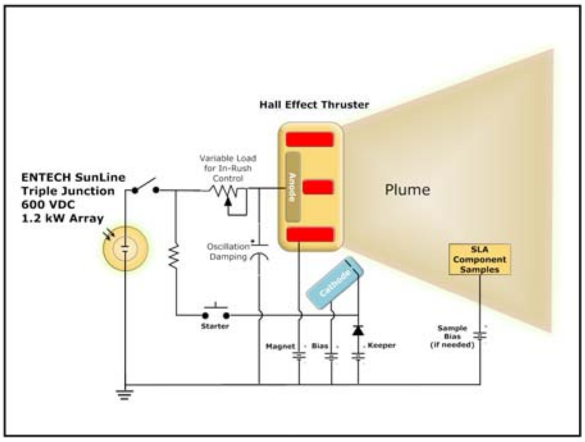

Fig. 13: Schematic of planned direct-driven HET and SLA test configuration.

provide 600 V output at open-circuit conditions. The peak power point is around 500 V, and the total power output of the array is over 1 kW under clear sky conditions.[4] The Russian thruster shown in Fig. 15, is a Model T-100 SPT, designed and constructed by the Keldish Research Center (KeRC), and capable of operating up to 1.3 kW.[4] This thruster is on loan to Auburn from the NASA Glenn Research Center. Testing will start in the next few months.


Fig. 14 : SunLine Concentrator array


Fig. 15: Auburn student inspects Russian T-100 thruster

CONCLUSION

The journey to get any new technology first flown and then commercialized in space is long and hard. However, the payoffs are quite high when the new design can increase the reliability of solar arrays and thus benefit the entire space satellite industry. Reducing on-orbit failures will ultimately reduce insurance costs. This tedious journey requires extensive ground testing and analysis as well as flight testing. It is important to find the niche where the new technology can fill a void or fix a problem; otherwise the known industry standard is "stick with what you know."

An example of a new technology that should be embraced is the Stretched Lens Array. It can be super-insulated and super-shielded with minimal mass penalty due to its 8X concentration. Ground testing has shown its resistance to radiation, electrostatic discharge, micrometeoroid bombardment, and the other hazards of the space environment. These attributes make it an optimal candidate for GEO missions because they have previously been shown to be the most susceptible to anomalies like these.

The SLA is an optimal array for missions in harsh orbits because of its unique portfolio of attributes. The SLATE T-4 flight demonstration will be the final hurdle it will pass leading to significant, broad usage. In our opinion, it is the array of the future and it is working its way from imagination to reality.

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