INFLATABLE LENSES FOR SPACE PHOTOVOLTAIC CONCENTRATOR ARRAYS

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ABSTRACT

For 12 years, ENTECH and NASA Lewis have been developing Fresnel lens concentrator technology for space power applications. ENTECH provided the point-focus mini-dome lenses for the PASP+ array, launched in 1994. These silicone lenses performed well on orbit, with only about 3% optical performance loss after 1 year in elliptical orbit, with high radiation, atomic oxygen, and ultraviolet exposure [1]. The only protection for these silicone lenses was a thin-film coating provided by OCLI. ENTECH also provided the line-focus lenses for the SCARLET 1 and SCARLET 2 arrays in 1995 and 1997, respectively [2]. These lenses are laminated assemblies, with protective ceria glass superstrates over the silicone lens. In March 1997, ENTECH and NASA Lewis began development of inflatable Fresnel lenses, to achieve lower weight, smaller launch volume, reduced cost, less fragility, and other advantages. This paper summarizes the new concentrator approach, including key program results to date [3].

INTRODUCTION

Fig. 1 shows the present elements of the space photovoltaic array known as SCARLET (Solar Concentrator Array with Refractive Linear Element Technology). A team of organizations, led by ABLE Engineering, has developed the SCARLET series of arrays [2]. ENTECH has developed a manufacturing process to produce high-quality lenses comprising a thin ceria-doped microsheet superstrate laminated to a clear silicone rubber Fresnel lens. Over 800 of these patented lenses were produced and delivered in early 1997 for the 2.6 kW New Millennium Deep Space 1 array.

In May 1996, the JPL/L'Garde Inflatable Antenna Experiment (IAE) was successfully deployed on-orbit from the Space Shuttle, as shown in Fig. 2. This experiment demonstrated the potential of large inflatable structures for space concentrator applications. After researching the IAE, ENTECH proposed to NASA to develop inflatable Fresnel lens solar concentrators for space power applications, including photovoltaic and solar dynamic systems. In March 1997, a Phase I SBIR contract was awarded. One key goal of the program is to develop inflatable line-focus lenses for future ultralight versions of the SCARLET array.

INFLATABLE LENS APPROACH

A number of conceptual designs of the inflatable lens were investigated before selecting the self-deploying, integrated approach of Fig. 3. This approach includes the lens at the top of the inflated structure, thin film sidewalls, and a backplane radiator. Several prototypes of this design have been fabricated and tested, with excellent optical performance and very low areal mass. Fig. 4 shows one of these prototypes. The lens in this prototype is the SCARLET lens of Fig. 1, without the glass superstrate. The sides and ends are 12 micron Mylar® film, and the backplane radiator is 75 micron aluminum. When deflated, the stowage volume is extremely compact.

OPTICAL PERFORMANCE

All of the inflated prototype lenses produced exceptionally clear images under outdoor sunlight illumination. The optical efficiency of one prototype lens was carefully measured in an outdoor test. The short-circuit current output of a GaAs cell was measured, first under lens irradiance, and then under one-direct-sun irradiance. A pyrheliometer was monitored to verify constant direct solar irradiance throughout both measurements. The ratio of the two measured currents provides the net concentration, which is divided by the geometric concentration ratio (GCR, which is lens aperture width divided by cell active width) to determine lens optical efficiency. The optical efficiency was measured at 92% $\pm$ 1% at 7.4 X GCR. This is slightly better than the 89% $\pm$ 2% at 8 X GCR, typically measured for the rigid SCARLET lens, without anti-reflection (AR) coating on the glass.

AREAL MASS AND SPECIFIC POWER IMPLICATIONS

Fig. 5 summarizes the mass measurements for one of the prototype inflatable lens assemblies. Including the 75 micron aluminum radiator, the total measured mass of this prototype divided by the lens aperture area is 0.8 kg/sq.m. (Excluding the radiator, this areal mass is 0.6 kg/sq.m.) The significance of this low areal mass is shown in the graph of Fig. 5. With dual-junction cells already available, and triple-junction cells under development by several organizations (NREL, Tecstar, Spectrolab, and JX Crystals), 25% array efficiencies are near-term prospects. Combining the measured 0.8 kg/sq.m. inflatable lens prototype mass with this projected 25% array efficiency results in an array specific power of 400 W/kg.

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KEYS TO PERFORMANCE

One key to the excellent optical performance of the inflatable lens prototypes is the use of a symmetrical refraction lens, which provides more than 100 times larger shape error tolerance than flat Fresnel lenses or reflective optical concentrators [4]. Another key is the cylindrical shape of the symmetrical refraction lens, shown in Fig. 6. The natural shape for an inflatable structure is cylindrical for a two-dimensional version, or spherical for a three-dimensional version. The symmetrical refraction lens is thus ideally suited for inflatable applications.

LENS MANUFACTURING

For nearly 20 years, 3M has manufactured Fresnel lens material to ENTECH specifications using proprietary continuous processes. Fig. 7 summarizes the present status of these 3M processes for manufacturing both terrestrial and space lens materials. The space-qualified silicone lens material used in the SCARLET series of arrays is delivered to ENTECH by 3M in continuous rolls, with tens of meters of lens length on each roll. Thus, a proven, high-volume, economical process is available to make the new inflatable lens material. Furthermore, this process provides lens material in virtually unlimited length, which could be used to make very long inflatable lens assemblies. Such long assemblies would minimize both lens part count (per array) and end effects (structural and optical).

MICROMETEOROID PUNCTURE EFFECTS

One of the most frequently asked questions for inflatable space structures relates to micrometeoroid punctures. An analysis has been conducted to quantify both the porosity created by these punctures, and the gas leakage rates through them, for the inflatable lens arrays. NASA has published micrometeoroid data for the particle fluence versus particle size for low earth orbit (LEO) [5]. When these fluence data are integrated over all particle sizes, the total particle cross sectional area divided by the array projected area is about 1.5×10^{-7} per year. Inflated lens porosity has been estimated by assuming that each particle goes all the way through both the lens and the rear portion of the inflated structure, leaving behind two holes each equal in area to the particle cross section. Then the total porosity value is 3×10^{-7} after 1 year on orbit. After 2 years on orbit, the porosity will be 6×10^{-7}, after 3 years it will be 9×10^{-7}, and so forth.

Gas leakage rates have been estimated by assuming choked (sonic) flow across the hole area for each puncture, since the gas is leaking to the hard vacuum of space. With this assumption, the total gas leakage rate depends on the gas pressure, temperature, and molecular weight, as well as the total puncture area. To be conservative, the gas pressure has been assumed to be the design pressure for the Inflatable Antenna Experiment (IAE), namely 0.7 Pascal [6], although smaller pressures would easily support the lens against acceleration loads on orbit. The gas temperature range has been estimated, based on simple thermal analyses, to be in the range of 150-250K. To be conservative, the lower end of this range has been used to estimate gas leakage rates. Hydrogen is the preferred inflation gas, because of its low molecular weight, although other gasses could be used. Finally, an array efficiency of 20% has been assumed to define the array area per unit power output.

Figure 8 shows the results of the analysis in terms of total gas mass loss per unit array power, as a function of years on orbit. The parabolic shape of the curve is due to the continually increasing porosity with time. Note that even after 15 years on orbit, the total gas loss is still less than 2.5 kg/kW. These results imply that make-up gas could be launched along with a purely inflatable array at a very small mass penalty, especially for shorter missions. Alternatively, if no make-up gas is launched, a long period of time will be available after deployment for rigidizing the inflated structure, perhaps via relatively slow chemical reactions such as solar ultraviolet curing of stabilizing members.

CONCLUSIONS

From the development work done to date, the following conclusions can be made:

1. A new inflatable lens solar concentrator has been developed, with demonstrated 92% optical efficiency, 0.8 kg/sq.m. areal mass, and compact stowage.
2. These measured optical and mass results imply that an array specific power of 400 W/kg should be achievable in the relatively near term.
3. The inflatable concentrator uses a proven high-efficiency, error-tolerant lens, with a cylindrical shape that is ideal for inflatable deployment and support.
4. Manufacturability of the lens has already been established, using the same lens material system that performed successfully on the 1994-95 PASP+ array.
5. Micrometeoroid puncture analysis shows that purely inflatable versions of the new concentrator will require very small amounts of make-up gas, or that a long period of time will be available after deployment for implementing a more permanent rigidizing scheme.

REFERENCES

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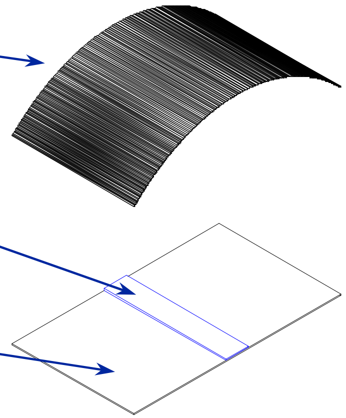
[5] D.J. Kessler et al., "Orbital Debris Environment for Spacecraft Designed to Operate in Low Earth Orbit," NASA TM 100471, 1989.

[6] R. Freeland, Personal Communication, Jet Propulsion Laboratory, Pasadena, CA, 1997.

Figure 1. Present SCARLET Space Array Approach.

- **Arched Linear Fresnel Lens:**
  - 80 micron Ceria Glass Superstrate
  - 220 micron 93-500 Silicone Lens
  - Aperture Width: 8 cm
  - Aperture Length: 21 cm
  - Focal Length: 9 cm
- **Photovoltaic Receiver:**
  - Monolithic Multi-Junction GaInP/GaAs on Germanium
  - Cell Width: 1 cm for ± 2 Degrees Sun-Pointing Error Tolerance
- **Radiator Panel for Cooling:**
  - Carbon Composite



Solar Concentrator Array with Refractive Linear Element Technology

Figure 2. Inflatable Antenna Experiment (IAE).

This Large L'Garde Dish Antenna Successfully Inflated On Orbit

NASA Photo 5/20/96

(Downloaded from Space News OnLine)

Note: For a Solar Concentrator Application, a Reflective Concentrator Needs >100 Times Better Shape Accuracy than a Symmetrical Refraction Fresnel Lens

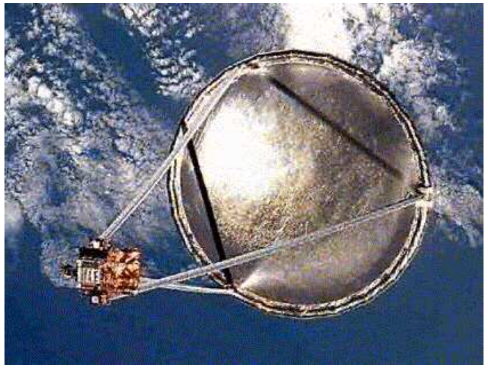


Figure 3. Inflatable Lens PV Concentrator Approach.

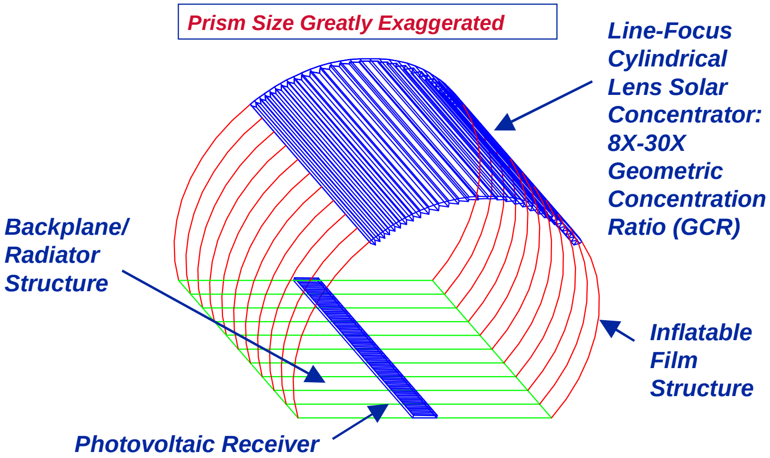


Figure 4. Prototype Inflatable Linear Fresnel Lens.

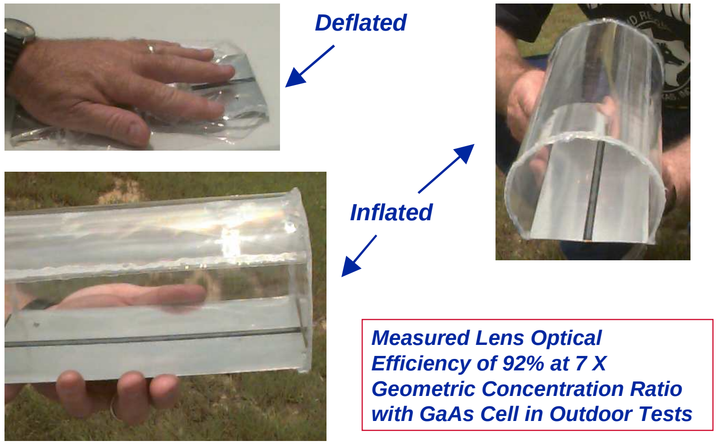
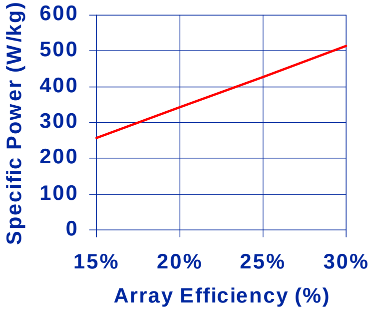


Figure 5. Inflatable Linear Fresnel Lens PV Concentrator.

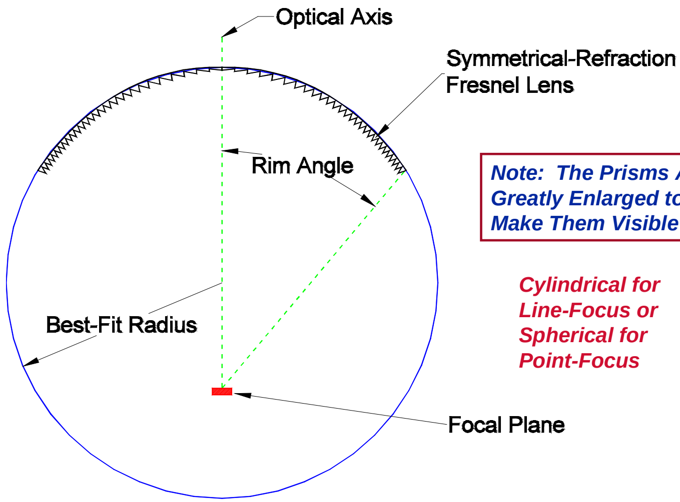
Prototype with 75 micron Al Radiator

Projected Specific Power Based on Measured Prototype Mass/Aperture



__Mass__: 27 grams *__Aperture__: 344 sq.cm.* *__Mass/Aperture__: 0.8 kg/sq.m.*

Figure 6. Inflatable Lens Geometry.



Note: The Prisms Are Greatly Enlarged to Make Them Visible

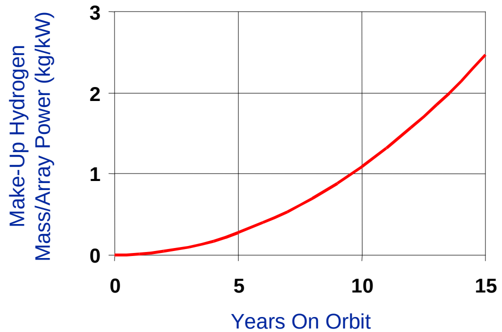
Cylindrical for Line-Focus or Spherical for Point-Focus

Figure 7. Continuous Fresnel Lens Material from 3M.

- 200 Meter Long Roll
- Proven Process for 100-cm-Wide, 0.05-cm-Thick Terrestrial Lenses in Acrylic, Polycarbonate, and Similar Thermoplastics
- Proven Process for 50-cm-Wide, 0.02-cm-Thick Space Lenses in Silicone Rubber (DC 93-500) and Similar Cast-and-Cure Materials
- Line-Focus, Point-Focus, and Panel or Gore Segment Patterns Can Be Produced

Figure 8. Micrometeoroid Puncture Gas Loss per Unit Array Power.

- NASA TM 100471 LEO Micrometeoroid Environment
- Every Particle Passes Clear Through Front and Back of Array, Leaving 2 Holes Equal to Particle Cross Sectional Area
- Hydrogen Gas at 0.7 Pa and 150K
- Choked (Sonic) Flow Through All Puncture Holes
- 20% Array Efficiency



These Are Very Small Mass Penalties